Energy Strategy Reviews 35 (2021) 100642

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: http://www.elsevier.com/locate/esr

Cutting through the biofuel confusion: A conceptual framework to check the feasibility, viability and desirability of biofuels

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ARTICLE INFO

Keywords:
Biofuels
Relational analysis
Conceptual framework
Taxonomy
Grammar
Energy system

ABSTRACT

Biofuels represent a complex issue in the sustainability discourse as they require the simultaneous consideration of different dimensions and scales of analysis. This situation explains the co-existence of contrasting 'scientific evidence' about their performance. This paper presents a novel conceptual framework that integrates four key aspects of the performance of biofuels: (1) the social factors determining the desirability of biofuel use on the demand side – why do we want to produce biofuels?; (2) the internal technical and economic constraints affecting the viability of their mode of production on the supply side – how can we produce biofuels?; (3) the external biophysical constraints limiting the feasibility of their production – what are the material limits imposed by the availability of natural resources?; (4) the level of openness of the biofuel system referring to the imports used to overcome local limits – the level of externalization of the requirement of natural resources and technical production factors reducing energy security. The proposed framework generates a biophysical characterization of the supply function of a biofuel system (which inputs are needed to generate the supply) contextualized against a biophysical characterization of the societal demand (what inputs the society is ready to invest in the energy system in order to obtain the supply).

1. Introduction

In the last 25 years, biofuels have attracted growing attention in the scientific community: the number of biofuel-related publications per year has significantly increased [1] and many dedicated journals have appeared. A great variety of papers have assessed 'the sustainability' of biofuels by focusing on specific criteria, such as Greenhouse Gases (GHG) mitigation (e.g. Refs. [2–6]), land grabbing and indirect land use changes (ILUC) (e.g., Refs. [7–9]) as well as the impact on food prices (e.g. Refs. [10–13]), or by focusing on a wider range of sustainability criteria for specific biofuel options (e.g. Refs. [14–17]). Several studies have highlighted important drawbacks in the supply of crop-based biofuels (also known as first generation biofuels), including impacts on livelihoods, food and water security, and the local and global environment (e.g. Refs. [18–20], for overviews). For this reason, advanced biofuels, based on the transformation of non-food plants and organic wastes, have been put forward as the natural alternative to first generation biofuels (e.g., Ref. [21]). However, there are skeptical views also about this new generation, flagging the need for further investigation into the potential challenges of this alternative [19,22].

Despite the vast literature, the assessment of the sustainability of biofuels, whether crop-based or advanced, has remained controversial and the uncertainty in relation to their possible benefits and risks has only been growing [23]. Indeed, biofuels represent a 'wicked issue' [24,25], i.e. an issue characterized by a diversity of conflicting values at stake, associated with high uncertainties and about which it is impossible to achieve an uncontested problem structuring. The 'wickedness' lies precisely in the fact that different scientific disciplines and sub disciplines adopt non-equivalent framings of the issue at hand, each one focusing on the analysis of a limited set of specific attributes of biofuels performance. The question whether a significant expansion of biofuel production represents a step in the right direction towards a more sustainable development of society has remained unsolved. Answering this question requires a procedure of holistic assessment that can support an informed reflection on *what* biofuels are, *why* they are relevant for society, and *how* their production and use is related to relevant criteria of performance.

Several assessment methods are reported in the literature to investigate the sustainability of biofuels [26–28]. These include energy analysis, life cycle assessment and the carbon and water footprint [29]. However, as mentioned, the majority of these assessments tend to be

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https://doi.org/10.1016/j.esr.2021.100642
Received 16 November 2019; Received in revised form 29 December 2020; Accepted 3 March 2021

Abbreviations

EC	Energy Carriers
EU	End Uses
GHG	Greenhouse Gases
MAGIC	Moving Towards Adaptive Governance in Complexity: Informing Nexus Security
NL	Netherlands
NP	Nitrogen and phosphorus
QST	Quantitative Story-Telling
PES	Primary Energy Sources
UCO	Used Cooking Oil

rather narrowly focused, looking, for example, at only one particular biofuel technology [30]. Moreover, these analyses are usually based on just one or a limited set of indicators (e.g., GHG emissions and energy efficiency) that can be reduced to a single index [23]. To the best of our knowledge, in the scientific literature it is difficult to find analyses of the sustainability of biofuels that address the concept in a multi-dimensional way [30]. Even when a larger set of indicators is provided, the protocol of analysis assumes that these indicators remain effective across a wide range of different contexts [31,32].

The complexity of the biofuel issue entails that it is impossible to provide 'the ultimate scientific evidence' of their sustainability using standard protocols. Depending on the attribute considered – e.g., reduction of GHG emissions, competition with food production, energy security, rural development – we have to adopt a flexible approach capable of tailoring the analysis to the chosen research question [33]. Checking the wide spectrum of potential (negative and positive) effects of biofuels requires the researcher to consider different spatial and temporal scales, different criteria, and different cases and contexts. For example, issues of uneven spatial distribution of where the biomass has come from, which regions have borne the negative impacts, which ones benefited and alternative techniques of production are typically not included in 'sustainability assessments' [32].

In this paper, we propose a novel conceptual framework based on metabolic analysis that can be used to characterize the sustainability of any energy system. The framework was developed within the EU Horizon 2020 project MAGIC [34] with the specific purpose of supporting Quantitative Story-Telling (QST) about the resource nexus [35]. QST aspires to check the robustness, the usefulness and the fairness of the narratives around EU policies related to sustainability and climate change. It involves a quantitative exploration of multiple narratives, avoiding spurious accuracy and focusing on salient features of the selected stories [36]. We focus here on the conceptual framework used to check the plausibility of narratives around biofuel policies. An exercise of QST about biofuels has been published elsewhere [37].

The rest of the paper is organized as follows. In section 2, we present the three main elements of the proposed conceptual framework: (i) a taxonomy of descriptive elements and accounting categories for characterizing typologies of biofuel supply systems; (ii) a grammar to integrate the characterization of biofuel performance; (iii) a characterization of the state-pressure relation between proposed technical solutions and desired characteristics of the society expected to adopt them. In Section 3, we illustrate the approach through a simplified example that characterizes the production and use of biofuels in the Netherlands (NL). Finally, section 4 underlines the potential and shortcomings of the proposed approach and indicates lines for future research. Note that in this paper we use the term biofuels as defined in the Renewable Energy Directive of the European Commission (Article 2): "biofuels' means liquid fuel for transport produced from biomass" [38].

2. A novel conceptual framework

2.1. The three theoretical pillars of the conceptual framework

The framework proposed here is based on the combination of several theoretical concepts developed in different scientific fields. In particular, three fields are essential: energetics, complex systems theory (relational analysis) and bioeconomics (the flow-fund model of Georgescu-Roegen).

Energetics is a genuinely transdisciplinary field dealing with the study of integrated sets of energy transformations. The term energetics was introduced in 1907 by Ostwald [39,40], a Nobel Prize winner in chemistry, as an intuition about the key importance of energy in shaping human society. Later, the development of non-equilibrium thermodynamics [41–44] provided energetics with a rock-solid scientific status as it provided the only possible explanation found in natural sciences for the presence of order and self-organization in living systems under the laws of thermodynamics. The concept of dissipative structures was then applied to explain the formation and the functioning of human societies [45–47], which were defined as metabolic systems [48–52]. Energetics and thermodynamic principles have since been used in a variety of diverse fields, such as biology, to explain the self-organization of living systems (including ecosystems) [53–55], and sociology [56,57] and anthropology [58], to explain the functioning of human society. Energetics gained a certain popularity in the 1970s up through the end of the 1980s due to the first oil crisis and concerns in response to the publication of "The limits to growth" [59]. In this period, a big push towards the field of energetics was given by energy experts (starting in the 1970s) exploring the issues of energy security and food security and more in general the relation between energy and society [60–67].

