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

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 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.

[1] One co-author of the CED method, R. 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, Finnveden et al. 2009), but not specifically with net energy return to society.

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 recognize 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 recognize 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 inspection these

[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)).

results appear identical to those presented in Fig. 5 in Modahl et al. (2013)[3]. Conversely, the central columns are calculated by subtracting the HHV of the fuel input. Introducing consistent HVs increases the results by 20-70%.

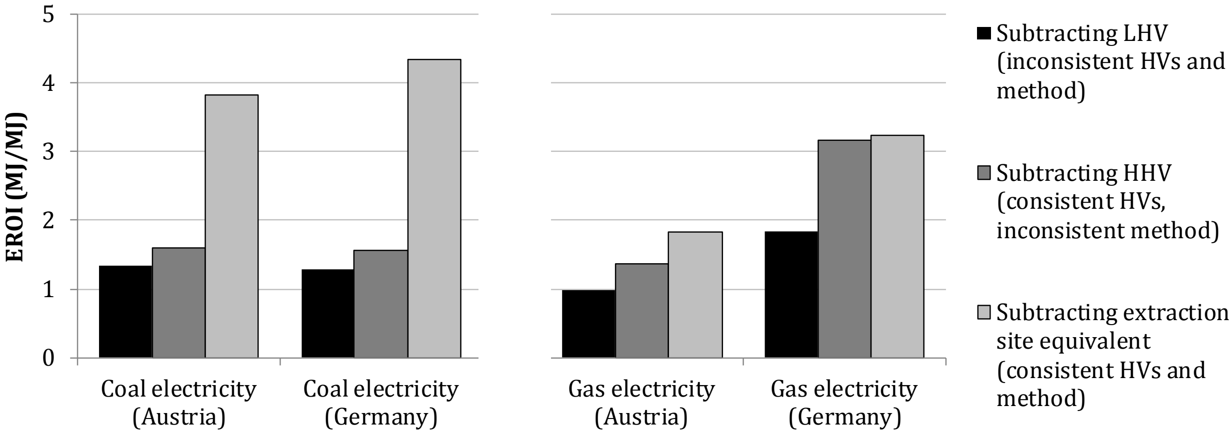

Fig. 1. Examples of energy return on investment (EROI; in Modahl et al. (2013) termed 'energy payback ratio') results for Austrian and German coal and gas power in Ecoinvent (2010). For each of the four cases, the left (black) columns represent results obtained when subtracting the lower heating value (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).

The second point is that the CED method tracks the total energy resources extracted from nature, not the energy diverted from society. CED includes energy losses at the extraction site, such as methane released from coal seams during mining, and along the entire supply chains, such as loss of energy content when coal is transported. These energy losses are not investments that need to be 'returned' or 'paid back' in order for a resource to constitute a net energy source. They are not used or converted for any purpose and they do not support human activity. The conceptual difference between EROI and CED has implications for what energy flows should be regarded as energy costs: From an EROI standpoint, energy that is lost does not in itself represent a cost, because human activities compete for access to usable energy;

[3] We are not able to reproduce the result in Modahl et al. (2013) that Czech coal power exhibits by far the lowest power plant efficiency but also by far the highest energy payback among coal power options.

from a CED standpoint, energy that is lost represents a cost, because it decreases the remaining resource.

We propose that analysts always adopt the CED accounting method for energy flows subtracted from CED results. Because CED measures energy extracted from nature and not energy available to society, it is important to account for losses in the energy content of the primary energy stream itself along the chain when subtracting this energy stream from the CED to estimate the energy expended by society. The right columns in Fig. 1 show EROI results established using this approach. The primary cause for the substantial jumps in EROIs for coal electricity is that storage or transport losses are not considered as investments. Correspondingly, the increases for gas electricity are due to fugitive methane emissions in extraction and transport not being considered as investments[4].

