Organic materials for construction: questionning the concept of feedstock energy

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Abstract

Among the various materials used in the construction sector, consumption of organic materials have a large influence on energy accounting due to their inherent energy content, known as feedstock energy. Current Life Cycle Assessment (LCA) standards require that this quantity be reported in the inventory table as consumed energy. The fact that feedstock energy is considered alongside energy stocks and losses may be intuitively necessary, but there are unresolved concepts related to this issue that need further exploration.

This paper aims at re-exploring the way that feedstock energy is handled in LCAs and proposes a new framework. A review of various kinds of energies and their underlying notions is presented and exposes the reasons for ambiguous meanings in the LCA method in order to evaluate the feedstock problem. This analysis shows that resource consumption indicators, inventory flows, and efficiency concepts are all confounded in the same *primary energy* concept. Furthermore, whereas energy stocks are currently accounted, the consequential combustion emissions are never considered.

From these various observations, a new frame is proposed, individually considering energy resource depletion indicators, energy flows, and energy efficiency, as well as accounting for emission stocks using the so-called *stock inventory* table.

1. INTRODUCTION

The European construction technology platform has set the reduction of resource consumption (energy, matter, materials) as its first research priority for sustainable construction [1]. The domestic material consumption in the European Union is dominated by construction minerals: it approximately ranges from 4.3 tons/capita in the United Kingdom to 18.4 tons/capita in Finland [2]. In the United States, civil engineering construction and buildings are estimated to respectively consume 415,000 and 787,000 TJ of total energy per year [3]. In parallel, the European commission points out Life Cycle Assessment (LCA) as a key method for assessing sustainable construction [4].

Among the various materials used in the construction sector, consumption of organic materials is relatively low compared to classical mineral materials. However, in LCA, consumption of organic materials has a large influence on energy accounting, because they contain chemical energy resources, called inherent or feedstock energy. This energy is accounted in the total primary energy, and also accounted as a separate quantity in the inventory table as presently recommended to practitioners [5, 6]. The fact that organics can be considered alongside energy stocks and energy losses makes accounting for feedstock energy intuitively necessary, but some practical concepts are still unclear.

Bitumen is an organic material obtained after crude oil distillation, at the bottom of the distillation tower in the refining plant. The most prevalent use of the bitumen is for pavements, where it is mixed with aggregates to create asphalt concrete (AC) parking lots and roadways. Performing LCA applied to road pavements, several studies have questioned the validity of accounting practices for feedstock energy contained in bitumen [7, 8], generally surmising that current practice does not accurately represent the actual flows moving in and out the technical system. Regardless, as a residual product of the crude oil refining process, bitumen contains a significant amount of chemical energy (upper heating value around 40

MJ/kg), which is goes essentially unused when bitumen is used as a construction material. However, fuel oil producers do not consider it a viable energy resource because it contains concentrated amount of pollutants, such as polycyclic aromatic hydrocarbons, sulphur atoms, heavy metals, and others. Its transformation to available fuel oil (or other, lighter petroleum fractions) would require intensive processing, including cracking, hydro-treating and de-asphalting. Direct combustion would require a specific technology to prevent from pollutant emissions [8] and is thus rarely practiced.

In that context, the present paper re-explores the energy concepts related to feedstock energy in LCA and proposes a new framework. The paper first presents a review of various types of energy and their underlying concepts and exposes the reasons for ambiguous meanings in the LCA method and tries to re-express the feedstock problematic. The second part of the paper proposes a new framework for feedstock accounting and discusses its possible applications.

2. RE-EXPRESSING THE PROBLEMATIC OF ENERGY

2.1 Definitions of energies in LCA and underlying concepts

LCA considers different types of energy within an analysis, as discussed below. Figure 1 illustrates the relationships between these different energy quantities.

- *Primary energy* refers to the direct source, without transformation, of crude energy.
- *Secondary energy* refers to all sources of energy that result from extraction and transformation of primary sources by technological processes. *Secondary energy* is contained into *primary energy*.
- *Process energy* refers to the energy that is consumed in order to manufacture a good. Process energy is obligatory issued from a secondary source and is thus contained into *secondary energy*.