Relational analysis has been developed within the larger field of complex system analysis. It was introduced in relational biology [68,69], further developed by Rosen (2005; 2012) [70,71] and proposed in the form of a mathematical framework (in the field of category theory) by Louie (2009; 2013; 2017) [72–74]. Relational analysis is different from the majority of quantitative frameworks in that it addresses the question: '*Why* does the system under study exist in the first place?' Addressing this question is essential for a strategic decision-making in the field of energetics. In fact, in order to understand the performance of an energy system it is essential to define *why* the relative set of energy transformations is useful for society.

Relational analysis uses the four Aristotelian causes to help the structuring of the perception and representation of the functioning of an energy system:

i. The final cause – '*why*' the system has been put in place;
ii. The efficient cause – '*how*' the system manages to express the functions required by the tasks to be achieved;
iii. The formal causes – associated with the recorded information about the structural organization of the elements that are combined and used to express the required functions. Formal causes are the representations of '*what*' are the structural elements operating in the system;
iv. The material causes – the biophysical basis of the system ('*what*' the system is made of), i.e. the actual material composition of the flows in the network of energy transformations.

The flow-fund model of Georgescu-Roegen uses thermodynamic principles to develop a heterodox economic theory. This conceptual tool, developed within the field of bioeconomics [75–78], addresses a key issue of sustainability: how to study the nature of the interaction of the 'technosphere' (the set of processes under human control) and the 'biosphere' (the set of processes outside human control). According to the flow-fund model, the metabolic pattern of a society can be described effectively by two different types of metabolic elements:

i. Fund elements – those agents whose identity remains constant through the duration of the representation (e.g., population, workers, technology, land uses), and
ii. Flow elements – input and output flows that either disappear (consumed) or appear (produced) through the duration of the representation.

This distinction is relevant because it allows the analyst to properly address the challenges posed by the existence of multiple scales [79]. Another essential feature of the flow-fund model is its ability to detect the external limits of an energy source. In fact, a given primary flow (a flow getting into the technosphere from the biosphere) can only be generated by either a fund element (e.g., the biomass produced in a hectare of land) or by the depletion of a stock (e.g., the mining of coal or the extraction of oil). In the case of a fund-flow exploitation – as in the case of biomass production – the flow is renewable, but the quantity of the supply is limited in both terms of pace and density. The flow depends on the characteristics of the exploited fund (e.g., the yield of biomass per hectare and the number of available hectares). Studying the characteristics of the fund generating the exploited flow provides information about the severity of the external constraints. In the case of stock-flow exploitation, depending on the capacity of extraction, we can increase the flow at will (by boosting the pace of exploitation), but the supply of the flow is not renewable. The exploitation is literally destroying the favourable gradient generating the supply (the stock of inputs).

In this paper, we combine the various theoretical concepts of these three fields to generate a conceptual framework for the quantitative characterization of the performance of energy systems:

i. A *taxonomy* for accounting different energy forms (described in section 2.2);
ii. An *energy grammar* to characterize the main features of an energy (biofuels) system (described in section 2.3);
iii. The *state-pressure relation* characterizing the expected relation between the metabolic characteristics of *a network niche* – i.e. what the network is expecting, in terms of inputs and outputs, from a node belonging to it – and the metabolic characteristics of *the instance of the relative node* occupying it – i.e. what the node is actually "taking from" and "giving to" the network (described in section 2.4).

This conceptual framework allows us to integrate and explore four key factors of sustainability – feasibility, viability, desirability, and level of openness – in a flexible quantitative analysis of the performance of biofuels and of energy systems in general.

2.2. *Defining a taxonomy for a proper energy accounting*

Taxonomy is "the study of the general principles of scientific classification" [80]. A pre-analytical choice of a taxonomy is essential for the quality of the process of crunching numbers. Defining a taxonomy entails defining the elements used in the characterization of an energy system, i.e., defining 'what the system is' and 'how it works'. This characterization should start from an identification of expected relations over structural elements (instances or tangible elements associated with the expression of expected processes of transformation) and functional elements (typologies or notional elements fulfilling an expected task whose characteristics depend on the combination of the lower-level structural elements composing them). An overview of the expected relations over the accounting categories describing an energy system is given in Fig. 1.

According to the laws of thermodynamics, 'energy' cannot be made by humans in the technosphere. Therefore, society relies on primary energy sources made available by natural processes (favourable physical gradients) for the generation of secondary energy flows (energy carriers). This implies that the label 'energy' is too generic a semantic category for use *as such* in the accounting [81]. We can only account

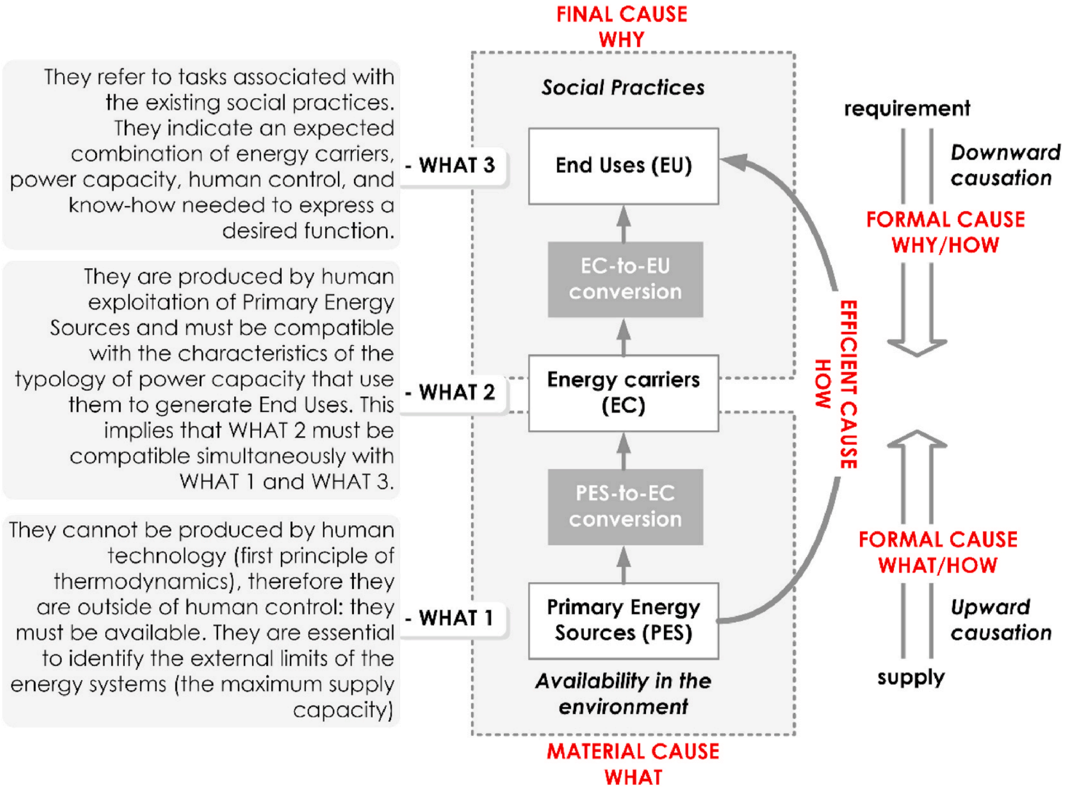

Fig. 1. Expected relations over the categories of accounting describing an energy system in a given socio-ecological system.

energy quantities in relation to different energy forms – e.g. 'Primary Energy Sources' (PES) versus 'Energy Carriers' (EC) (secondary energy). Other specific accounting categories (e.g., thermal energy versus mechanical energy) may be needed for more detailed analyses (e.g., considering the difference in quality between 1 MJ of fuel and 1 MJ of electricity). Hence, the definition of *what* is a quantity of energy depends on *why* this quantity is relevant. For example, we do not account gravitational energy when analysing the energy performance of biofuels. Proper accounting depends on the pre-analytic choice of a taxonomy that defines a set of relevant categories and their specific relations within a given energy system. Assessing quantities of energy in generic terms does not provide useful information for energetic analysis [81,82].

