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A Framework for Energy Use Indicators and Their Reporting in Life Cycle Assessment

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EDITOR'S NOTE:

This is 1 of 6 articles generated from the 20th SETAC Europe LCA Case Study Symposium entitled "LCA in promoting eco-innovation and sustainability: education, research and application" (November 2014, Novi Sad, Serbia). The symposium identified how LCA can contribute to innovation and enhance the (re)design of new and existing products and services, by respecting ecodesign principles. The papers in this series reflect the recent application of LCA in industrial and energy sectors in Europe.

ABSTRACT

Energy use is a common impact category in life cycle assessment (LCA). Many different energy use indicators are used in LCA studies, accounting for energy use in different ways. Often, however, the choice behind which energy use indicator is applied is poorly described and motivated. To contribute to a more purposeful selection of energy use indicators and to ensure consistent and transparent reporting of energy use in LCA, a general framework for energy use indicator construction and reporting in LCA studies will be presented in this article. The framework differentiates between 1) renewable and nonrenewable energies, 2) primary and secondary energies, and 3) energy intended for energy purposes versus energy intended for material purposes. This framework is described both graphically and mathematically. Furthermore, the framework is illustrated through application to a number of energy use indicators that are frequently used in LCA studies: cumulative energy demand (CED), nonrenewable cumulative energy demand (NRCED), fossil energy use (FEU), primary fossil energy use (PFEU), and secondary energy use (SEU). To illustrate how the application of different energy use indicators may lead to different results, cradle-to-gate energy use of the bionanomaterial cellulose nanofibrils (CNF) is assessed using 5 different indicators and showing a factor of 3 differences between the highest and lowest results. The relevance of different energy use indicators to different actors and contexts will be discussed, and further developments of the framework are then suggested.*Integr Environ Assess Manag* 2016;12:429–436. © 2015 The Authors. *Integrated Environmental Assessment and Management* published by Wiley Periodicals, Inc. on behalf of SETAC.

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INTRODUCTION

Energy use is a common impact category in life cycle assessment (LCA), which is an established method for environmental assessment and management (ISO 2006; Evangelinos et al. 2014; Hellweg and Milà i Canals 2014). Life cycle energy use—sometimes referred to as the embedded, imbedded, or embodied energy use—reveals how much energy is required to produce a product or service throughout its life cycle. The main rationales behind the energy use impact category are the importance of energy for sustaining human wellbeing and the limited energy resources worldwide (Smil 2003). Energy use is often assessed together with other impact categories—such as global warming potential, acidification potential, and toxicity potential—to shed light on different types of environmental impacts (Baumann and Tillman 2004). Energy use can also be the only impact category considered in an LCA study, which could then be referred to as "life cycle energy analysis." In fact, that approach is older than the LCA method itself. It dates back to energy analyses of products conducted by Hannon (1972) and Makhijani and Lichtenberg (1972). One rationale for implementing energy use as the only impact category in LCA could be that energy use is considered the most relevant impact category. Another possible rationale is that energy use indicators have been shown to be good proxy indicators for environmental impacts in general (Huijbregts et al. 2006, 2010).

In this article, energy use is referred to as being an impact category within LCA, and more specific operationalizations of the impact category are referred to as energy use indicators. In a previous study, a number of different energy use indicators in LCA studies of biofuels were identified (Arvidsson et al. 2012). These indicators included embedded fossil production energy, imbedded fossil energy, energy requirement, nonrenewable energy requirements, energy consumption, cumulative

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primary energy demand, cumulative fossil energy demand, well-to-wheel energy, primary energy consumption, energy balance, net energy balance, net energy gain, and net energy. It was noticed by Arvidsson et al. (2012) that the use of these indicators was inconsistent and poorly described. The same indicator name was used in different studies but with a different meaning. It was also found that the indicators differed in particular with regard to whether only nonrenewable or also renewable energy use were included, and whether the indicator was based on primary or secondary energy use. For some indicators, the energy content of the feedstock was included as energy use. For others, the energy content of the product was included but as negative energy use, that is, as energy gain. Most often, a description of the energy use indicator was lacking, so it was difficult to understand what the indicator included. The choice of energy use indicators often seemed to be unconscious and arbitrary. To try to amend this problem, a set of more well-defined indicators was suggested that can be selected depending on the requirement of the specific decision-making situation (Arvidsson et al. 2012). However, it was also acknowledged that other energy use indicators could be of interest to certain actors in certain situations. It was also shown that the life cycle energy use of the biofuel palm oil methyl ester could vary by an order of magnitude for the different suggested energy use indicators and go from negative to positive. Other studies have also pointed out the lack of clarity in energy use indicator construction and reporting in LCA, see for example Frischknecht et al. (2015) and Arvesen and Hertwich (2015).

In this article, a more general framework for energy use indicator construction and reporting in LCA studies will be presented. In such a framework, a difference is defined between 1) renewable and nonrenewable energy, 2) primary and secondary energy, and 3) energy intended for energy purposes versus energy intended for material purposes. Our aim is to contribute to a more purposeful selection of energy use indicators and to make consistent and transparent reporting of energy use in LCA. This focus is of importance for the scientific rigor of LCA and for the adequate interpretation and use of life cycle energy use results in different situations, such as in policy making and within companies.