Primary energy represents the amount of energy that is removed from the natural environment. LCA standards [5] consider the *total primary energy*, which is the cumulative value of the whole system. *Primary energy* has been defended by the LCA scientific community as the "most meaningful parameter in judging the energy efficiency of systems since losses due to transformation and transport are fully taken into account" [10].

According to [11], "when organics are used as materials, the energy associated with much of this input remains incorporated in the product". This energy is called *feedstock energy*.

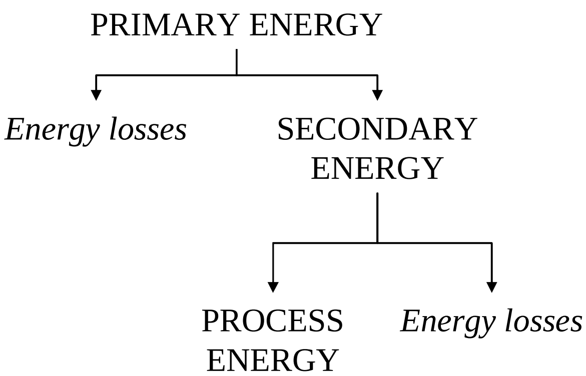

Figure 1: Relationships between various energy quantities used in LCA

Behind the energy values used in LCA, one can identify three different underlying concepts:

1. Energy efficiency of the technosphere accounting for the "loss of energy",

2. The valuation of the energy that is taken from the ecosphere. According to [12], it represents the extractible energy taken from the natural environment,
3. Account for the energy stock contained into primary matter.

2.2 The different methodological status of energy values

From this brief review, one can understand that energy is a specific quantity in LCA: it can be an inventory flow, a reference inventory flow, or an indicator.

Process energy is a classical inventory flow, simply related to the energy consumption of a production process.

Secondary energy is a reference flow as defined by the European Platform of LCA [13]: it is the flow to which all other input and output flows (i.e. all elementary flows and non-reference product and waste flows) quantitatively relate. Secondary energy brings additional information other than just energy consumption; it is necessary information to relate the LCA technological system upstream to the power source, and then account for environmental impacts of these energy producing processes (see Figure 2).

Total primary energy is an indicator: it represents a non-renewable energy resource protection as a safeguard subject for human society [12]. Characterisation factors are applied to various kinds of energy containing matter: upper heating value for fossil resources or unsustainably used renewable resources, and fission energy for nuclear resources [12].