Fig. 1 shows that we need at least three non-equivalent definitions to characterize an energy system:

i. '*what 1*' – What are the available gradients outside of human control (PES such as wind, falling water, coal, solar radiation) that must be exploited for the production of energy carriers (EC)? This information is relevant to study the feasibility of energy transformations (i.e., compatibility with external constrains).
ii. '*what 2*' – What energy carriers (forms of energy under human control such as electricity, biofuels, process heat) should be considered useful energy forms for society? Note that not all secondary energy forms are necessarily useful for all possible End Uses (EU). For example, 1 MJ of gasoline does not power a laptop, 1 MJ of electricity does not power a Jumbo jet. This information is relevant to study the viability of energy transformations (i.e., compatibility with internal constrains).
iii. '*what 3*' – What are the end uses (associated with social practices) that combine energy carriers, typologies of power capacity and human control in the right mix for expressing the functions/tasks required by society? This information is relevant to study the desirability of energy transformations (i.e. compatibility with social values and practices). This last definition of energy form is no longer related only to technical aspects of energy conversions, but also addresses the nature of the activities taking place in society – i.e., why the energy transformations are needed. Yet, this third definition is essential for technical analysis, because the existence of expected tasks requiring end uses determines the performance of the energy system in the first place.

As shown in Fig. 1, the three different meanings of '*what is an energy form that is relevant for the accounting*' depend on each other in an impredicative way (i.e. chicken-egg relation). Therefore, an energy system is effective only if it allows the establishment of this set of impredicative relations over the three answers to the question 'what form of energy is this?' According to relational analysis, this can be explained using the four Aristotelian causes [70,83] (also shown in Fig. 1) in order to get a shared vision of the process we want to analyse:

Final cause – At the interface with societal processes, the final cause determines the relevance and the value of the energy system for society. Why do we want to have biofuels? Is it about security of mobility? Is it about reducing GHG emissions? Is it about preserving jobs in agriculture? This input of information is external to both the strategic and technical analysis of the energy system. Note that in spite of its key importance, the 'why' question is generally ignored in technical analyses.

Efficient cause – The efficient cause connects the category of *primary energy sources* to the category of *end uses.* This is the most elusive concept in the analysis, because the efficient cause eludes the simplifications of reductionism. An energy system is relevant only if it can achieve a final cause. It must be able to express the various processes transforming a material cause (e.g. PES) into the expression of the final cause (e.g. EU). However, the analysis of efficient cause cannot be based on reductionism because the various processes needed to express a given efficient cause cannot be described using a single descriptive domain (i.e. a representation based on a single scale and dimension of analysis). In fact, according to the principle of energetics, there are at least two distinct sets of conversions associated with the expression of an efficient cause:

i. Moving from a primary source to a secondary source, i.e. the exploitation of a PES (e.g. coal) generating a supply of EC (e.g. electricity). In metabolic terms, this phase is described as catabolism, i.e. the destruction of gradients (primary inputs) to provide required secondary input. An example would be a power plant burning coal to generate electricity.
ii. Moving from a secondary energy flows to an end use, i.e. the transformation of an EC (e.g. gasoline) into an EU (e.g. going on a trip). In metabolic terms, this phase is described as anabolism, i.e. the use of secondary input for the expression of useful tasks. An example would be a car using gasoline to provide mobility to people.

In metabolic systems, both steps are required and, therefore, have to be properly coupled. However, when coming to a quantitative analysis of the overall system, these different conversion processes require the adoption of non-equivalent (and non-reducible) descriptive domains – i.e. selection of a scale allowing the characterization of relevant attributes - and models of analysis. The factors determining the performance of these two conversions are different. If we use as indicator the overall conversion PES→EU (e.g. the overall effect of the transformation of coal into refrigerated food in a fridge), we simply lose track of the individual factors determining the PES/EU ratio. That is, the ratio PES/EU does not provide any useful information about either the exploitation of the PES into EC (e.g. the efficiency of the power plant generating electricity) or the conversion of the EC into EU (e.g. the efficiency of the refrigerator in using electricity).

On the other hand, it is also true that an energy system is only relevant if it can express an effective chain of conversion PES → EC → EU. Indeed, the performance of a set of energy transformations is an emergent property of the various elements of an energy system. The overall 'performance' of an energy system is determined by the specific combination of lower-level processes, each of which can only be observed at the local level and requires their own locally specific definition of performance (as they are instances depending on their specific history and specific context). For this reason, a reductionist approach cannot work and a more holistic analysis is required. We must distinguish between: (i) the characteristics of the 'efficient cause' considered as *a boundary object* that determines the meaning of a given combination of energy transformations (the emergent property of various processes of transformation); and (ii) the characteristics of lower-level components (structural elements engaged in individual local transformations) that can be characterized in terms of unitary processes or technical coefficients (reflecting the formal causes). Studying the emergent property of the whole energy system requires a proper combination of all these pieces of information. This is the ultimate objective of the energy grammar presented in section 2.3.

Formal cause – The formal cause is associated with the existence of expected and recorded patterns of organization of the structural elements (e.g., instances of plants) expressing the lower-level local conversions – e.g. blueprints, cybernetic controls. The structural elements can be used in both catabolic (PES → EC) and anabolic (EC → EU) transformations of energy. It is here that complexity theory enters into play. In fact, there is an open semantic relation between 'functional' elements (typologies associated with the expression of expected functions) and 'structural' elements (those guaranteeing the expression of specific local patterns of energy transformation), which can be established across levels of analysis. When framed in the jargon of hierarchy theory, the effective combination of functional and structural types is called a holonic relation (from the terms holon and holarchies [84,85]). This 'holonic coupling' – called functional entailment in relational theory [70] – entails a semantic openness (the existence of many-to-one mapping) in the representation. Put it in another way, there is a systemic degeneracy in the mapping of the characteristics of functional elements (efficient cause) onto the characteristics of structural elements (formal causes).

For example, the supply system of biodiesel (the functional element) is composed of different types of feedstock and different types of industrial processes (the structural elements). This degeneracy has important consequences for the energy accounting [86,87]. The profile of inputs and outputs describing the metabolic characteristics of the functional element (e.g. biodiesel supply) cannot be directly derived from the knowledge of the technical coefficients of the structural elements (e.g., inputs and outputs of sunflower, rapeseed, or soya cultivated on different soils with different techniques). To handle this epistemological challenge, further information regarding the quantification of the expected relations between structural and functional elements is needed (what is hereinafter termed 'grammar'). Two types of information inputs are needed to integrate the representation of functional and structural elements: (i) the technical coefficients (profiles of inputs and outputs) of each one of the structural elements; and (ii) how these structural elements are combined and used to achieve a common end-use inside the functional element. The existence of this semantic mapping between functional and structural elements implies that engineering analyses focusing on the performance of individual structural types (i.e., instances) are not necessarily addressing the whole set of functionality problems of the energy system. What is needed is a grammar (described below) specifying how the various structural and functional elements are related and the relative importance (weight) of the characteristics of the various structural and functional elements in the system.

