Setting the design space of biorefineries through sustainability values, a practical approach

Parada, Mar Palmeros; Asveld, Lotte; Osseweijer, Patricia; Posada, John A.

DOI
10.1002/bbb.1819

Publication date
2018

Document Version
Accepted author manuscript

Published in
Biofuels, Bioproducts and Biorefining

Sustainable biorefineries, an analysis of practices for incorporating sustainability in biorefinery design

Authors and affiliations

Mar Palmeros Parada, Patricia Osseweijer and John A. Posada Duque

Department of Biotechnology, Faculty of Applied Sciences, Delft University of Technology, Julianalaan 67, 2628BC Delft, The Netherlands.

Corresponding author

John A. Posada Duque

Department of Biotechnology, Faculty of Applied Sciences, Delft University of Technology, Van der Maasweg 9, 2629HZ, Delft, The Netherlands.

Tel.: +31 (0)15 278 87 07

E-mail address: J.A.PosadaDuque@tudelft.nl

This paper was published in the journal *Industrial Crops and Products*, 2017, volume 106, pages 105-123. DOI: 10.1016/j.indcrop.2016.08.052.

Abbreviations

CSI, crop sustainability metric; EISI, enhanced inherent safety index; PCEI, process cost and environmental impact; TEA, techno-economic evaluation; 1D, mono-dimensional; 1G,1st generation; 2D, bi-dimensional; 2G, 2nd generation; 3D, tri-dimensional; 3G, 3rd generation.

Keywords

Biorefinery Design, Biorefinery Supply Chain, Integral Sustainability Assessment, Sustainable Biorefinery.

Abstract

The incorporation of sustainability in the design of biorefineries is central for the development of the biobased economy. In this paper sustainability methods and metrics in current biorefinery design practices are analyzed to identify challenges and opportunities for future improvements in the field. Generally, there is a need for an integral analysis that includes societal impacts and goes beyond the automatic use of metrics for predefined issues. Although efforts have been made to develop more integral sustainability analyses for biorefinery design, they are often challenged by disciplinary boundaries that yield a narrow scope of analysis (e.g. conversion process, supply chain), and are blind to contextual settings or stakeholder perspectives. Multi and trans-disciplinary, inclusive and context aware approaches are identified as opportunities to overcome them in future developments.

1. Introduction

The biobased economy has been promoted as a sustainable alternative for replacing fossil resources in the production of energy, chemicals and materials. In this context, biorefineries are being developed as technological means for the transition to this economic approach, opening the possibility to add value to biomass through a more sustainable production. However, controversies related to the actual sustainability impacts of biobased products have been raised in the last years (Condon et al., 2015; Rosegrant and Msangi, 2014). As result, sustainability has become a central topic for the development of the bioeconomy and future biorefinery systems. A clear example are the sustainability criteria that the European Commission has set for domestic and imported bioenergy in order to receive government support or to count in national renewable energy targets (Tom et al., 2012).

Sustainability of biobased products is increasingly monitored and evaluated through certification schemes that measure impacts of biobased production (European Comission, n.a.). However, considering sustainability criteria during the design stage of biorefineries could result in alternative design options and consequently have a significant influence in improving their overall performance. This observation is reflected in the extensive and broad academic work on sustainable biorefinery design, from, for example, a sustainability assessment of an electrolysis-enhanced biomass to liquid fuel process (Bernical et al., 2013), to evolutionary algorithms for bioenergy supply chain optimization (Ayoub et al., 2009) and life cycle optimization methods for the design of sustainable product systems and supply chains (Yue et al., 2013) . Consequently, concepts and methods used in these studies vary significantly, and are sometimes conflicting among different sources.

Recent publications have attained to analyze conceptual and methodological developments towards sustainable biorefineries. However, these studies are limited to, for instance, sustainability issues generally associated with biorefineries (Azapagic, 2014), or specific methodologies and methods used in certain disciplines, like optimization frameworks for biorefinery supply chains (Eskandarpour et al., 2015), assessment methodologies of biorefinery value chains (Parajuli et al., 2015) and process integration approaches for sustainable biorefineries (El-Halwagi, 2012). Regardless of the importance that these studies have in their academic niche, e.g. optimization in supply chain, sustainable biorefinery design is not restricted to a single discipline, or to a single design approach. This paper takes a step back and presents a broader overview on advances for sustainability incorporation in biorefinery design, across disciplines and research areas related to design. As part of this review, current design practices, methods and metrics for sustainable biorefineries are analysed with regards to different aspects of sustainability, including environmental and societal impacts, and stakeholder participation. From this analysis, challenges, needs and opportunities for further development and research on design practices are identified with the aim to contribute towards the development of sustainable biorefineries.