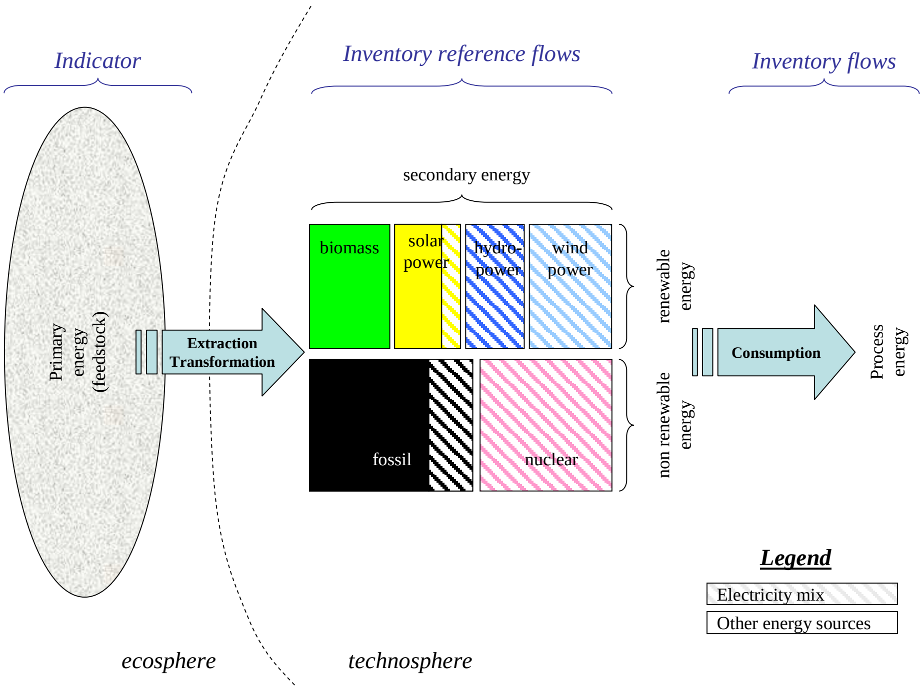

Figure 2: Methodological status of energy quantities in LCA

2.3 Avoiding ambiguity by re-expressing the energy problematic

According to the previously mentioned literature, the three notions of energy efficiency, energy resource depletion, and energy stocks, are all included in the primary energy concept. Additionally, in the case of organic materials, another ambiguity is with the stock concept. According to [11], the feedstock energy should be counted as a consumed energy because the organic matter is eventually combusted and, if it is not combusted, it "represents a loss of available resource". From this perspective, what initially is a resource depletion indicator becomes an inventory flow: as total primary energy is expressed in energy units (MJ), it is often confused with an inventory flow and understood as "consumed energy". All these combined observations lead to the lack of understanding of energy accounting in LCA.

To reconsider the problem, the methodological status of the different energy values should be clearly stated and the energy efficiency and the stock concepts should be more clearly defined.

3. RENEWING THE FRAME FOR ENERGY ACCOUNTING IN LCA

The separate consideration of the notions of non-renewable energy resource depletion indicator, energy efficiency and energy stock, leads to different methodological solutions. These solutions are discussed below.

3.1 Primary energy is not an inventory flow

First, primary energy should not be included in the inventory table because it is not an inventory flow, but rather a non-renewable energy resource depletion indicator [12]. Only process energy and secondary energy should feature in inventory tables. However, once the technological system is defined, total primary energy should be calculated from the inventory table, as it is done for all other environmental impact indicators. Furthermore, primary energy is this resource depletion indicator is only focused on energy resources.

Abiotic Depletion Potential (ADP) is a broader indicator for resource depletion as it gathers both energy resources and mineral resources, and includes a scarcity factor [14]. ADP (expressed in kg of antimony (Sb) equivalent) reflects the amount and quality of material resources taken in the natural environment in a finite global reserve, but does not include other types of resources, such as land occupation, which are considered in a separate category. Other indicators based on *exergy*, such as cumulative exergy extraction from the natural environment (CEENE) are proposed (including land occupation) [15, 16], but does not include the reserve notion.

Both ADP and CEENE already include the primary energy concept because they use characterisation factors for organic materials related to the amount of inherent energy. ADP characterisation factors set primary energy equal to the material's upper heating value [14]; for CEENE, they correspond to the *chemical exergy*, i.e. the Gibb's free energy value of the combustion chemical reaction. The latter method better reflects the amount of extractible energy from primary matter, but it is in fact of the same order of magnitude than the upper heating value for organic materials [15].

3.2 Energy efficiency is not an LCA indicator

The energy efficiency is linked to the loss of energy, i.e. the energy that is not recoverable, nor usable. According to the first law of thermodynamics, mentioning "consumed" energy, as often done in LCA, is not an exact terminology. Energy is never destroyed during a process; it changes from one form to another. According to the second law of thermodynamics, the energy form is always degraded as entropy is growing.

The concept of *exergy* accounts for these thermodynamic laws. In thermodynamics, the *exergy* of a system is defined as the maximum useful work possible during a process that brings the system into equilibrium with a heat reservoir. When the surroundings are the heat reservoir, exergy is the potential of a system to cause a change as it achieves equilibrium with its environment. After the system and its surroundings reach equilibrium, the exergy is equal to zero. Exergy is always destroyed when a process involves a temperature change. This destruction is proportional to the entropy increase of the system together with its surroundings.

The following definition for the energy efficiency of a system is generally used in thermodynamics:

$$\eta_{system} = Ex_{system,real} / Ex_{system,ideal} \tag{1}$$

where η is the energy efficiency of a system (no unit), Ex_{real} is the real exergy balance of the technological system to evaluate (MJ), Ex_{ideal} is the exergy balance of a system that performs the same task, but works in a reversible way (MJ) i.e. without entropy production.