The proposed framework is illustrated by applying it to a number of energy use indicators that are frequently used in LCA studies, namely cumulative energy demand (CED), nonrenewable cumulative energy demand (NRCED), fossil energy use (FEU), primary fossil energy use (PFEU), and secondary energy use (SEU). It will also be shown that for some of these aspects, it is not clear from their names or existing standards how energy use is accounted for and which energy types are included. It is therefore important to be specific about these aspects in studies where energy use is used. To illustrate how different energy use indicators can give varying results, the life cycle energy use of the bionanomaterial cellulose nanofibrils (CNF) is shown for 5 different indicators. These 5 indicators are the same as, or specified variants of, the 5 indicators that were described using the framework. The relevance of different energy use indicators to different actors is further discussed, and finally, possible developments of the framework are suggested. The aim of this article is not to provide an exhaustive list of studies that use different energy use indicators; however, some examples of studies that use the energy use indicators discussed will be given to illustrate that they are indeed used in the LCA field.

THE ENERGY USE FRAMEWORK

The suggested framework is graphically illustrated in Figure 1, with the product or service life cycle to the right. To the left, different possible energy inputs are shown. In the suggested framework, energy inputs are categorized based on a number of relevant aspects.

The first aspect is whether the energy originates from renewable sources, such as biomass and solar energy, or nonrenewable, such as coal and U.

The second aspect is whether the energy is given as primary energy or secondary energy. Primary energy is the form of energy that was extracted from nature, for example, crude oil or coal (Øvergaard 2008). Secondary energy is energy in the

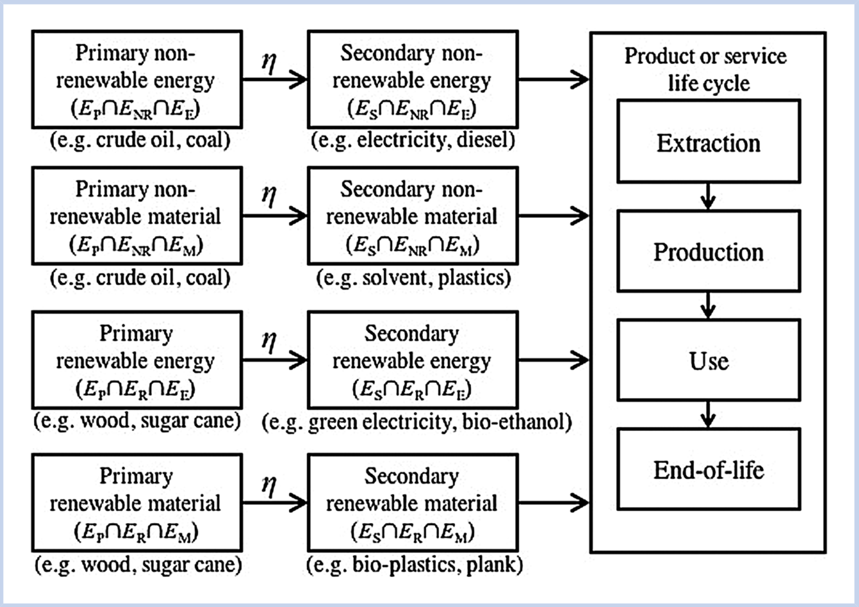

Figure 1. Graphical illustration of the suggested framework for energy use indicators in LCA. E_P stands for life cycle primary energy use, E_S for life cycle secondary energy use, E_R for life cycle renewable energy use, E_{NR} for life cycle nonrenewable energy use, E_E for life cycle energy use intended for energy purposes, E_M for life cycle energy use intended for material purposes, and η for the primary-to-secondary energy conversion factor.

form of energy commodities used for different activities, for instance, as electricity or fuel (Øvergaard 2008). Mathematically, these 2 types of energy are related as follows:

$$E_S = \eta E_{P,} \quad (1)$$

where E_S is the secondary energy, E_P is the primary energy, and η is the primary-to-secondary energy conversion factor. This conversion factor can take values between 0 and 1, that is, $\eta \in [0,1]$. This means that $E_S \leq E_P$, as also noted by Davis and Sonesson (2008).

The third aspect of the energy use framework is whether the energy input is intended for energy purposes, such as fossil fuels or electricity, or intended to be used as a material, as with a solvent or construction material. For simplicity, these 2 categories are referred to as being intended for energy or material purposes, respectively. Note that this categorization is based on secondary energy uses, that is, whether the secondary energy is intended for energy or material purposes. Primary energy sources are thus referred to as energy or material, depending on their intended use later on. Note also that whether something is categorized as intended for energy or material purposes is not an inherent property but is situation specific and depends on the user's intention.

As a complement to the graphical illustration of the framework in Figure 1, it is also possible to illustrate the same framework mathematically. A general energy use indicator I can be written as:

$$I = (x_P E_P \cup x_S E_S) \cap (x_R E_R \cup x_{NR} E_{NR}) \cap (x_E E_E \cup x_M E_M), \quad (2)$$

where E_P stands for life cycle primary energy use, E_S for life cycle secondary energy use, E_R for life cycle renewable energy use, E_{NR} for life cycle nonrenewable energy use, E_E for life cycle energy use intended for energy purposes, and E_M for life cycle energy use intended for material purposes. The parameters x_P, x_S, x_R, x_{NR}, x_E, and x_M are coefficients that indicate whether or not their respective type of energy is included in the energy use indicator. They have either a value of 0 or a value of 1. A value of 0 means that the respective energy type is not included in the energy use indicator, whereas a value of 1 means that the energy type is included. Note that for the case of primary and secondary energy, x_P and x_S cannot both be 1—one of them must be 0.

