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Sustainability of Energy Carrier Production from Renewable and Non-renewable Resources: A Source-sink Exergy Analysis

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Abstract

A concise exergy based model is proposed to address the sustainability issues of energy carrier production from renewable resources and non-renewable resources. The source-sink system that gives the initial potential (e.g. work) is defined. Steps required to transform this potential into an energy carrier are integrated as elements of the model. The model describes the relationship between the elements and how changing characteristics of any element can directly impact the sustainability of energy carrier production. Exergy is proposed as a suitable metric to link the elements of the model, ultimately providing useful information for decision-makers.

Keywords: exergy, non-renewable energy, renewable energy, source-sink system, sustainability

Résumé

Un modèle est développé pour étudier la production de vecteurs d'énergie à partir de ressources renouvelables et non-renouvelables, dans un contexte de développement durable, sur la base de l'analyse exergétique. Un système source-puits qui fournit le potentiel initial (ex : le travail) est définit. Les étapes requises pour transformer ce potentiel en un vecteur d'énergie servent à définir les éléments du modèle. Les relations entre les éléments du modèle et les caractéristiques de ces éléments déterminent si le vecteur d'énergie s'inscrit dans un contexte de développement durable. L'exergie est proposée comme unité de mesure pour lier les éléments du modèle et servir de critère décisionnel.

Mots clés : exergie, énergie renouvelable, énergie non renouvelable, développement durable

1. Introduction

Research on energy carriers such as hydrogen, biofuels and electricity, which are producible from diverse resources such as biomass, fossil resources, sunlight and rivers, is ongoing worldwide. In terms of sustainability, this research is defined, in part, with the objective of reducing the pace of depletion of non-renewable resources and reducing greenhouse gas (GHG) emissions. Ways to produce these energy carriers have received much attention in past decades focussing mainly on technological improvement. In sustainability analysis, such technologies and the energy carriers they produce must be considered in their global context. This context is very broad and many human and environmental issues need to be properly addressed. This paper focuses on the field of thermodynamics and its possible contribution to sustainability analysis. This context, so it seems, is rapidly evolving with, for example, more shale gas and tar sand exploitation and increased biofuel use. This rapid evolution makes it hard to monitor and manage sustainability issues. Moreover, some energy carriers are mixed (e.g. ethanol with gasoline), while some energy carriers are used to produce other energy carriers (e.g. natural gas use in tar sands exploitation).

Energy Return On Investment (EROI) is widely used as a metric in decision making as it provides a comparison between the “energy usable in newly produced fuel” with the “energy consumed in producing the new fuel” [1]. Exergy return on investment provides a similar comparison based on exergy as a metric. Results obtained with the EROI approach are variable, depending on the selection of the energy carriers studied. These results are also variable depending on the definition of the system related to the study and the choice of material and energy flows considered. Moreover there is a pending question on what would be the value of EROI for the production of a specific energy carrier to be sustainable. A minimum EROI of 3 has been suggested for survival and 6 for growth [1]. Variable results and difficulty of interpretation of current methods such as EROI led to focus research not on the results of such research but on the methodology. This paper is part of the pursuit of a general goal: to develop more complete methods that encompasses to the broadest extent material and energy flows and thermodynamics. This leads to a renewability indicator [2] to be developed for renewable resources (RRs) analysis. Since today’s energy carriers often comprise, in their production processes, RRs and non-renewable resources (NRRs), this paper focusses on the possibility to develop a unique model that would consider both RRs and NRRs. The objective of this model is to help select and analyze material and energy flows related to the sustainability of energy carrier production. The first step in this research, presented here, defines the general model and its associated elements.

This model is based on exergy, which has been considered as a metric to consider sustainability issues related to material and energy used by society [3-5,6,7], and source-sink based exergy analysis, which has been introduced in the literature to address energy carrier production from renewable and non-renewable resources [2,8]. In this work, an integrated exergy-based model is proposed to address the sustainability issues of energy carrier production from RRs and NRRs.

2. Model development

For selecting and analyzing the energy and material flow directly related to the sustainability of energy carrier production from RRs and NRRs, a new model is developed in this work. The model integrates several relevant elements whose relationship is presented in Figure 1:

- Source-sink (So-Si) system that gives the initial potential (e.g. work) of NRRs and RRs;
- Renewable energy cycle (REC) from which RRs are extracted;
- Processes that transform RRs or NRRs into energy carrier(s);
- Energy carrier production;
- Offsite resources consisting of the energy and matter required to drive the processes;
- Theoretical loop that links the energy carrier to the offsite resources.

The sustainability of the energy carrier is associated not only with each of these elements, but also with the relationships between them. For example, for an energy carrier produced from NRRs, a change in So-Si characteristics could offset efficiency improvements made to the processes, resulting in less sustainable energy carrier production.