This energy efficiency concept can be applied to a simple thermodynamic system, or to more complicated system, such as technological systems in LCA: this methodology is called Exergetic Life Cycle Assessment (ELCA) and is a currently be used as an assessment technique in the LCA field [e.g., 18].

Previous research suggests that the valuation of primary energy is linked to the capability of primary matter to produce usable energy; this “extractible energy” depends on the available technology at the moment of the study [12]. The purpose of ELCA is to analyse the exergy flows of technological systems, using various technological solutions, in order to maximise their efficiency.

In LCA methodology, indicators reflect the environmental impacts generated by the technosphere in the ecosphere. Energy efficiency is a useful indicator for eco-designing technological systems, but it remains inside the technosphere once natural resources have been removed. Although very useful to ensure a maximal useful energy yield from natural resources in a LCA study [19], it is not an indicator reflecting an environmental impact category.

3.3 The energy stock concept

The third notion underlying primary and feedstock energies is to consider organic matter as an energy stock. As previously mentioned, convention is to account for the feedstock energy as a consumed energy because the organic matter is eventually combusted and, if it is not combusted, it “represents a loss of available resource” [12].

This statement means two things: first, the effective availability of the stock for energy production is not important; second, the feedstock energy should be counted as consumed energy, i.e. be included as an inventory flow.

The key notion of the stock is the initial choice for the use of organic primary matter for an energy source or a material. In this latter case, the energy contained into the material is accounted for in the inventory due to the depletion of an available resource. There is, with this precise methodological recommendation, confusion between an inventory flow and a resource depletion indicator. The loss of available resource is already taken into account using one of following indicator: primary energy, Abiotic Depletion Potential, or exergetic resource, as previously discussed in this paper.

The stock represents a scenario for a potential future: the end of life of organic materials. If the inherent energy of matter is rightly considered lost from the ecosphere and included in an indicator, consequently there is no matter to consider whether or not the material is eventually combusted. However, from the inventory perspective, the decision whether or not to account for the production of process energy makes a difference, as well as the emissions issued from the combustion of this stock. These emissions are typically ignored, even though organic materials indeed contain airborne emissions stocks, and, in particular, carbon stocks.

In summary, accounting organic matter stocks should include both energy and emissions, and differentiate stocks from effectively combusted materials.

3.4 The “stock inventory” as a renewed frame

We propose to consider stock by introducing a separate inventory table, called *stock inventory*, which contains the process energy generated by the combustion of the material, as well as the corresponding emissions. As long as the technological system does not include the end of life of the organic material, then the *stock inventory* remains separated from the main inventory. If the primary organic matter is, during its life cycle, mixed with another material, their stock inventories are added. If the end of life is included in the technological system, then combustion is considered to occur and both *stock inventory* tables are added. This is similar to established energy accounting approaches (e.g., [14]), but accounts emission profiles for the feedstock sources.