Ignoring differences in HV or failing to adjust for supply chain losses leads to results that are inconsistent and potentially misleading. For example, with the approach used by Modahl et al. (2013) and used here to generate the left and central columns in Fig. 1, the conversion loss of power stations is not treated as an investment to produce energy, but energy loss while coal is transported is treated as such. In sum, these results are neither meaningful indicators of energy resource demand, because they do not include the conversion loss at the power stations, nor of net energy return, because they include losses prior to the power station.

Other studies also fail to properly treat heating values or supply chain losses. Raugei et al. (2012) measure some inputs as CED in HHV and some as LHV at point of use when determining EROI for fossil fuel power. Aitken et al. (2014) combine LHV in the EROI numerator with HHV CED in the denominator.

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[4] The importance of properly treating fugitive methane emissions in LCA-EROI will likely increase in the future, as recent evidence (Krey et al. 2014) indicates that such emissions are higher than assumed for gas supply chains in Ecoinvent (2010).

A third issue addresses the measurement of the numerator in relation to the measurement of the denominator. Traditional EROI measures energy equivalents at the point where fuel is used. By contrast, CED measures primary energy withdrawn from nature. LCA-based EROI usually combines these different ways of measurement in a way which leads to inconsistency across the numerator and denominator pairs, as the numerator is defined at the point of delivery and the denominator is based on CED. Alternatively, EROI analyses of electricity sometimes address the issue by converting electricity output to a primary energy equivalent (e.g., Raugei et al. (2012)). Nonetheless, if the numerator and denominator are not measured by the same rule, one loses the intuitively appealing interpretation that EROI > 1 is the absolute minimum requirement a resource must meet in order to constitute a net energy source (Cleveland et al., 1984; Herendeen, 2004).

As the idea of EROI is to measure the diversion of energy already useful to society, it would be preferable to measure useful energy rather than CED in the denominator. We are not able to work out a feasible way of accurately removing energy losses from CED, however[5]. As a next best option, one may attempt to achieve consistency in the numerator and denominator pairs by using the CED accounting method for the energy stream in the numerator. Since we use the CED concept in the denominator, one may argue that we should use CED in the numerator as well to convert the useful energy produced back to its primary equivalent, i.e. adjusting for inefficiencies along the way in the same manner as we do for the denominator.

[5] Methane emissions from coal mines happen to be explicitly represented as energy flows in Ecoinvent; hence they are easy to eliminate in calculations. Other types of losses are not explicitly represented as energy flows; hence they are more difficult to identify. One could try to estimate energy losses based on process activity levels or fugitive emissions values, but this task is complicated by the large number of energy-related processes and insufficient transparency in underlying assumptions. Alternatively, one can take a simplified approach and assume that losses are removed by multiplying CED by an assumed factor < 1, but this may be inaccurate.

Table 1 demonstrates the basic application of this approach[6], showing EROI values for examples of fossil fuels represented in Ecoinvent. These EROIs appear remarkably low in comparison to previous estimates of 60-80 for US coal and 27-35 for Chinese coal, and 10-50 for oil produced in recent decades (Hall et al., 2014). An investigation into why these discrepancies occur falls outside the scope of this communication. As long as the discrepancies remain unexplained, they represent a reason for caution in interpreting LCA-EROI estimates.

Table 1. EROI values for examples of fossil fuels represented in Ecoinvent (2010), obtained by consistently using the CED method to determine both the numerator and denominator in the EROI ratio.

Ecoinvent process name	EROI (X:1)
Hard coal supply mix (Austria)	12
Hard coal supply mix (Germany)	16
Light fuel oil, at regional storage (Europe)	5.9
Heavy fuel oil, at regional storage (Europe)	5.0
Natural gas, high pressure, at consumer (Austria)	4.8
Natural gas, high pressure, at consumer (Germany)	8.2

Finally, another problematic aspect is that CED does not distinguish commercial energy from extracted or co-extracted energy burned at the site of extraction to extract more of the very same energy. One could argue that only the former type has been appropriated by society and constitutes energy which society has ‘at hand’, and that the latter type does not affect the ability of a resource to be a net supplier of useful energy (Brandt and Dale, 2011; Herendeen, 2004). We are not able to find a practical way of removing non-commercial energy from CED.