In the case of biofuels, we have to identify different formal causes in the two sets of conversions (see Fig. 1): (i) the production of feedstock and the conversion of feedstock into biofuels (PES→EC, catabolic step); and (ii) the use of biofuels in internal combustion engines to guarantee mobility or transport (EC→EU; anabolic step). When analyzing specific local processes, specific types of formal causes map onto specific types of organized structures/technologies (e.g., different processes of feedstock production). This implies that the identity of these formal causes is essential for the definition of 'what energy forms' should be considered in the grammar. For example, depending on the type of engines available in society (EC→EU), we may have a forced requirement of specific fuels (e.g., biodiesel versus bio-gasoline). Depending on the type of natural resources available for exploitation (PES→EC), we can only exploit a certain set of primary energy sources (e.g., it is impossible to produce sugarcane feedstock in northern Europe).

Material cause – The material cause determines the nature of the biophysical roots of the energy system as it relates to the interface with natural processes outside of human control (see Fig. 1). Given the complete dependence on primary energy sources for initiating the energy conversions, the identification of the material causes associated with the energy system (what is the primary energy source required for establishing the whole process) is key for assessing the feasibility of the supply of energy carriers. Indeed, the availability of material cause is the ultimate limiting factor to EC production. The distinction between fund-flow and stock-flow exploitation helps the analyst to describe the nature of this biophysical limit. In the case of biofuels, we can either exploit primary energy sources (biomass from feedstock produced from ecological funds) or exploit tertiary flows (waste flows derived from the use of secondary flows, such as manure for biogas or used cooking oil for biodiesel). In both cases, these flows have clearly definable biophysical limits that define their feasibility (external constraints). This is another example of an impredicative definition of relations in the grammar: the identification and definition of the set of PES (the '*what 1*' in Fig. 1) determines the possible set of transformations (and their potentiality) considered in the grammar (the '*what 2*' and '*what 3*' in Fig. 1).

2.3. *Developing grammars: giving meaning to the accounted flows*

In linguistics, a grammar serves to organize different typologies of words (nouns, verbs, adjectives, etc.) into meaningful sentences [88]. In analogy, in the representation of an energy system, a grammar is a set of expected relations between a given set of semantic categories and a given set of formal categories (reflecting the defined relations between functional and structural elements) within a given taxonomy of accounting [79]. A grammar tracks the quantitative relations over the specific energy transformations and hence it is important to design a conceptual map that structures the various analytical processes in relation to a set of quantitative indicators. As illustrated in Fig. 2, we propose four sustainability criteria for assessing the performance of a biofuel system (and more in general any other type of energy system):

Feasibility – The identification of the feedstock used to produce biofuels defines the nature of the material cause and therefore allows the framing of the biophysical analysis of constraints. The impredicative analysis of feasibility can work in two ways:

i. *How the conversion PES → EC (the catabolic side) determines the constraints.* Given a defined final cause (i.e., the set of EU that society needs to reproduce a given state) and starting from the definition of the material cause (i.e., the availability of PES for producing biofuels), we can calculate the maximum supply of EC possible. This gives us the maximum supply that may be expected from a defined biofuel system, given the technology and the available PES.
ii. *How the EC → EU conversion (the anabolic side) determines the constraints.* In this case, the required expression of EU defines the required quantity and mix of EC. Given the characteristics of the supply system, we can calculate the amount of PES needed to cover the required level of consumption. This approach allows us to calculate whether the chosen supply system can cover entirely the required supply and, in the case of external constraints limiting the availability of PES, what fraction of the expected supply can be covered.

Within this framework, it is also possible to contextualize the concept of *environmental pressure* (i.e. the existence of biophysical constraints and environmental impact) referring to the requirement of primary sources, primary sinks and the type and level of stress on ecological funds. However, these definitions can only be obtained at the level of technical processes (when observing structural elements) and not at higher levels! In fact, it is only at the level of local processes (when patterns reflect the information associated with the formal cause) that it is possible to identify an external referent – i.e. an observable pattern of inputs and output flows associated with the operations of organized structures (the expected characteristics of the process).

Viability – The analysis of viability refers to the transformation of secondary flows inside the technosphere. The viability is determined by the requirement of internal inputs that have an opportunity cost for society. How expensive is it to exploit PES? What technical problems are faced? When considering a scaling-up of the supply of biofuels, the internal constraints become very important. In fact, compared with fossil fuels, the process of producing and processing first generation agro-biofuels (including feed-stocks) requires a much higher internal consumption of energy carriers (and other production factors) [89]. A high requirement of energy carriers to generate energy carriers reduces the net supply of energy carriers that will be available to society (and increases the demand for land, water, fertilizers, and labour). This translates into a lower economic viability (higher costs) and tougher competition with other possible land uses with higher economic return.

Desirability – The criteria of desirability potentially covers many different aspects. The following questions are useful to study the desirability of a biofuel system: (i) Why are biofuels produced? (identifying concerns); (ii) What type of costs and benefits should be considered when biofuels are produced and used at the large scale?; (iii) What are

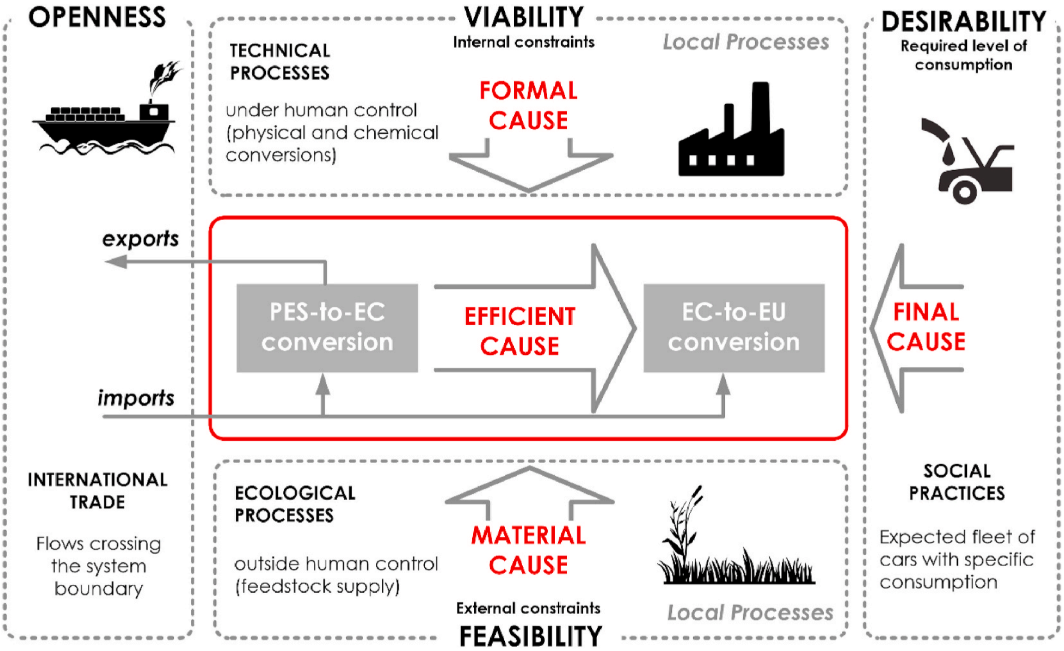

Fig. 2. The relations over the factors relevant for studying the feasibility, viability, desirability and level of openness (externalization) of biofuel systems.

the energy forms in the categories of PES, EC and EU that should be considered for assessing the pros and cons of the production of biofuels?; How dependent is the actual production of biofuels on externalization and what are the implications of this dependence (e.g., the practical implications of lack of security, ethical implications related to the externalization of impacts to other social-ecological systems)? This last question flags the relevance of the fourth factor illustrated in the grammar shown in Fig. 2.