The values of the coefficients can be used to define an energy use indicator in this framework. Table 1 shows the coefficients of the 5 energy use indicators discussed later in this article, and Figure 2 shows a representation of each indicator using the graphical framework of Figure 1. Note that the number of unspecified coefficients (marked as "not defined" in Table 1) is not an indicator of the energy use indicator's general quality but rather shows which additional aspects must be specified after choosing a particular energy use indicator.

ANALYSIS OF ENERGY USE INDICATORS USING THE PROPOSED FRAMEWORK

Cumulative energy demand

Cumulative energy demand (CED) is a frequently used energy use indicator in LCA studies. Indeed, it has been shown to be a good proxy indicator for other types of environmental impacts (Huijbregts et al. 2010). Cumulative energy demand is also frequently used for calculations of life cycle-based energy returns on energy investment (EROI) for different types of energy production (Arvesen and Hertwich 2015). The philosophy behind the CED is to include all energy extracted from nature as energy use (Hischier et al. 2010; Frischknecht et al. 2015). This means that the CED considers primary energy use, both renewable and nonrenewable, and energy flows intended for both energy and for material purposes. Figure 2 shows the CED illustrated according to the graphical framework in Figure 1. The CED can also be written by combining Equation 2 and the coefficients from Table 1:

Table 1. Description of the discussed energy use indicators based on the coefficients[a] in the mathematical framework in Equation 2

Coefficients	CED	NRCED	FEU	PFEU	SEU
x_P	1	1	n.d.	1	0
x_S	0	0	n.d.	0	1
x_R	1	0	0	0	n.d.
x_{NR}	1	1	n.d.	n.d.	n.d.
x_E	1	1	1	1	1
x_M	1	1	n.d.	n.d.	n.d.

CED = cumulative energy demand; FEU = fossil energy use; n.d. = not defined; NRCED = nonrenewable cumulative energy demand; PFEU = primary fossil energy use; SEU = secondary energy use

[a] x values.

$$I_{CED} = E_P \cap (E_R \cup E_{NR}) \cap (E_E \cup E_M). \quad (3)$$

The CED includes the maximum amount of energy as far as this framework allows, because the primary energy is always larger than, or equal to, the secondary energy (i.e., $E_S \leq E_P$) and because both primary and secondary energy cannot be included (i.e., $x_P \neq x_S$). This means that:

$$I_{CED} = \max(I). \quad (4)$$

Note, however, that it may also sometimes be difficult to tell whether or not something is in fact an energy extraction from nature (Arvidsson et al. 2012). To illustrate, branches falling from a tree during harvest, which are not used but left on the field, may or may not be seen as extracted energy. Such details should preferably be specified when using the CED indicator if relevant for the study.

Nonrenewable cumulative energy demand

A variant of the CED is the NRCED, which is used for midpoint impact assessment in the ReCiPe method (Goedkoop et al. 2013). Similar to the CED, the philosophy behind the nonrenewable cumulative energy demand (NRCED) is to include energy extracted from nature in the form of primary energy. Yet the NRCED only includes the nonrenewable energy extracted. The rationale for excluding renewable energy use is that nonrenewable energy sources face a comparatively higher risk of depletion. The NRCED is illustrated graphically in Figure 2 and can be written as follows using Equation 2 and the coefficients from Table 1:

$$I_{NRCED} = E_P \cap E_{NR} \cap (E_E \cup E_M). \quad (5)$$

Note that this means that $I_{NRCED} \leq I_{CED}$, because $E_{NR} \leq E_{NR} + E_R$.

Fossil energy use

Fossil energy use (FEU) is a frequently used energy use indicator in LCA studies. It can synonymously be referred to as