[6] We convert the energy produced back to its primary equivalent based on the supply chain for the fuel delivered. While this approach is acceptable for the common fuels investigated here, it may be problematic in cases where there are disproportionally large losses, as the large losses will translate into higher EROI. The problem may be avoided by basing the conversion on another supply chain (or a system-wide average) which is selected as a reference.

3.2 On the accounting of non-combustible fuel energy sources

CED is based on the concept of primary energy withdrawn from nature: for example, 3.87 MJ is withdrawn per kWh (or 3.6 MJ) of wind electricity and 3.79 MJ per kWh of hydroelectricity (Ecoinvent, 2010). Ecoinvent defines eight CED indicators separately, but refrains from providing an aggregate CED metric "[d]ue to the existence of diverging concepts and the unclear basis for the characterization of the different primary energy carriers" (Hischier et al. (2010), p. 34). On the other hand, CED-based EROI analyses add together separate CEDs and often also present general definitions of the EROI denominator as the sum of non-renewable and renewable primary energy (e.g., Raugei et al. (2012), Modahl et al. (2013)).

In contrast to CED, traditional EROI, energy statistics and energy system models do not rely on the concept of primary renewable energy (Krey et al., 2014; Murphy et al., 2011). General recommendations of Murphy et al. (2011) are that EROI analysis is "undertaken with both heat equivalents and quality-adjusted energy if possible", and that quality-adjustment is based on some consideration of relative fuel prices. Alternatively, quality-adjustment may build on the concept of exergy (Murphy et al., 2011).

It is a misconception among LCA practitioners that EROI measures energy inputs in the form of non-renewable and renewable primary energy. EROI does not need to measure primary energy *per se*; the crucial point is to measure energy diverted from society in a unit of equivalence. Furthermore, adding together chemical energy (as in fossil CED) and energy forms such as absorbed sunlight or captured wind involves an implicit weighting of energy forms which fits poorly with the idea of EROI. This is because the weighting merely reflects differences in the compound efficiencies by which primary energy forms (e.g., sunlight, oil) are converted to final energy carriers, irrespective of the quality or value of energy carriers to society. On the other hand, price- or exergy-based approaches to energy aggregation seek to establish equivalence in terms of energy quality or value (Murphy et al., 2011). Approaches that attempt to address energy quality or value are more consistent with the purpose of EROI.

While this issue is of little empirical importance in contemporary energy systems[7], it will become important if the share of renewables increases.

4 Conclusions and policy implications

The CED metric from LCA measures energy withdrawn from nature, while EROI is concerned with energy diverted from society to make energy available to society. When CED is used to determine EROI, energy flows such as fugitive dust emissions from coal stockpiles can be misclassified as investments of commercial energy, and energy forms such as absorbed solar radiation in solar power plants are mischaracterized as qualitatively equivalent to chemical energy content of combusted fuels. Another issue is heating value inconsistencies in the Ecoinvent LCA database, which requires attention by EROI analysts. A failure to recognize and handle such issues leads to results for coal and gas power that are wrong and misleading, as they give an erroneous impression of the net energy performance of coal relative to gas, and of coal and gas relative to renewables. Such flaws can be removed from calculations by adopting consistent energy accounting, as our numerical examples demonstrate (Fig. 1 and Table 1).

Declining EROI for dominant fuels threatens to reduce the availability of energy for purposes other than obtaining energy, hence, arguably, making it more difficult for societies to direct sufficient energy to satisfying human needs and desires (e.g., for food, health care, leisure), and to achieve economic growth (Ayres and Voudouris, 2014; Hall et al., 2014). A pertinent question for policy makers is hence whether new technologies, such as those

[7] Indeed we add together the different CEDs ourselves in the numerical examples (Fig. 1 and Table 1).

utilizing renewable energy, offer an EROI attractive compared to that of difficult-to-access oil and gas. An adequate calculation of the EROI for both fossil and renewable energy sources is required to answer this question.