Openness – Considering the whole set of relations shown in Figs. 1 and 2, we see that any existing energy system is determined by the combination of a ‘downward causation’ – i.e. what is expected by the supply system (why/what) – and an ‘upward causation’ – i.e. what can be established when considering the limits provided by economic, technical and biophysical processes (how/what). However, due to the option of trade, the final cause (the targets expected by the downward causation) can either be guaranteed by a mix of local supply systems operating inside the boundaries of the system (domestic production) or by outsourcing the supply to other social-ecological systems, via imports. In the latter solution (externalization), a mix of virtual supply systems operating outside the boundaries of the system under study will provide the required production factors. The balance between the two solutions has important implications in terms of energy security, local environmental impact, and externalization of problems to other social-ecological systems.

Openness is an extremely important aspect of the assessment, especially when assessing the performance of energy systems in developed countries [90]. As shown in Fig. 2, two distinct quantitative representations of ‘external constraints’ are needed: (i) the *local* biophysical constraints and environmental impact associated with the requirement of PES and generation of waste and pollution inside the borders of the biofuel system (local processes), and (ii) the *externalized* biophysical constraints and environmental impact associated with the use of primary and secondary resources embodied in the imported PES and/or EC (the degree of dependence on external processes). The analysis of openness is not only relevant for energy systems, but also for food production systems [37].

2.4. *Contextualizing the performance of biofuel systems: characterizing the state-pressure relation between the node and its niche in a metabolic network*

Having defined a taxonomy and developed a grammar, we can now characterize the state-pressure relation between the proposed energy system (the technical ‘solution’) and the social-ecological system of which it forms part. This involves a biophysical characterization of the supply function of the energy system (what inputs are needed to generate what supply?) contextualized against a biophysical characterization of the societal demand (what inputs is society ready to invest in the energy system to obtain what desired supply?).

To characterize the state-pressure relation we borrow concepts from complexity theory. In particular, the organization of a social-ecological system can be studied as a relational thermodynamic network [91,92]. This approach combines: (i) direct information about the metabolic characteristics of the structural elements of a network node (determined by formal causes); and (ii) mutual information about the expected characteristics associated with the network niche of a node. The network niche is the functional identity that the whole network expects from the metabolic elements operating in a node, whereas the identity of the node is the structural identity of the elements transforming inputs into outputs in the node.

The state-pressure relation between a biofuel supply system – considered as a node of metabolic transformations– and the society in which it is operating – determining its network niche – can thus be described by:

i. The biophysical supply associated with the identity of a typology of biofuel system defined by a given combination of structural elements (formal and material causes). The state of this *node* (the element where inputs get in and outputs get out) defines: (i) the supply of biofuels it can deliver; and (ii) the required inputs from society (capital, secondary inputs and labor); and (iii) the required inputs from nature (primary sources/material cause);
ii. The biophysical demand associated with a given instance of socio-economic system defined by the inputs wanted by the society (the output the society requires from the node – the final cause) and the investments that society is willing to make to obtain these inputs (the

inputs that society is giving to the node - the material and the efficient cause). These expectations can be characterized in terms of (i) the supply of biofuels wanted by society; and (ii) the capital, secondary inputs and labor made available for realizing and operating the typology of biofuel systems (what society is willing to invest in biofuels).

In more formal terms, the state-pressure relation refers to the forced compatibility between:

i. The characteristics of the metabolic state of the node – the set of processes of conversion of inputs and outputs defined by the network for that node. The state of the node is determined by the size of the fund elements – the converters making up the node - and the metabolic pace of the processes of conversion – the rate of transformation of inputs into outputs per unit of fund size;
ii. The characteristics of the metabolic niche capable of absorbing the pressure associated with the state – the quantity of inputs that the network supplies to the node and the quantity of outputs that the network can absorb from the node.

The correspondence of these two types of information generates a double contingency effect [93,94]: a metabolic network in order to be functional has to be able to match the "top-down definition" (what is expected by the network niche) and the "bottom-up definition" (what is established by the structural elements in the node). In conclusion, a metabolic element operating in a network – i.e. a functional realization of a biofuel supply system – must match the profile of inputs and outputs expected by the rest of the network (i.e. it must be compatible with the constraints imposed by the social-ecological system of which it forms part). This impredicative definition of identity is typical of metabolic systems (e.g. the famous chicken-egg dilemma) and defies quantification according to the paradigm of reductionism [83,95]. A grammar capable of identifying and visualizing the conditions of compatibility is illustrated in Fig. 3.

On the left side of Fig. 3, we have the profile of inputs and outputs needed by a typology of biofuel system to express a given supply. These are the characteristics of the *node*, assuming it is possible to realize an instance of it. On the right side, we have the profile of inputs that the society is requiring and the outputs that the society is willing to invest in the supply system for the expression of its function. These are the characteristics of the *network niche*. Note that the pattern associated with a metabolic processor (illustrated on the left side of Fig. 3) is expressed at the level of individual structural elements (e.g., a crop field of rapeseed used for producing biodiesel), but it can also be calculated at the level of functional elements, in notional terms, at a higher hierarchical level of organization – i.e. the combination of the various processes used in the production of biodiesel from oil crops.

The analysis of feasibility is important because it introduces another key aspect. Even if we are considering the performance of energy systems, we have to consider other types of inputs and outputs in our analysis in order to guarantee its policy relevance. Indeed, besides PES (needed to power the energy supply system), other types of primary inputs provided by nature are needed for the operation of the supply system. In the case of biofuels, these primary sources include land, water, and biodiversity associated with the production of feedstock. Regarding flows under human control, besides energy carriers (such as electricity and fuels), there are other relevant technical inputs such as blue water, fertilizer, pesticides and fund elements such as labor and technological capital. The same applies to the generation of outputs. Besides the outputs required by society – the supply of biofuels – there are also undesired outputs, such as nitrogen and phosphorus (NP) leakage in the water table (related to agricultural production) and GHG emissions in the atmosphere, that have to be absorbed by the environment. This implies that the characterization of the state-pressure relation requires an expansion of the set of accounting categories to include also non-energy flows, such as hours of labor, kg of feedstock, hectare of land, cubic meter of water, tonnes of fertilizers, tonnes of CO_2. Note that the flows referring to the external constraints (the exchange of flows with nature) can be obtained through imports and, therefore, the economic perception of the viability of biofuel production (whether it is technically or economically viable) does not coincide with the definition of feasibility (whether there are enough PES within the social-ecological system to have the production). For instance, the assessment of a production system of biofuels based on the import of large amounts of feedstock has to consider the externalization of the environmental impact to other social-ecological systems. If the goal is reducing emissions, externalizing emissions through import of feedstock is not an admissible solution (all GHG eventually end up in the same atmosphere).