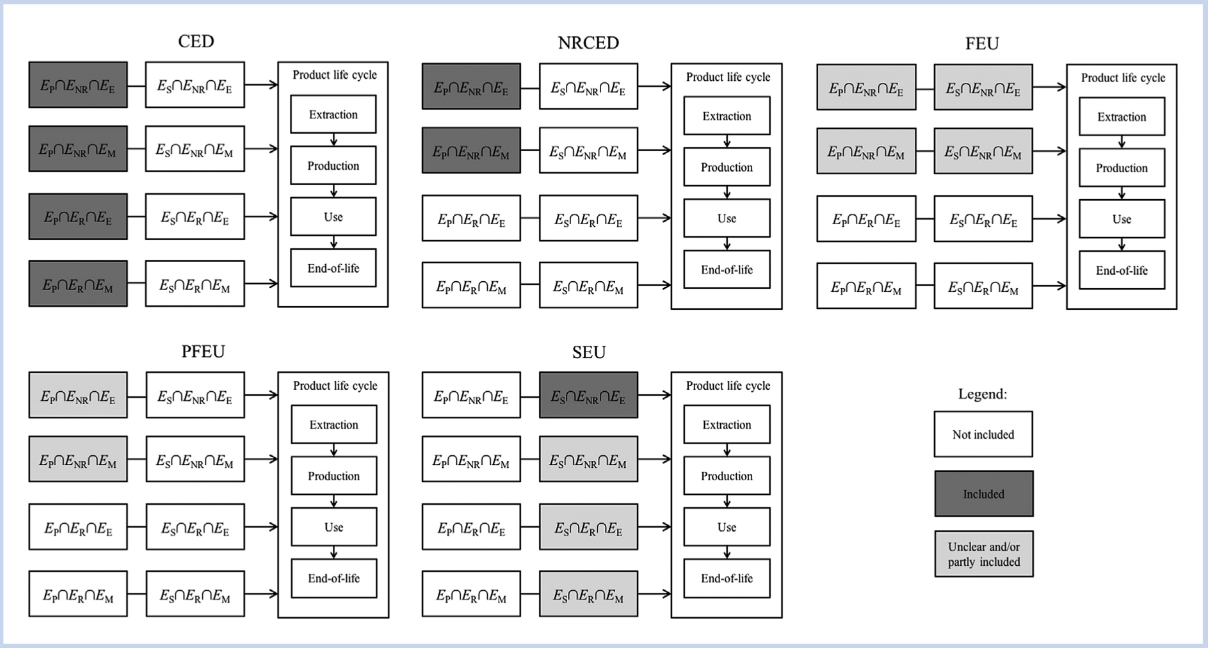

Figure 2. The cumulative energy demand (CED), nonrenewable cumulative energy demand (NRCED), secondary energy use (SEU), fossil energy use (FEU), and primary fossil energy use (PFEU) indicators illustrated by the graphical framework in Figure 1.

embedded fossil production energy (Arvidsson et al. 2011) or fossil energy requirement (Achten et al. 2010). It is clear that the FEU indicator does not consider renewable energy, and the value of x_R is thus 0. Regarding x_{NR}, the term "fossil" is not completely synonymous with the term "nonrenewable," so whether or not additional nonrenewable energy types (such as nuclear power) are also included should preferably also be clarified when using the FEU. Whether primary or secondary energy is considered and whether or not energy intended for material purposes is considered are also unclear variables. The value of x_E is probably 1 because including energy use for obvious energy purposes (such as electricity and fuel) is standard in LCA. However, the values of x_P, x_S, and x_M are not clear for this energy use indicator (Table 1). This lack of clarity can be illustrated graphically as we see in Figure 2.

Primary fossil energy use

In some studies, there is a reference to primary fossil energy use (PFEU) (Ahlgren et al. 2008). Similarly, the IMPACT2002+ impact assessment method employs primary nonrenewable energy use as a midpoint indicator (Olivier et al. 2003). This energy use indicator is more clearly defined than the FEU because it is clarified that primary (not secondary) energy is considered, that is, $x_P = 1$ and $x_S = 0$. It is also more clearly defined because only fossil energy is considered, $x_R = 0$. Nevertheless, in terms of nonrenewable energy, this indicator has the same lack of clarity as the FEU considering the discrepancy between fossil and nonrenewable. The value x_M is also unclear for PFEU; that is, whether material energy is also considered. Such a lack of clarity, as shown in Figure 2 and Table 1, should preferably be avoided because it is otherwise hard to evaluate and compare the results of different studies that claim to use the same energy use indicator.

Secondary energy use

Secondary energy use (SEU) has been implemented in some LCA studies (Cederberg and Stadig 2003; Davis and Sonesson 2008). Contrary to most of the previous energy use indicators discussed in this article, this indicator does not consider primary energy but secondary energy instead. The SEU is thus the sum of energy inputs to the product life cycle at the inventory level in the form of energy carriers such as heat, fuels, and electricity.

It is clear that the SEU does not consider primary energy ($x_P = 0$) but secondary energy ($x_S = 1$). It is again assumed that any LCA study would include energy used for energy purposes in the energy use indicator, thus $x_E = 1$. However, the other coefficients in Equation 2 are not clear for this indicator: x_R, x_{NR}, and x_M (Table 1). Therefore, this energy use indicator is not clearly defined (Figure 2).

Because $E_S \leq E_P$, the SEU typically yields lower numerical results than other energy use indicators, and the exact difference depends on the primary-to-secondary conversion efficiency as quantified by the parameter η. For energy systems based on fossil fuels, η is typically around 0.3 due to energy losses in combustion. However, for wind- and solar-based systems, it is very close to 1 (Rydh and Sandén 2005), because typically only minor losses occur after energy extraction. Accordingly, for wind- or solar-based energy systems, $E_S \approx E_P$.

CASE EXAMPLE: THE ENERGY USE OF CELLULOSE NANOFIBRILS

To illustrate the importance of a conscious energy use indicator choice and of transparent reporting, the life cycle energy use of producing 1 kg CNF (cradle-to-gate) was assessed. Cellulose nanofibrils is a bio-nanomaterial primarily developed to provide enhanced properties to other materials such as increased strength and transparency (Khan et al. 2012; Dufresne 2013). The assessed CNF is produced by first producing cellulose pulp and then pretreating the pulp with enzymes. This is done to break some of the bonds holding together the microsized fibers of the pulp. Next, the larger fibers are disintegrated into nanofibrils by microfluidization or homogenization (Pääkkö et al. 2007; Ankerfors 2012). The main processes in the life cycle are hence the production of pulp, enzymatic pretreatment, treatment by micro-fluidization, and transports. To highlight the potential difference between renewable and nonrenewable energy in the assessment, coal-based electricity and crude oil-based heat were assumed. Unbleached sulfate pulp produced in Sweden and transported by a diesel-driven truck was also assumed. Other assumptions were made according to Arvidsson et al. (2015), and the same inventory data as in that study was used.