CED is not meant to offer a ready-made means for EROI analysis. Contrary to the widespread perception that EROI can easily be calculated from CED, awareness and proper handling of methodological differences are prerequisite for robust assessments. A lack of such awareness leads to results that are misleading and diminish the reliability of EROI assessments for policy-support.

Appendix A

This appendix shows how the EROI results for coal electricity (Austria) in Fig. 1 and hard coal supply mix (Austria) in Table 1 are calculated, as two examples. Other EROI results presented in Fig. 1 and Table 1 are calculated in the same manner in principle, but with different data.

The total cumulative energy demand (CED) per kWh of electricity (‘el’) output of an Austrian coal power plant is:

$$CED_{el} = 11.60\ MJ/kWh$$

The EROI value represented by the left (black) column for coal electricity (Austria) in Fig. 1 is calculated as follows:

$$EROI_{el,left} = \frac{3.6\ MJ/kWh}{CED_{el} - 8.91\ MJ/kWh} = 1.3$$

The energy input of 8.91 MJ to ‘Electricity, hard coal, at power plant/ AT/ kWh’ is the lower heating value (LHV) of the fuel supplied to the power plant. The higher heating value

(HHV) is approximately 5% greater than the LHV for hard coal in Ecoinvent (Dones et al., 2007). The EROI value represented by the central (dark grey) column for coal electricity (Austria) in Fig. 1 is hence calculated as:

$$EROI_{el,central} = \frac{3.6\ MJ/kWh}{CED_{el} - 8.91\ MJ/kWh \cdot (1 + 5\%)} = 1.6$$

Utilizing the additional information shown in Fig. A.1, the right (light grey) column for coal electricity (Austria) in Fig. 1 is hence calculated as follows (units are not shown in the equation; the numbers 3.6 and 8.91 have units *MJ/kWh*, 0.0451 has units *kg/MJ*, 0.003 and 0.997 have units *kg/kg*, and 0.9990, 29.22, 0.5293 and 25.97 all have units *MJ/kg*):

$$EROI_{el,right} = \frac{3.6}{CED_{el} - 8.91 \cdot 0.0451 \cdot \left(0.003 \cdot (0.9990 + 29.22) + 0.997 \cdot (0.5293 + 25.97)\right)} = 3.8$$

The total CED per kg of hard coal supply mix (‘coal, sm’) in Austria is:

$$CED_{coal,sm} = 28.67\ MJ/kg$$

Again utilizing additional information shown in Fig. A.1, the EROI value for hard coal supply mix in Austria in Table 1 is calculated as follows (units are not shown in the equation; the number 0.0451 has units *kg/MJ*, 0.003 and 0.997 have units *kg/kg*, and 0.9990, 29.22, 0.5293 and 25.97 all have units *MJ/kg*):

$$EROI_{coal,sm} = \frac{0.003 \cdot (0.9990 + 29.22) + 0.997 \cdot (0.5293 + 25.97)}{CED_{coal,sm} - 0.003 \cdot (0.9990 + 29.22) - 0.997 \cdot (0.5293 + 25.97)} = 12$$

It may be noted that CED_{el} and $CED_{coal,sm}$ cannot be determined from the information given in Fig. A1, because Fig. A1 represents only a limited segment of the supply chain. A full analysis with the Ecoinvent database is required to obtain CED_{el} and $CED_{coal,sm}$ values.