Using the conceptual map illustrated in Fig. 3, we can develop detailed grammars describing the relations between functional and structural processors tailored on specific research questions that can help reduce the confusion in the discussion over biofuels. For example, a quantitative analysis aimed at assessing the possibility of using biofuels to replace fossil energy (requiring the re-use of biofuels in their own

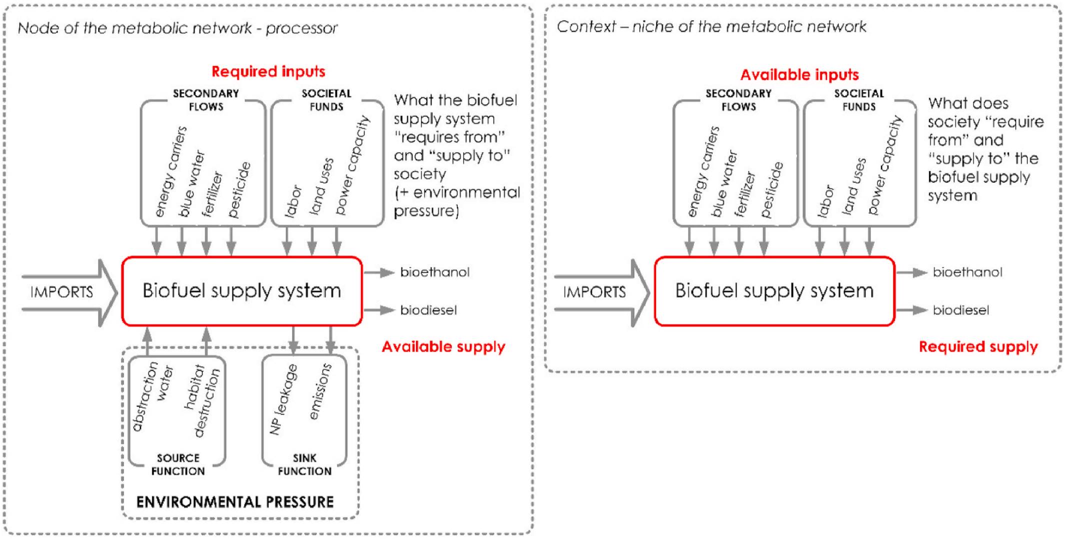

Fig. 3. The characteristics of the metabolic node (on the left) vs the characteristics of the metabolic niche (on the right).

production) is different from a quantitative analysis aimed at assessing the potential of biofuels to reduce GHG emission (in which fossil energy is used to produce biofuels). This is a crucial feature of the method we are illustrating. The metabolic processor on the left side of Fig. 3 is useful to study the emissions of a biofuel production system, however, if we want to study the possibility of producing biofuel to substitute fossil energy we have to use another grammar (as illustrated in Fig. 4). Thus, the choice of the accounting system and the grammar for generating quantitative results depends on the research question. Indeed, when coming to the generation of indicators of performance for biofuels, “one size does not fit all”.

In conclusion, any quantitative analysis of the performance of biofuels must be based on a shared agreement on: (i) the definition of the taxonomy of accounting categories; (ii) the validity of the grammars selected to assess the specific attributes relevant for the performance of biofuels; and (iii) the specific characterization of state-pressure relations tailored to a given research question: “material arrangements only have meaning within, and in relation to, the practices in which they are enfolded and through which they are reproduced” [96].

3. An application of the conceptual framework: biofuel production in the Netherlands

In this section, we illustrate the application of the general conceptual framework presented to characterize the performance of a given biofuel system in a defined social-ecological system (the Netherlands) and in relation to a specific research question. The Netherlands (NL) was selected as an example because it is a major biofuels exporter and one of the greatest contributors to the biofuel science and R&D expenditure in the EU [1]. The analysis presented does not intend to assess the biofuel strategies adopted by Netherlands, but only to illustrate the novelty of the assessment and its transparency in terms of assumptions and calculations. An assessment of biofuels policies based on Quantitative Story Telling has been published elsewhere [37].

3.1. *Structuring the analysis*

The assessment of the sustainability of biofuels follows the following four steps:

STEP #1: define the purpose of the analysis (research question).

In this example, we check whether the NL could possibly substitute the actual supply of liquid fuels used by the country with biofuels (i.e. final cause). This step is essential because of the diversity of justification narratives associated with biofuels. As explained in Cadillo-Benalcazar et al. [37], the production of biofuels in EU has been justified in relation to a variety of final causes, including energy security, reduction of GHG emissions, and rural development. Each one of these final causes requires a different grammar to capture the relevant attributes of performance.

STEP #2: generate a grammar structuring the analysis in relation to the chosen research question.

The choice of the grammar for the accounting depends on the chosen purpose of the analysis (the final cause or why are we producing biofuels?). As noted earlier, the representation of the metabolic processor of biofuel systems shown on the left side of Fig. 3 reflects the way biofuels are currently produced, i.e. by using fossil energy carriers as inputs of the process. However, to show the importance of developing ad hoc grammars tailored to a research question, in this example of application we analyse a self-sufficient production process in which the energy carriers consumed in the process are generated by the process itself. This means that we must consider the implications of the internal loop of biofuels consumed to generate biofuels (see the left side of Fig. 4). This internal loop represents a complication because for low values of the output/input ratio of energy carriers (e.g., below 2/1), it entails a non-linear decrease of the ratio net/gross supply [97]. This conceptual complication and the equation used to calculate the relation between output/input and gross/net supply is explained in detail in the Supplementary Material.

STEP #3: Characterize the typology of biofuel system under study.

In this case, using the existing knowledge of technical coefficients and using the set of relations described by the grammar illustrated on the left of Fig. 4, we can generate a table with the relevant values for the analysis (see Table 1). For the sake of simplicity, we only consider two well-known typologies of biofuels production systems – biodiesel from rapeseed and bioethanol produced by wheat – and, as a third option, the supply of biodiesel from Used Cooking Oil (UCO), the production of which dramatically increased in recent years in the Netherlands to over 300,000 tonnes) [98]. Further explanations of the calculations and data sources are provided in the Supplementary Material.

STEP #4 checking the congruence between the metabolic characteristics (the metabolic processor) of the typology of supply system (in Table 1) with the metabolic characteristics of the instance of social-ecological systems that should adopt it – the NL in 2016 – (right side Fig. 4).

In order to carry out this check we first have to quantify the actual level of consumption of fossil liquid fuels of the Netherlands. Table 2

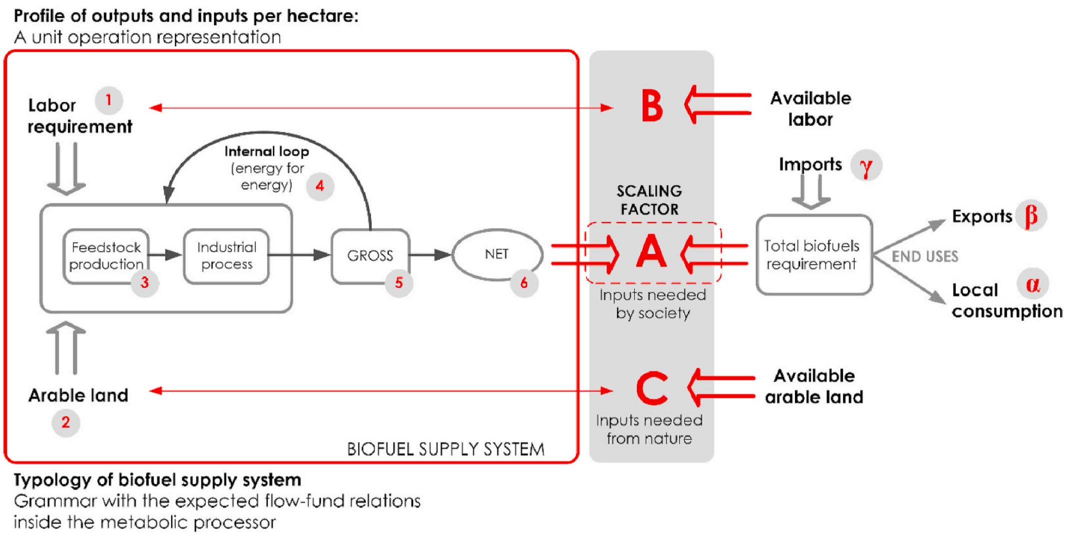

Fig. 4. The grammar of biofuel production in relation to the capability of substituting for fossil energy (on the left) and its use in the analysis of the state-pressure relation (on the right).