Cellulose nanofibrils were assessed in this study using 5 different energy use indicators: 1) CED, 2) NRCED, 3) CED with only energy intended for energy purposes ("CED energy only"), 4) "total SEU" (with both renewable and nonrenewable energy and energy intended for energy and material purposes), and 5) nonrenewable SEU (NRSEU) with energy intended for energy purposes only ("NRSEU energy only"). In a previous publication by Arvidsson et al. (2015), only the CED was assessed for this fossil-based production system. The CED and NRCED have already been described in Equations 3 and 5, respectively. The other 3 energy use indicators are described below using Equation 2:

$$I_{\mathrm{CED\ energy\ only}} = E_{\mathrm{P}} \cap (E_{\mathrm{R}} \cup E_{\mathrm{NR}}) \cap E_{\mathrm{E}}, \qquad (6)$$

$$I_{\mathrm{total\ SEU}} = E_{\mathrm{S}} \cap (E_{\mathrm{R}} \cup E_{\mathrm{NR}}) \cap (E_{\mathrm{E}} \cup E_{\mathrm{M}}), \qquad (7)$$

$$I_{\mathrm{NRSEU\ energy\ only}} = E_{\mathrm{S}} \cap E_{\mathrm{NR}} \cap E_{\mathrm{E}}. \qquad (8)$$

As can be seen in Figure 3, some energy use indicators give notably different results. The CED gives the highest result. Excluding either the renewable energy (as in the NRCED) or the energy used for material purpose (as in the CED energy only) leads to similar results. This is because most of the renewable energy is in the form of the biomass material energy harvested to constitute the CNF, which is excluded for different reasons in these 2 indicators (either for being renewable energy or for being energy used for material purposes). The total SEU is higher than both the NRCED and the CED energy only indicators. This is because this biomass energy that is intended for material purposes constitutes a large share of pulp production's energy use, and there are very low primary-to-secondary energy conversion losses when the biomass is converted to pulp. The NRSEU energy only yields the lowest energy use of the 5 indicators. This is because all renewable energy is excluded for this indicator, and the fossil energy use is reduced by approximately a factor of 3 due to primary-to-secondary energy conversion losses. It can thusly be concluded from Figure 3 that there is a difference in energy use of a factor of 3 between the highest result (for the CED indicator) and the lowest result (for the NRSEU energy only indicator). One can also conclude that the life cycle phases that would be considered hotspots would differ depending on the choice of energy use indicator.

ENERGY USE INDICATOR RELEVANCE TO DIFFERENT ACTORS

In a conference contribution by Svanström et al. (2013), the relevance of different energy use indicators to different actors was discussed. In general, the goal and decision-making context of a study should guide method choices (Tillman 2000). New challenges related to energy use and energy efficiency may even make it necessary to shift to other indicators compared to those used in the past because different indicators respond to different concerns. This matter will be further discussed in the following paragraphs.

There are 3 main choices to be made when constructing an energy use indicator according to the proposed framework: 1) accounting for energy use as primary or secondary, 2) including renewable and/or nonrenewable energy use, and 3) including energy intended for energy purposes and/or material purposes. Below, the choices that would seem the most relevant are discussed for 2 main actors: governmental agencies—focusing on national policies—and companies—focusing on their production and products. The role of governmental agencies is to consider impacts on society as a whole, to protect their citizens, and to provide appropriate conditions and rules for enterprises (for example, in terms of

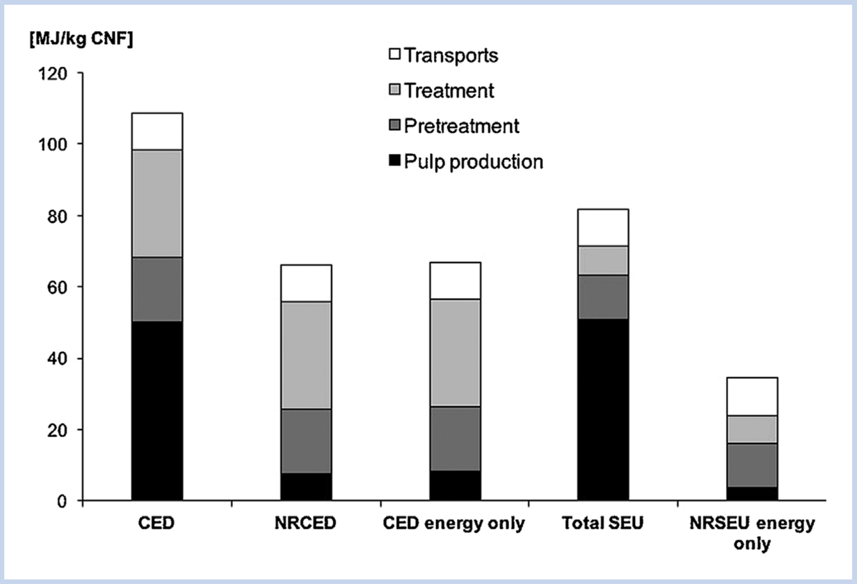

Figure 3. Cradle-to-gate energy use results for cellulose nanofibrils (CNF), assessed using 5 different energy use indicators: Cumulative energy demand (CED), nonrenewable cumulative energy demand (NRCED), cumulative energy demand intended for energy purposes only ("CED energy only"), the total secondary energy use ("total SEU"), and the nonrenewable secondary energy use intended for energy purposes only ("NRSEU energy only").

energy supply). Companies, on the other hand, traditionally have a narrower focus on their manufacturing processes and sometimes extend to a larger part of their products' life cycles.

The choice between primary and secondary energy should be determined by whether or not it is relevant to include primary-to-secondary energy conversion losses in the study. Choosing primary energy, and thereby including such potentially considerable losses, could be seen as more comprehensive. This approach responds to concerns over the limited availability of energy reserves (if nonrenewable energy is considered) and the limited total energy generation potential (if renewable energy is also considered). Therefore, primary energy is probably the most relevant choice for most actors' LCA studies.