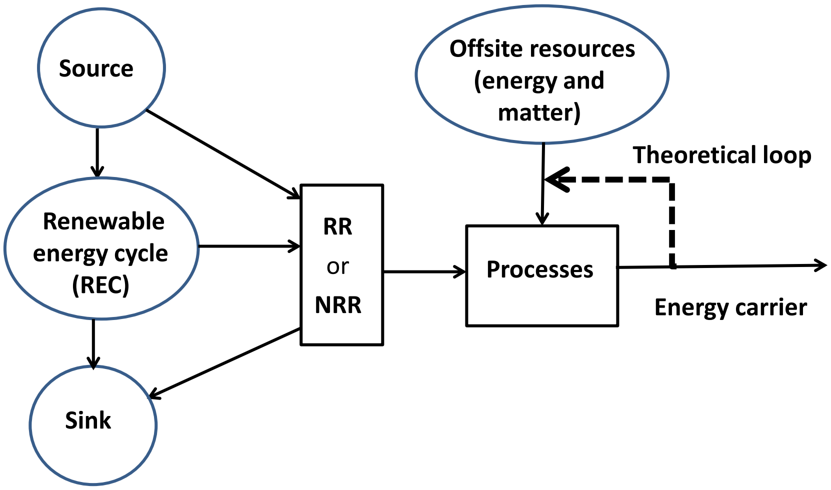

Figure 1. Diagram of the integrated model of energy carrier production from renewable resources (RRs) and non-renewable resources (NRRs)

2.1 Flow diagram

The flow diagram in Figure 1 defines the relationship between the elements of the model. The model diagram helps to represent energy carrier production from NRRs and RRs in a concise manner. Solid arrows represent possible material and energy flows. Dashed arrows represent a theoretical flow. Energy and material flows are not apparent in this model as they are regrouped under a general terminology. However, several potential combinations are available; for example offsite resources and processes can be related to diverse processes such as waste treatment, transport and resource extraction. The theoretical loop can thus comprise a link to all these flows, as represented in previous work [2] to study sustainability of an energy carrier from RRs. This concise diagram enables study of the relationship between chosen elements focussing on the sustainability of energy carrier production. The elements of the model and their relationships are described below.

2.2 Source-sink system

The source and the sink are the initial elements of energy carrier production. The source-sink system gives the initial potential needed to produce any energy carrier. Exergy expresses the maximum work available from two defined systems originally named source and sink by Carnot [9]. Nowadays, these two systems generally refer to a “system or substance” and a “reference environment”; the “dead state” is one possible reference environment [5].

A generalized expression of exergy was elaborated by Han Guangze et al. [10], based on a dead state as a reference:

$$dEx = \sum \; X_i - X_{i,0} \;\; dx_i \qquad (1)$$

where X_i and x_i are the *i* th general intensive and extensive properties, respectively, and the subscript “0” refers to a quantity evaluated at the dead state.

In equation 1, the potential, expressed by the differential in the intensives properties, is needed to produce an energy carrier. This potential can be related to the characteristics of the source and the sink. The extensive property enables evaluation of the actual amount of work available from this potential.

The potential in a RR is defined by the characteristics of the sun (source) and space (sink). These source and sink characteristics are not affected when RRs are drawn from the REC. This is not the case for NRRs when the characteristics (potential and quantity) of the initial So-Si system can be affected when exploited. For example, the characteristics of the source change when unconventional oil is considered instead of conventional oil extraction (different physical and chemical properties); the characteristics of the sink change when the amount of CO_2 increases in the atmosphere due to fossil resource exploitation.

The energy flow from the source and to the sink making up the REC, that in turn provides RRs, is not linked to the sustainability of energy carrier production. Still, it is linked to the amount of energy carrier that can be ultimately produced from the REC. This particularity of RRs was considered in choosing to use exergy as a metric in the development of a renewability indicator [2].

The material and energy flows from the source to the sink for a NRR is linked to the sustainability of energy carrier production and should be considered to show to which extent a NRR is unsustainable. Appropriate identification of the So-Si system enables selection of the flows related to sustainability in respect to RRs and NRRs.

2.3 Renewable energy cycle and renewable resource

The diagram in Figure 1 illustrates the production of an energy carrier from the initial So-Si system. Many renewable energy cycles (such as water and carbon cycles) are related to the sun’s energy (source) and infrared heat emission to space (sink), enabling, in theory, complete renewability. Complete theoretical renewability is made possible by the fact that a REC can be considered as a materially closed cycle. For example, carbon can be captured by photosynthesis and released by combustion, leading, over a certain period of time, to no change in atmospheric CO_2 concentration. From a broad perspective, this cycle captures and releases energy without increasing the entropy of the biosphere.