Table 1

Set of relations over the relevant attributes defining the typology of biofuel supply system. The numbers in parenthesis refer to Fig. 4. The data sources and calculations are presented in the supplementary material.

Biofuel type	Labor requirement (1) - hours	Land requirement (2) - hectares	Feedstock required (3) - tonnes	Energy requirement (4) - GJ	Biofuel Gross Supply (5) - tonnes	Gross/Net ratio[g]	Biofuel Net supply (6) - tonnes
Biobioethanol (wheat)	2.9[a]	0.42[d]	1.4[d]	18[d]	1 (27 GJ)	3.0/1	0.3 (9 GJ)
Biodiesel (rapeseed)	6.4[b]	0.58[e]	1.7[e]	17[e]	1 (37 GJ)	1.8/1	0.5 (20 GJ)
Biodiesel (UCO)	400[c]		1.1[f]	6[f]	1 (37 GJ)	1.2/1	0.8 (31 GJ)

[a] Labor includes working hours employed for the cultivation (2.2 h/t of bioethanol) and processing phase (0.7 h/t of bioethanol).

[b] Labor includes working hours employed for the cultivation (5.7 h/t of biodiesel) and processing phase (0.7 h/t of bioethanol).

[c] Labor includes working hours employed for the collection of UCO (around 400 h/t of biodiesel) [99] and processing phase (0.7 h/t of bioethanol).

[d] Land, energy and feedstock requirements per tonne of bioethanol from wheat have been calculated from Ecoinvent dataset [100].

[e] Land, energy and feedstock requirements per tonnene of biodiesel from rapeseed have been calculated from Ecoinvent dataset [101,102].

[f] Energy and feedstock requirement for UCO have been calculated from Ecoinvent dataset [103].

[g] The Gross to Net ratio is here used to calculate the gross amount of biofuel needed to get one tonne of net biofuel (available to society).

Table 2

Data on local consumption, import and export of fossil fuels (gasoline and diesel) in NL in 2016.

	Fuel type	NL 2016 (thousand tonnes)	NL 2016 (kg/p.c.)
Import			
	Gasoline	10,787	632
	Diesel	16,818	985
Export			
	Gasoline	20,282	1187
	Diesel	29,298	1715
Local consumption			
	Gasoline	4132	242
	Diesel	5962	349

shows the demand (local consumption, import and export) in NL in 2016 (data from Eurostat).

In relation to the supply of bioethanol, to replace gasoline, we have the following values:

$\alpha = 242$ kg/p.c./year (for local consumption), $\beta = 1187$ kg/p.c./year (for export).

In relation to this flow of fuels, NL is importing $\gamma = 632$ kg/p.c./year.

In relation to the supply of biodiesel, to replace diesel, we have the following values:

$\alpha = 349$ kg/p.c./year (for local consumption), $\beta = 1715$ kg/p.c./year (for export).

In relation to this flow of fuels, NL is importing $\gamma = 985$ kg/p.c./year.

Following, we check the actual availability of labour in the Dutch economy for the energy sector (for the production of energy carriers) and the actual availability of land for the production of useful biomass under human control (for the production of food, fibre plus biomass for energy purposes).

The current supply of labour to the energy sector in the NL is:

$\mathbf{B} = 4$ h p.c./year (including all the activities carried out in the energy sector for all the carriers – electricity included – and for the handling of the exported energy products). This value is calculated by dividing the hours of paid work in the energy sector (number of workers x yearly hours of workload) divided by the size of the Dutch population.

The current supply of land for producing biomass in the NL is:

$\mathbf{C} = 0.06$ ha of arable land p.c.

After defining these values, we can check the congruence over the state-pressure relation determined by the metabolic characteristics of different typologies of biofuel supply systems considered and the metabolic characteristics of NL.

3.2. *Checking the state-pressure compatibility of the bioethanol supply system*

Based on the grammar in Fig. 4 and the information given in Table 1, we generate three scenarios in relation to the chosen final cause. We use a range of targets at different levels of ambitions with the sole purpose of illustrating the methodology and stimulating a reflection about the potential of biofuels to substitute fossil fuels.

Scenario #1 – Producing the equivalent of 1429 kg of gasoline per capita per year ($\alpha + \beta$) needed by the Dutch economy for local transport and mobility and for guaranteeing the economic revenue of the Dutch economy through exports. Considering that the energy content per kg (27 MJ/kg) of bioethanol is only about half that of gasoline produced from oil (42 MJ/kg) – i.e., 1 kg of gasoline is equal to 1.55 kg of bioethanol – we would need an area of land that is more than 100 times the total arable land of NL and a quantity of labour (21 h/p.c./year) that is more than five times that currently used in the whole Dutch energy sector.

Scenario #2 – Producing energy with bioethanol to cover the internal consumption of gasoline (α), equal to approximately 242 kg/p.c./year. This scenario will require a net supply of 376 kg/p.c./year of bioethanol. This translates into the requirement of more than 8 times the arable land that is currently available and 70% of all the hours of labour currently used by the whole energy sector of NL (for supplying also other fuels, process heat and electricity including exports!).

Scenario #3 – Producing the equivalent of 10% of the total current consumption of gasoline (0.1 α). This scenario would still require more than 80% of the entire arable land of NL.

3.3. *Checking the state-pressure compatibility of the biodiesel supply system*

As for the substitution of conventional diesel with biodiesel, the results for the three scenarios are:

Scenario #1 – Producing the equivalent of the 2064 kg of diesel/p.c./year ($\alpha + \beta$) needed by the Dutch economy to guarantee local transport and mobility plus the economic revenue through exports. This scenario would need an area of land – 4.1 ha/p.c./year – that is more than 33 times all the arable land of NL and an amount of labour hours that is 6.4 times the actual amount used in the whole energy sector.

Scenario #2 – Producing an amount of biodiesel that covers only the internal consumption (α), i.e. 349 kg/p.c./year. This scenario will require 0.34 ha/p.c. – that is 5.7 times more arable land than that available. In terms of hours of labour, this scenario requires the same labour hours as currently used by the whole energy sector of NL.

Scenario #3 – Producing 10% of the total internal consumption of biodiesel (0.1 α). Still this minimal target would require more than half of the arable land of NL and cover only the internal diesel consumption.