The reason for choosing secondary energy, and not including primary-to-secondary energy conversion losses, could be that such losses are location specific and not related to the performance of the foreground production system. Accordingly, if companies want to benchmark the life cycle energy use of their products with those produced by competitors, secondary energy use may be a more suitable option. This is because it prevents effects from different (often national) energy production systems and focuses on the foreground production system. In marketing, it could be seen as inconvenient and even unfair for a company to let its products bear the disadvantage of an inefficient (low η) background energy production system.

The choice between renewable and/or nonrenewable will depend on the relevance that the actor attributes to renewable energy use. Clearly, nonrenewable energy use is problematic because the energy cannot be replenished. Including nonrenewable energy use would therefore seem relevant in most actors' LCA studies. With renewable energy on the rise worldwide, excluding renewable energy from the energy use indicators will likely become increasingly inappropriate. However, fund-type renewable energy is recreated at a slower rate and may become depleted in a similar way to nonrenewable energy if overused (Wall 1990). Flow-type renewable energy is replenished at the same rate it is used and cannot become depleted (Wall 1990). Because fund-type energy also risks depletion, and if a notable share of the energy used along the life cycle is fund-type, it is questionable to exclude renewable energy. Even for flow-type energy, although the energy source itself is not limited, the rate at which it can be extracted is limited. One example is with the available area for solar panels and suitable locations for wind turbines. Consequently, the share of renewable energy used along the life cycle ($E_R/(E_R + E_{NR})$) and the types of renewable energy sources determine the relevance of including it in LCA studies. Again, with the current rise in renewable energy worldwide, it is suggested that both governmental bodies and companies should want to include both renewable and nonrenewable energy when assessing life cycle energy use.

Regarding energy intended for energy and/or material purposes, the inclusion of energy used for energy purposes would probably be executed in most LCA studies. However, whether energy intended for material purposes should be included is less obvious. When the energy in material inputs—such as input fossil solvents and wooden planks—is included, it provides a more comprehensive view on energy use. Similar to energy intended for energy purposes, energy embedded in materials is also extracted from nature. In addition, the energy embedded in materials could, in many cases, just as well have been used for energy purposes instead. It may in fact be used for energy production in its end-of-life phase (such as with the incineration of waste plastics). It thus makes sense to include energy use both for energy and material purposes and particularly for actors concerned with the limited availability of energy in society, such as governments.

POTENTIAL FURTHER DEVELOPMENTS OF THE FRAMEWORK

Although the presented framework can capture 3 important aspects of energy use indicators, further developments are possible. For example, there are other ways of dividing energy sources based on origin besides the classic categories of renewable and nonrenewable. One such categorization that has already been mentioned is the difference between flow-, fund-, and stock-type energy (Wall 1990). One reason for using this extended categorization is that the potential depletion of fund-type energy resources such as biomass has been outlined as a potential problem (Berndes 2014). For this reason, the use of fund-type renewable energy can be argued to be more critical than the use of flow-type renewable energy. It may therefore be relevant to develop energy use indicators that differentiate between these 2 types of renewable energy. The framework in Figure 1 could be developed for this purpose by dividing the renewable energy input to the product life cycle into 2 different inputs (flow- and fund-type energy) and renaming the nonrenewable energy as stock-type energy. Equation 2 could correspondingly be modified by dividing E_R into 2 different terms, flow-type (E_{FL}) and fund-type (E_{FU}) energy, and renaming E_{NR} to stock-type energy (E_{ST}):

$$I = (x_P E_P \cup x_S E_S) \cap (x_{FL} E_{FL} \cup x_{FU} F_{FU} \cup x_{ST} E_{ST}) \cap (x_E E_E \cup x_M E_M), \tag{9}$$

where x_{FL}, x_{FU}, and x_{ST} are the coefficients for flow-type, fund-type, and stock-type energy, respectively. The relevance of this development of the framework will depend on the share of fund-type energy in the life cycles ($E_{FU}/(E_{FL} + E_{FU} + E_{ST})$).

There are a number of energy use indicators used in LCA studies that consider energy outputs—such as the energy content of products and byproducts—as energy gains that reduce the energy use per functional unit. One such indicator is the net energy balance (NEB), sometimes referred to as net energy gain (NEG) (Achten et al. 2010) or energy balance (Manik and Halog 2013). This designation is often used in LCA studies of fuels. The rationale for this indicator is that in some cases the end product (typically a fuel) contains usable energy whereas energy of different types is also used along the life cycle. Whether or not a fuel is reasonable to produce can hence be determined by assessing if the energy in the end product and byproducts is larger than the energy used along the life cycle. Contrary to the previously mentioned energy use indicators, this indicator says something about the energy efficiency of the product's life cycle. This outcome hints at another potential further development of the framework to account also for such aspects. The NEB can be expressed via the following simplified equation:

$$I_{NEB} = E_{use} - E_{gain}, \tag{10}$$

where E_{use} stands for energy use and E_{gain} for energy gain. Sometimes, the terms energy input ($E_{input} = E_{use}$) and energy output ($E_{output} = E_{gain}$) are used instead in Equation 10. The philosophy behind the NEB is the same as for the EROI (Arvesen and Hertwich 2015) and net energy ratio (NER)

(Pleanjai and Gheewala 2009; Achten et al. 2010; de Souza et al. 2010; Manik and Halog 2013) indicators. Nonetheless, the EROI and NER indicators use division instead of subtraction to relate the energy gained in the end product and byproducts to the energy used along the life cycle (i.e., $E_{\text{gain}}/E_{\text{use}}$).