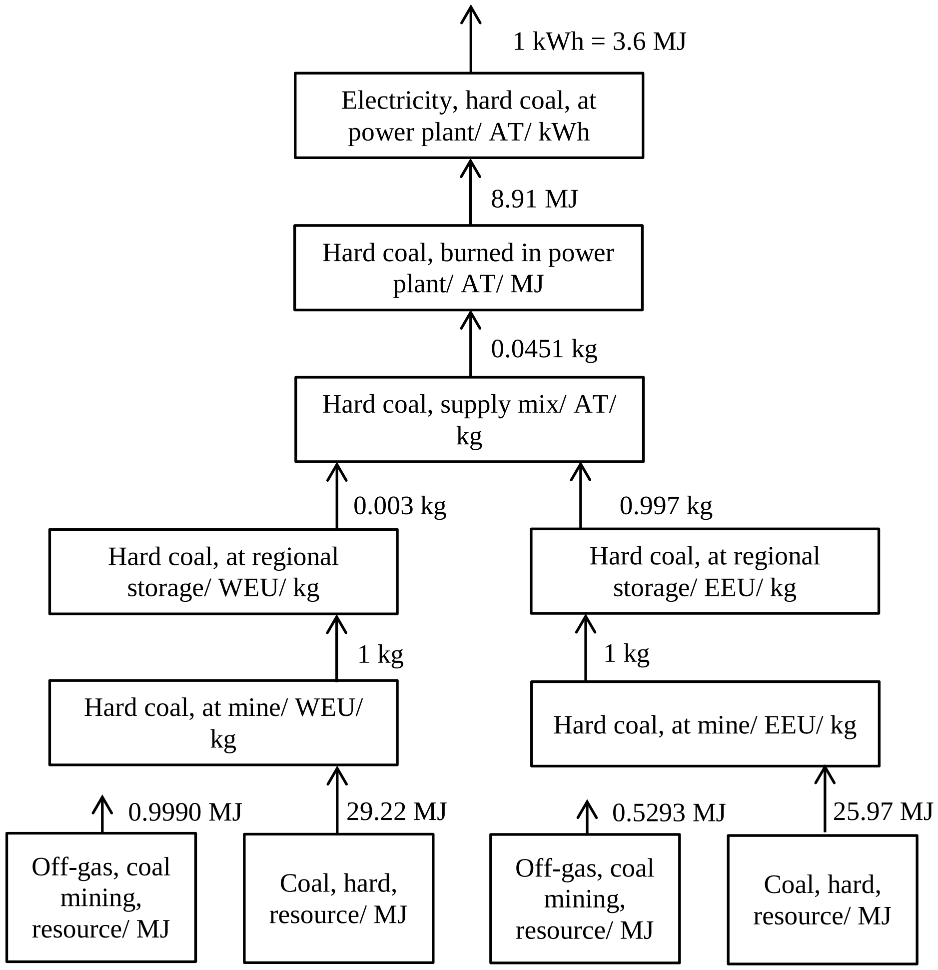

Fig. A.1. Schematic representation of a segment of the supply chain for the Ecoinvent process 'Electricity, hard coal, at power plant/ AT/ kWh', which is the Ecoinvent process used to establish EROI values for coal electricity (Austria) in Fig. 1. The supply chain segment depicted here involves also the Ecoinvent process 'Hard coal, supply mix/ AT/ kg', which is used to establish EROI for hard coal supply mix (Austria) in Table 1. The numbers are to be interpreted as follows: There is a direct input of 8.91 MJ of 'Hard coal, burned in power plant' per kWh of output of 'Electricity, hard coal, at power plant'; there is a direct input of 0.0451 kg of 'Hard coal, supply mix' per MJ of output of 'Hard coal, burned in power plant'; etc. The input of 8.91 MJ represents the lower heating value (LHV) of the fuel supplied to the power plant; the power plant efficiency (LHV basis) is 3.6 / 8.91 = 40.4%. 'Off-gas, coal mining, resource' represents leakage of methane from coal mines, and is expressed in higher heating value (HHV). In the schematic representation, the two arrows leaving the two 'off-gas, coal mining' boxes are not connected to other boxes because the gas leaks out and is not captured. Other energy losses are not modelled explicitly as energy flows, but are implicit in the compound efficiency of the supply chain. 'Coal, hard, resource' represents the removal of coal from nature, and is also expressed in HHV. Region codes: AT = Austria; WEU = Western Europe; EEU = Central and Eastern Europe. All data are from Ecoinvent (2010).

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