From the REC, what is called a renewable resource (RR) is made available to be processed and part of its energy content ultimately transformed into an energy carrier. Since a REC operates under relatively fixed source-sink conditions, sustainability issues are mainly related to the offsite resources needed to exploit a REC. An exergy based sustainability indicator that has been developed in earlier work [2] and considered in other research [11,12] to account for offsite resources use in the exploitation of a REC is suitable for a sustainability analysis of most energy carrier production from RRs (e.g. ethanol from biomass, electricity from wind or waterfalls) [2,11,12].

2.4 Non-renewable resource

NRRs represent the resources that are mined from the earth and do not come from RECs. Even if the fossil resources come from a REC, they are considered NRRs because of their very short time span of exploitation (decades) compared to the time needed for a REC to "produce" them (thousands if not billions of years).

A flow of water between two water reservoirs with a height differential is an interesting analogy to illustrate how a NRR can be considered in a So-Si system. Consider that water represents any specific NRR and is available in a finite amount. Consider the higher reservoir as the source (So) and the lower reservoir as the sink (Si). In this context, sustainability would imply, to make the best use of this resource, that one should bring less possible water from the source to the sink to produce an energy carrier (e.g., electricity). Earth's biosphere can be considered as a variable source and variable sink from which NRRs are extracted. The potential and quantity of an energy carrier that can be produced from NRRs is related to the So-Si system [8].

2.5 Processes and energy carrier

Many processes are generally required to transform RRs or NRRs into an energy carrier, including any process related to the energy carrier such as extraction, transport, and transformation. These processes rely on offsite material and energy resources. The energy carrier is considered as any energy form that is delivered to the proper location (e.g. electricity, gas, biofuel) for utilization.

2.6 Offsite resources and theoretical loop

The concept of offsite resources and a theoretical loop developed here takes its origin in early production methods where resources were extracted and used without much transformation (e.g., coal). Onsite energy production was considered with basic economic and technological analyses [13,14] to determine their viability. For example, coal was used to drive devices (steam machines) to extract coal; tar sands were confined and set on fire to extract the oil. When coal or tar sands came from a unique site, obviously, the devices could not consume more coal or tar sands than what was extracted for the process, in order to be economically and technically viable [13,14]. These processes operate with an internal loop of consumption with onsite resources; energy is produced and consumed on site. There is a direct physical link as the quantity of energy carrier that can be delivered from the plant is affected by the internal loop.

Over time, as technology and transportation measures improved, more material and energy could come from offsite resources and brought onsite to exploit specific RRs or NRRs. The use of offsite energy and material to produce an energy carrier (e.g. natural gas consumed in the transformation of tar sands) led to complex questions about how much energy was needed to extract and produce an energy carrier. Concepts such as EROI are used to consider some offsite energy. Since offsite material and energy are required to produce an energy carrier, a general question arises about the net gain of such processes. Utilization of offsite material and energy also raise complex questions about the actual reduction of CO_2 emissions to the atmosphere when CO_2 capture would be implemented (related to concepts of CO_2 capture and CO_2 emission avoidance) [15].

Offsite material and energy used to produce an energy carrier can be considered with a theoretical loop of consumption by transposing the original concept of onsite energy use into a theoretical one. This theoretical loop can be developed to link the energy carrier produced to all material and energy resources needed to produce it. This holds for RRs [2,11,12] and NRRs [8].

When exergy is considered as a metric for the theoretical loop of consumption, a fraction of the exergy of the energy carrier is considered to theoretically substitute matter and energy of offsite resources (e.g. for pollution abatement, environmental restoration, process operation) [2,11,12].

2.7 The theoretical loop link: exergy as a metric

Exergy is described as a relevant metric to characterize transformation of matter and energy and is often considered to study processes [3-7,16,17]. Exergy is defined as the maximum work that can be produced from matter or energy under defined environmental conditions. For material and energy use, exergy accounting is based on the initial concept of cumulative exergy consumption (CExC) developed by Szargut et al [3]. In the late 1990s, Cornelissen [4] and Berthiaume and Bouchard [18] reached a similar conclusion on a possible extension of the CExC concept. This extension is based on the fact that CExC is derived from energy analysis and a subsequent modification of this concept was necessary to properly account for exergy losses in processes considering the full life cycle. CExC represents the sum of all exergy inflow of a sequence of processes to deliver a product, but exergy outflows are not accounted for. This leads to the observation that, to account for exergy losses, exergy of products must be subtracted from the CExC, thus leading to the irreversibility concept [4] or Net exergy consumption (CNEx) [18]. In a recent paper [19], the same relation was proposed under the name of cumulative exergy losses. CNEx has been adopted by other researchers [12,20] and can be considered as a metric linking the exergy of the energy carrier and offsite resources.