3.4. Checking the state-pressure compatibility of an UCO-based biodiesel supply system

The general framework of analysis illustrated in Fig. 4 can also be used for the analysis of biofuel production from wastes. However, in this case we deal with a production process that does not depend on primary flows (production of biomass on land) as primary energy sources, but on tertiary flows (wastes). Hence, the grammar must be tailored to the case. The external constraint represented in the original grammar by the availability of land (availability of PES), has to be replaced by the availability of wastes (availability of tertiary energy sources), in this case UCO. Data on the UCO biofuel production system is provided in the lower part of Table 1.

We consider the same set of scenarios:

Scenario #1 – Producing the equivalent of 2064 kg of diesel/p.c./year ($\alpha + \beta$).

Scenario #2 – Producing the equivalent of the internal biodiesel consumption (α), i.e., 349 kg/p.c./year.

Scenario #3 – Producing 10% of the total internal consumption of biodiesel (0.1 α).

The required quantity of primary sources – UCO recycled from local consumption – to guarantee the production in the three scenarios is, respectively: 2270 kg of collected UCO p.c./year (scenario #1); 384 kg of collected UCO p.c./year (scenario #2); 38 kg of collected UCO p.c./year (scenario #3). Comparing these expected values with the availability of UCO in the NL, we see that this solution is problematic. The amount of UCO collected from households in NL is 0.21 kg/p.c./year [80]. To this, we could add an additional supply of UCO from restaurants and industrial processes to arrive at an availability of about 2 kg of UCO/p.c./year. This translates into a maximum supply of 1.8 kg of biodiesel/p.c./year. This quantity is completely irrelevant compared to any of the three scenarios. Even worse is the situation with regard to the labour requirements for the process. The estimate given in Table 1 refers to a study of door-to-door collection that is definitely not economically viable [81]. Since this process is still not well established, the technical coefficients shown in Table 1 should be considered rough estimates. Nonetheless, we may conclude that this solution does not make much sense (for a more detailed analysis of the troubles with UCO in the NL, see Ref. [37]).

The state-pressure relation emphasizes an important feature of the analysis, i.e., the level of openness of the supply system. A comparison the maximum supply of UCO that could be provided by the available waste sources with the actual supply of UCO suggested by the statistics reveals the role that the flow γ (in Fig. 4) plays in the actual structure of flows. As a matter of fact, a fraud was discovered in NL in which imported palm-oil (a banned biofuel feedstock) was sold as UCO in order to obtain the benefits for advanced biofuels foreseen by European Union regulations [104–107].

3.5. Discussion of the results

Putting into context the assessments referring to the two first types of biofuels (those requiring land) there is a big 'elephant in the room' that has to be considered. The use of arable land in NL is associated with a key opportunity cost. In fact, Dutch arable land is intensively used for producing food and the 'ghost' land embodied in imported agricultural commodities is estimated at 15/20 times the available arable land [108, 109]. Clearly, it is up to the Dutch to decide the priorities for the use of their land. However, the two state-pressure characterizations (sections 3.2 and 3.3) clearly indicate that a significant expansion of biofuel production in the country is impractical.

Our analysis confirms the well-known finding [110,111] that the first generation of biofuels (from crops) has two major systemic problems:

i. A low power density which entails a large demand for land and hence competition with other land uses and high environmental impact, and
ii. A low energy return on the (energy) investment because of the large internal requirement of energy inputs (the difference between gross and net) that dramatically decreases the productivity of production factors such as land, labour, water, technology.

As for the generation of biofuels from wastes, the production is limited by the local availability of wastes, which can imply large costs when they have to be collected, concentrated and transported over large distances.

4. Conclusions

In this paper, we presented a conceptual framework to characterize and contextualize in quantitative terms the performance of biofuel systems in terms of feasibility, viability, desirability and openness. This framework builds on energetics, relational analysis, and the flow-fund model of Georgescu-Roegen. It provides: (i) a taxonomy of accounting categories; (ii) a grammar to establish meaningful relations over the factors used to represent the performance of biofuels; and (iii) a framework for carrying out a state-pressure analysis studying the compatibility of the metabolic characteristics of the biofuel system with the metabolic characteristics of the social-ecological systems expected to use it.

The framework facilitates a quantitative characterization of *typologies* of energy production systems against the characteristics of specific instances of social-ecological systems expected to use them. In this way, we can assess the sustainability of the proposed solution by comparing the expected metabolic pattern of a given typology of biofuel "supply system" against the established metabolic pattern of the "demand system" of biofuel (a specific society). If they are not compatible, then the typology of supply system analysed does not represent a sustainable solution for that specific society. Alternatively, the instance of society does not provide the required "admissible context" for the chosen technology of biofuel production.

This framework helps to *tame* the confusion about the performance of biofuels. The taxonomy clarifies that "energy" is a complex concept requiring a careful pre-analytical choice of categories of accounting organized over different equivalence classes. The grammar allows the characterization of: (i) the technical processes of production; (ii) the interaction with the natural processes taking place in the biosphere; (iii) the interaction with the social processes taking place in the economy; and (iv) the effect of the level of openness of the social-ecological systems via trade. The state-pressure relational analysis contextualizes the performance of the energy system in relation to their admissible context – i.e. the socio-economic system in which they are operating and their embedding natural environment. This framework enhances the diversity of the quantitative information used in the process of decision-making. The chosen examples illustrate that the assessment of the performance of biofuel systems generated with this conceptual framework is transparent and can be tailored to both the definition of the purpose of the analysis and the specific characteristics of the society under study.

Our applications have focused on a single typology of process and a single final cause – i.e. guaranteeing the supply of liquid fuels by replacing fossil fuels with biofuels. In reality, a mix of different biofuel production systems is found, each with different technical coefficients, so more elaborated grammars should be used to analyse the state-pressure relation. In addition, in practice, there are several different final causes to be addressed simultaneously in the characterization of the performance of energy systems. The resulting multi-criteria analysis requires the generation and use of different grammars characterizing in non-equivalent ways different state-pressure relations.

In conclusion, by making a distinction between notional representations of typologies of productions processes (characterizations of nodes/supply systems) and observed characteristics of instances of social-ecological systems (characterization of niches/demand systems), we can contextualize the performance of a biofuel system in relation to different research questions and specific situations. We can carry out a pre-screening of the feasibility, viability and desirability of a given technical option without the need of gathering an enormous quantity of data. This procedure supports QST, as we do not have to go through the full analysis of the details of a given scenario associated with a series of pre-analytical choices resulting in complicated models. Rather than looking for the 'best course of action' or 'optimal solutions' in relation to technical processes described "in general terms" and out of context for a limited set of attributes of performance (e.g. GHG emissions, land use, efficiency), our conceptual framework allows to tailor the definition of both the purpose of the analysis and the resulting characterization of performance to the case or story of interest.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors are grateful to Sandra G.F. Bukkens for extensively editing the final version of the manuscript. The authors acknowledge support by the European Union's Horizon 2020 research and innovation programme under grant agreement no. 689669 (MAGIC) and the government of Catalonia (AGAUR) under grant agreement 2017-SGR-230. The Institute of Environmental Science and Technology (ICTA) has received financial support from the Spanish Ministry of Science and Innovation (MICINN) through the "María de Maeztu" program for Units of Excellence (CEX2019-000940-M). This work reflects the authors' view only; the funding agencies are not responsible for any use that may be made of the information it contains.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.esr.2021.100642.

CRediT author statement

M. Ripa: Conceptualization, Methodology, Data curation, Writing – original draft, J.J. Cadillo-Benalcazar: Writing- Reviewing and Editing, M. Giampietro: Conceptualization, Writing- Reviewing and Editing, Funding acquisition.

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