It is not always clear how the E_{gain} and E_{use} in Equation 10 are calculated in terms of primary or secondary energy, renewable and/or nonrenewable energy, and energy intended for energy and/or material purposes. For instance, the writings in some publications indicate that secondary rather than primary energy is considered in the NEB (Pleanjai and Gheewala 2009; Achten et al. 2010). However, the CED, and thus primary energy, is often used to calculate the life cycle-based EROI (Arvesen and Hertwich 2015). By discriminating between the energy gain and energy use terms, Equation 2 can be further developed so it can also transparently describe energy use indicators such as the NEB:

$$
\begin{aligned}
I = {} & [(x_{\text{P}}E_{\text{P}} \cup x_{\text{S}}E_{\text{S}}) \cap (x_{\text{R}}E_{\text{R}} \cup x_{\text{NR}}E_{\text{NR}}) \cap (x_{\text{E}}E_{\text{E}} \cup x_{\text{M}}E_{\text{M}})]_{\text{use}} \\
& -[(x_{\text{P}}E_{\text{P}} \cup x_{\text{S}}E_{\text{S}}) \cap (x_{\text{R}}E_{\text{R}} \cup x_{\text{NR}}E_{\text{NR}}) \cap (x_{\text{E}}E_{\text{E}} \cup x_{\text{M}}E_{\text{M}})]_{\text{gain}}.
\end{aligned} \tag{11}
$$

If we depart from this extended equation (Eqn. 11), then Equation 2 can be seen as a special case for which no energy gains are subtracted from the energy use results.

There exist several types of indicators that attempt to capture energy quality in a life cycle perspective. “Exergy” indicates the ability of different energy types to conduct work and has been suggested as relevant for LCA (Ayres et al. 1998; Rosen et al. 2012). Meanwhile, “emergy” recalculates the energy use back into the corresponding amount of solar energy that would be required to produce the energy. It has thus been suggested as superior to assessing life cycle energy use (Brown and Herendeen 1996). “Entropy” can be said to quantify the energy not available for work, and entropy generation has been shown to correlate well with different life cycle environmental impacts (Samiei and Fröling 2014). The relationship between these energy-quality indicators and life cycle energy use is not trivial, and some additional assumptions are required to assess life cycle exergy, emergy, and entropy. Additional work is therefore required to also capture such indicators of energy quality in a unified indicator framework.

CONCLUSIONS

In this article, a framework for more conscious and purposeful construction of energy use indicators and transparent energy use reporting in LCA studies has been presented. This framework can be illustrated graphically, as in Figure 1, but can also be expressed mathematically, as in Equation 2. It considers 3 different aspects: 1) the choice between primary and secondary energy use, 2) the choice of including renewable energy, nonrenewable energy, or both, and 3) the choice of including energy used for energy purposes, energy used for material purposes, or both. It has been shown that typical energy use indicators in LCA—such as the CED, NRCED, FEU, PFEU, and SEU—can be described by the framework. The framework can also be used to highlight a lack of clarity in energy use indicator construction.

The assessment of CNF revealed that the life cycle energy use of this material could vary by a factor of 3 depending on the choice of energy use indicators.

The relevance of energy use indicator choices to different actors has been discussed. It has accordingly been suggested that most actors would probably find it relevant to include all types of energy (both renewable and nonrenewable, for both energy and material purposes) as primary energy.

Potential developments of the framework have also been outlined. These potential developments include division between flow-, fund-, and stock-type energies, the inclusion of energy gains, and the ability to describe indicators of energy quality.

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REFERENCES

Achten WMJ, Vandenbempt P, Almeida J, Mathijs E, Muys B. 2010. Life cycle assessment of a palm oil system with simultaneous production of biodiesel and cooking oil in Cameroon. *Environ Sci Technol* 44:4809–4815.

Ahlgren S, Baky A, Bernesson S, Nordberg Å, Norén O, Hansson PA. 2008. Ammonium nitrate fertiliser production based on biomass—Environmental effects from a life cycle perspective. *Biores Technol* 99:8034–8041.

Ankerfors M. 2012. Microfibrillated cellulose: Energy-efficient preparation techniques and key properties. Stockholm: KTH Royal Institute of Technology. 49 p.

Arvesen A, Hertwich EG. 2015. More caution is needed when using life cycle assessment to determine energy return on investment (EROI). *Energy Policy* 76:1–6.

Arvidsson R, Fransson K, Fröling M, Svanström M, Molander S. 2012. Energy use indicators in energy and life cycle assessments of biofuels: review and recommendations. *J Clean Prod* 31:54–61.

Arvidsson R, Nguyen D, Svanström M. 2015. Life cycle assessment of cellulose nanofibrils production by mechanical treatment and two different pretreatment processes. *Environ Sci Technol* 49:6881–6890.

Arvidsson R, Persson S, Fröling M, Svanström M. 2011. Life cycle assessment of hydrotreated vegetable oil from rape, oil palm and Jatropha. *J Clean Prod* 19:129–137.

Ayres RU, Ayres LW, Martinás K. 1998. Exergy, waste accounting, and life-cycle analysis. *Energy* 23:355–363.

Baumann H, Tillman A-M. 2004. The hitchhiker's guide to LCA: An orientation in life cycle assessment methodology and application. Lund (SE): Studentlitteratur. 543 p.