Considering all material and energy flows with exergy as a metric is a weighting method that is less direct than the methods where a physical link is considered (e.g. oil to extract oil; coal to extract coal). Exergy, as a metric for the theoretical loop, must be interpreted accordingly. Nevertheless, since it is possible to account, with exergy, for all offsite resources (material and energy), the results obtained can provide greater contrast than energy based methods. For example, in ethanol from corn analysis, energy analysis often yields nearly a 1:1 ratio to compare the energy produced to the energy consumed and exergy analysis yields approximately a 1:4 ratio with the sustainability indicator [2]. Such contrast provided with exergy as a metric provides useful and interesting information for decision making.

3. Discussion

Once the model is established, the effect of changing the characteristics of the system elements on the sustainability of the energy carrier produced can be evaluated. These modifications can be considered with respect to NRRs (So, Si, process, theoretical loop and offsite resources and energy carrier) or RRs (RR extraction, process, theoretical loop and offsite resources and energy carrier). In a recent paper [11], the effect was evaluated that different process would have on the sustainability of the energy carrier produced. The authors considered a theoretical loop and offsite resources in the sustainability indicator to determine the most promising processes. Even though they concluded that all processes were non-renewable their analysis offers options to improve the sustainability of biodiesel production. Considering process improvement under a sustainability indicator is an example of the usefulness of an integrated approach that links some of the elements of the model proposed here.

Considering again the analogy with water reservoirs for NRRs, if the higher and the lower reservoirs always remain at the same level, a sustainability assessment would focus on the efficiency of the processes producing the energy carrier from the water flow. In this case, efficiency improvement would imply less resource consumption for any specific quantity of energy carrier produced (assuming no change in offsite resource characteristics). For example, in a constant So-Si characteristics context for fossil fuels, efficiency improvement can lead to less fossil fuel resource consumption and less CO_2 emissions per unit of energy carrier produced.

Sustainability issues associated with energy carrier production (e.g. hydrogen or electricity from fossil fuels) from NRRs can be considered with variable So-Si characteristics. The nature/location of fossil fuel resource and CO_2 emissions (possibly including capture and storage) represent variable So-Si characteristics. These characteristics can directly affect the offsite resources required to produce the energy carrier. For example, when the energy carrier is produced from an unconventional fossil fuel resource (such as tar sands) and CO_2 capture and storage are considered, NRR consumption increases compared to the use of conventional fossil fuel resources without CO_2 capture.

Changing So-Si characteristics may offset the effect that efficiency improvement would have on sustainability of energy carrier production. For example, taking a reservoir where the water is at a differential of 102,041 m, 1 kJ of energy could ideally be produced per each kg of water that is brought to the lowest level. Taking first an initial situation (A) where the water flow can be used to produce electricity through a device with 70% efficiency, yields a production of 0.7 kJ/kg_{water}. Consider now that the So-Si characteristics and the efficiency of the process change (situation B), so the height differential is no longer 102,041 m but, for example, 20% less, thus leading to a differential of 81,633 meters and a process with 80% efficiency. This process would be characterized by a ratio of 0.64 kJ/kg_{water}. Even in a context of efficiency improvement, less energy carrier production from the same water flow can be produced. Efficiency improvement may not necessarily imply sustainability of energy carrier production in this context. Moreover, the characteristics of other elements can also change (e.g., offsite resources), leading to an increase of the exergy required in the theoretical loop and thus affecting the sustainability of the energy carrier produced.

From the simple model presented in Figure 1, more complex situations could be addressed. For example, NRRs that are used to exploit renewable cycles could, with time, come from a different So-Si system. This could affect the sustainability of energy carriers from RRs.

4. Conclusions

As future energy scenarios increasingly include renewable energy, unconventional fossil fuel resource exploitation and CO_2 capture and storage, the proposed model based on So-Si exergy analyses combined with process analysis and a theoretical loop are expected to help identify the most sustainable energy carrier production systems from renewable and non-renewable energy resources and yield valuable information about such systems.

The proposed model could serve to select and analyze material and energy flows to determine the sustainability of energy carrier production from RRs and NRRs. The model reveals that all its elements must be considered to determine the sustainability of energy carrier production and that process improvement, on its own, cannot guarantee sustainability. The model also reveals that a REC is an essential part of sustainability analysis for renewable resources, and that the theoretical loop with exergy as a metric can form an essential part of a sustainability assessment of energy carrier production from RRs and NRRs. Moreover, changing the So-Si characteristics for NRRs (e.g. fossil resources, CO_2 confinement) poses a great challenge for sustainable energy carrier production. The proposed model could provide better understanding of the effect of integrated mixes of energy vectors that are becoming prevalent in our society.

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6. Biography

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