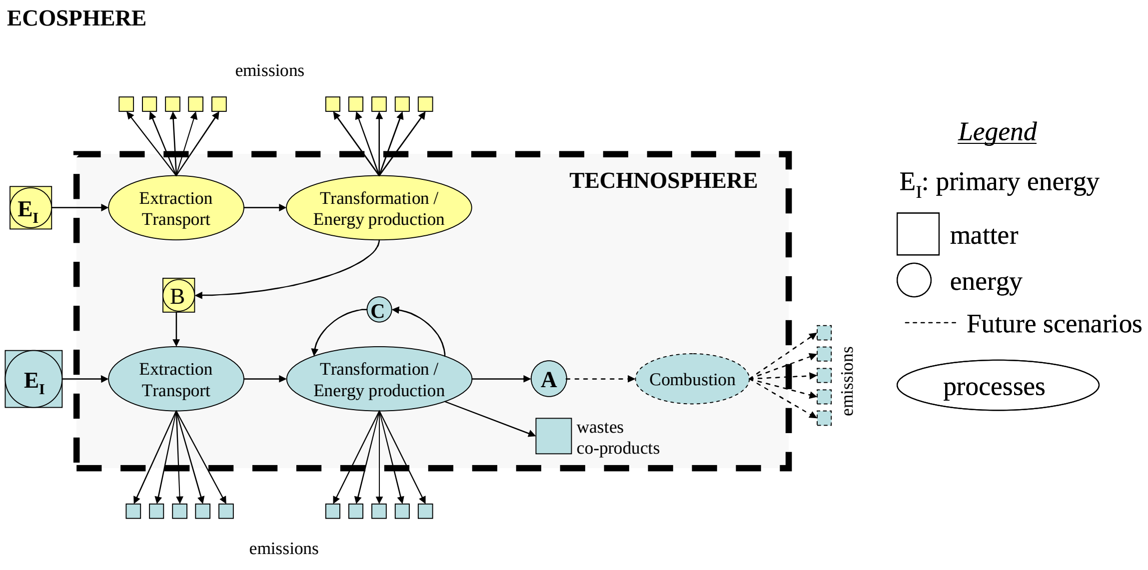

Figure 3: Technological system of organic primary matter being used as an energy resource

In Figure 3, an organic primary matter, containing E_I primary energy is extracted from the ecosphere, transported and transformed. It produces a material used to produce A process energy. If the frontiers of the technological system are set after the production of A, the *stock inventory* table contains the future use of the process energy A and combustion emissions. If the frontiers of the technological system are set after the production of A, the *stock inventory* table is added to the main inventory. In either case, E_I is accounted as removed from the ecosphere into a chosen indicator: i.e., primary energy, ADP or CEENE.

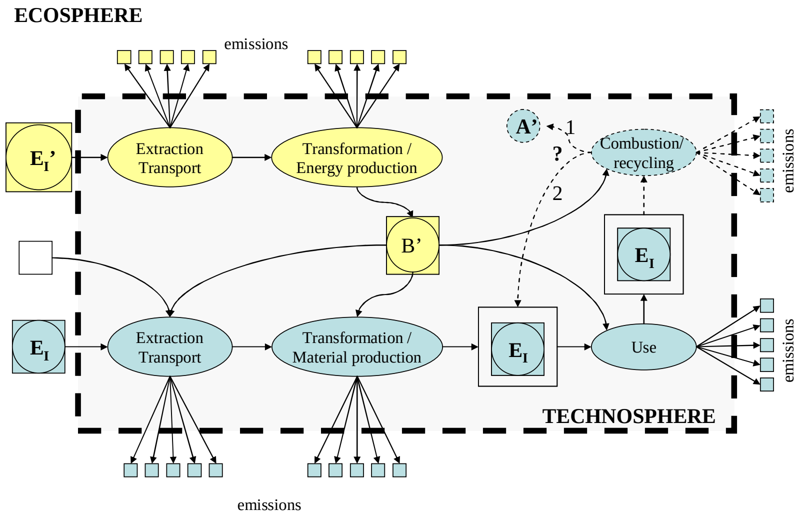

Figure 4: Technological system of organic primary matter being used as a material

Legend

E_I: primary energy

matter

energy

------- Future scenarios

processes

In Figure 4, the same organic primary matter, containing E_I primary energy is extracted from the ecosphere, transported and transformed into a material. At its end of life, this material can be combusted (scenario 1) or recycled (scenario 2). The *stock inventory* will contain the consumed process energy A, as well as corresponding emissions (these can contain emissions from other materials mixed with the considered organic material). This *stock inventory* will be added to the main inventory if scenario 1 is included in the technological system.

The *stock inventory* will depend on the technology that is be used to perform combustion. If no technology is readily or practically available, then the stock inventory should be approximated based on uncontrolled combustion emissions.

4. CONCLUSIONS

The purpose of the present paper was to question the concept of feedstock energy and to propose a new framework for energy accounting in LCA.

The analysis of notions underlying energy concepts in LCA have highlighted that resource consumption indicators, inventory flows and the efficiency concept are all confounded in the same primary energy concept, which has lead to misunderstanding. Furthermore, whereas energy stocks are currently accounted, combustion emissions are never considered.

From these various observations, a new framework is proposed that separately considers energy resource depletion indicators, energy flows, energy efficiency, and accounting for emission stocks using the so-called *stock inventory* table.

As a consequence of this framework, when the feedstock energy is used, for example by recovering energy from waste incinerators, allocation takes place of emissions and resources to, respectively, waste handling and energy produced.

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