Berndes G. 2014. How much biomass is available? In: Sandén BA, editor. Systems perspectives on biorefineries. Gothenburg (SE): Chalmers University of Technology. p 42–55.

Brown MT, Herendeen RA. 1996. Embodied energy analysis and emergy analysis: A comparative view. *Ecol Econ* 19:219–235.

Cederberg C, Stadig M. 2003. System expansion and allocation in life cycle assessment of milk and beef production. *Int J Life Cycle Assess* 8:350–356.

Davis J, Sonesson U. 2008. Life cycle assessment of integrated food chains—A Swedish case study of two chicken meals. *Int J Life Cycle Assess* 13:574–584.

de Souza SP, Pacca S, de Ávila MT, Borges JLB. 2010. Greenhouse gas emissions and energy balance of palm oil biofuel. *Renew Energy* 35:2552–2561.

Dufresne A. 2013. Nanocellulose: A new ageless bionanomaterial. *Mater Today* 16:220–227.

Evangelinos KI, Allan S, Jones K, Nikolaou IE. 2014. Environmental management practices and engineering science: A review and typology for future research. *Integr Environ Assess Manag* 10:153–162.

Frischknecht R, Wyss F, Büsser Knöpfel S, Lützkendorf T, Balouktsi M. 2015. Cumulative energy demand in LCA: the energy harvested approach. *Int J Life Cycle Assess* 20:957–969.

Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, van Zelm R. 2013. ReCiPe 2008. A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and endpoint level. The Hague, the Netherlands: Dutch Ministry of Housing, Spatial Planning and Environment (VROM). 126 p.

Hannon BM. 1972. Bottles, cans, energy. *Environment* 14:11.

Hellweg S, Milà i Canals L. 2014. Emerging approaches, challenges and opportunities in life cycle assessment. *Science* 344:1109–1113.

Hischier R, Weidema B, Althaus H-J, Bauer C, Doka G, Dones R, Frischknecht R, Hellweg S, Humbert S, Jungbluth N, et al. 2010. Implementation of Life Cycle Impact Assessment Methods Data v2.2. St. Gallen (CH): Swiss Centre for Life Cycle Inventories. 163 p.

Huijbregts MAJ, Hellweg S, Frischknecht R, Hendriks HWM, Hungerbühler K, Hendriks AJ. 2010. Cumulative energy demand as predictor for the environmental burden of commodity production. *Environ Sci Technol* 44:2189–2196.

Huijbregts MAJ, Rombouts LJA, Hellweg S, Frischknecht R, Hendriks AJ, Meent Dvd, Ragas AMJ, Reijnders L, Struijs J. 2006. Is cumulative fossil energy demand a useful indicator for the environmental performance of products? *Environ Sci Technol* 40:641–648.

[ISO] International Organisation for Standardization. 2006. Environmental management—Life cycle assessment-principles and framework. Geneva (CH): International Organisation for Standardization. 12 p.

Khan A, Huq T, Khan RA, Riedl B, Lacroix M. 2012. Nanocellulose-based composites and bioactive agents for food packaging. *Crit Rev Food Sci Nutr* 54:163–174.

Makhijani AB, Lichtenberg AI. 1972. Energy and well-being. *Environment* 14:10–18.

Manik Y, Halog A. 2013. A meta-analytic review of life cycle assessment and flow analyses studies of palm oil biodiesel. *Integr Environ Assess Manag* 9:134–141.

Olivier J, Manuele M, Raphaël C, Sébastien H, Jérôme P, Gerald R, Ralph R. 2003. IMPACT 2002+: A new life cycle impact assessment methodology. *Int J Life Cycle Assess* 8:324–330.

Øvergaard S. 2008. Issue paper: Definition of primary and secondary energy. Oslo (NO): Statistics Norway. 7 p.

Pääkkö M, Ankerfors M, Kosonen H, Nykänen A, Ahola S, Österberg M, Ruokolainen J, Laine J, Larsson PT, Ikkala O, et al. 2007. Enzymatic hydrolysis combined with mechanical shearing and high-pressure homogenization for nanoscale cellulose fibrils and strong gels. *Biomacromolecules* 8:1934–1941.

Pleanjai S, Gheewala SH. 2009. Full chain energy analysis of biodiesel production from palm oil in Thailand. *Applied Energy* 86(Suppl1):S209–S214.

Rosen MA, Dincer I, Ozbilen A. 2012. Exergy analysis and its connection to life cycle assessment. Life cycle assessment handbook: A guide for environmentally sustainable products. Beverly (MA): Scrivener Publishing. p 185–215.

Rydh CJ, Sandén BA. 2005. Energy analysis of batteries in photovoltaic systems. Part II: Energy return factors and overall battery efficiencies. *Energ Convers Manage* 46:1980–2000.

Samiei K, Fröling M. 2014. Sustainability assessment of biomass resource utilization based on production of entropy—Case study of a bioethanol concept. *Ecol Indic* 45:590–597.

Smil V. 2003. Energy at the crossroads—Global perspectives and uncertainties. Cambridge (MA): MIT Press. 443 p.

Svanström M, Arvidsson R, Fransson K, Fröling M, Molander S. 2013. Who needs to know what about energy use? Palm oil biofuel case. In: 6th International Conference on Life Cycle Management; 25–28 August. Gothenburg, Sweden. p. 1–4.

Tillman A-M. 2000. Significance of decision-making for LCA methodology. *Environ Impact Assess Rev* 20:113–123.

Wall G. 1990. Exergy conversion in the Japanese society. *Energy* 15:435–444.