2. Concepts and Definitions

In the reviewed literature some concepts from different research areas are used in different ways. Therefore we discuss the most relevant concepts to present a coherent analysis of the reviewed literature. When necessary, contrast with similar concepts is presented to avoid ambiguities.

2.1 Biorefinery

The biorefinery concept has been used to refer to the biomass processing facility only (NREL, 2009), and also to biomass processing in a broader sense. The International Energy Agency (IEA) states that "biorefining is the sustainable synergetic processing of biomass into a spectrum of marketable food & feed ingredients, products (chemicals, materials) and energy (fuels, power, heat)" (IEA Bioenergy, 2014). Thus, through this definition, IEA describes the concept as a process, a facility or a cluster of facilities integrally covering the upstream, midstream and downstream processing of biomass (de Jong and Jungmeier, 2015).

Biorefineries are usually referred to as of 1st or 2nd generation according to the feedstock used as raw material. 1st generation (1G) biorefineries are those that use food crop resources such as corn sugar and vegetable oil, while 2nd generation (2G) biorefineries are those that process non-food materials, such as agricultural residues, wood and energy crops typically high in lignocellulose (Guo et al., 2015). Biorefineries that use algae biomass as feedstock have been referred to as 3rd generation (3G) biorefineries (Parajuli et al., 2015). The most established type of biorefineries are 1G, while 2G and 3G are still under development due to technical or economic challenges (Gerssen-Gondelach et al., 2014). As an illustration, ethanol biorefineries processing US corn and Brazilian sugarcane lead the global production with contributions of 58% and 25% respectively (Renewable Fuels Association, 2014), whereas cellulosic ethanol only started commercial operations in 2014 (Service, 2014).

Biorefineries can be further defined as systems based on four main features (Cherubini et al., 2009): i) platforms, such as sugars, oil and syngas; ii) energy and material products, like bioethanol, glycerol, lactic acid; iii) dedicated feedstocks and residues, e.g. forest residues, sugar and oil crops;

and iv) processes, such as fermentation, gasification and pyrolysis. Then, the combination of these four features defines a specific biorefinery system, from feedstock to product.

2.2 Supply Chain

Supply chain refers to the link of actors and operations that allows the flow of materials from producer to consumer, passing through processes that convert these materials into products (Goetschalckx, 2011). Given the diversity of operations involved, the supply chain is often a network of different actors that may include convergent and divergent flows (Goetschalckx, 2011; Sharma et al., 2013).

Typically, a biorefinery supply chain includes five stages: feedstock production, feedstock logistics, conversion (or production), product distribution and product end-use (Liu and Eden, 2014). However, in the biobased economy the supply chain is sometimes specified as biomass supply chain, which indicates the biomass-to-conversion plant part of the chain, as described by Sharma *et al.* (Sharma et al., 2013). These supply chain stages are coordinated through supply chain management (SCM) to ensure an efficient product delivery to customers at a minimum cost to the system (Sharma et al., 2013; Yan et al., 2012).

In biorefinery research, supply chain and value chain are sometimes used interchangeably; however these two concepts have different implications (Holweg and Helo, 2014). Value chain refers to the value aspect of the chain, sometimes conveyed as demand originated at the customer side, while supply chain typically refers to the flow of materials from supplier to final customer (Andrew, 1999; Ramsay, 2005). Hence, while value chain activities focus on effective value creation considering also product innovation and marketing, supply chain activities are centered on the efficient delivery of materials (Feller et al., 2006). Additionally, in some aspects supply chain stages can also overlap with the biorefinery system (for instance, separate pretreatment and fermentation facilities as part of decentralized supply chains); however, these two concepts refer to different aspects of the biorefinery, as illustrated in Figure 1. In this paper, the term “biorefinery project” is used to generically refer to both the biorefinery system and its supply chain.

2.3 Life Cycle

The life cycle of a product is defined as “consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal”(ISO, 2006). In contrast to a biorefinery system, supply chain and value chain, the life cycle concept typically refers to the scope of analysis of a system. Thus, a product’s life cycle refers to a system that starts with raw material extraction from the environment, like water or fossil oil, it covers any transportation, manufacturing and use of the product, and it ends with waste management related to the product’s disposal (Shabnam et al., 2012). A life cycle that considers these stages can also be referred to as a cradle-to-grave life cycle (Eskandarpour et al., 2015). A cradle-to-gate life cycle, indicates a system boundary until the production stage, while cradle-to-cradle refers to a life cycle that includes reuse, recovery or recycle of a product or its parts (Silvestre et al., 2014).

2.4 Design in Engineering

Design activities involve strategic decisions that will specify aspects of a project. After these decisions are taken, decisions at tactical and operational levels are made for design implementation. From strategic to tactical and operational levels, the space and the time scale of these decisions are reduced: on one side strategic decisions affect the project in long time scales, while operational level decisions affect the project in short time scales. Thus, broad strategic decisions are taken with the creation of design concepts that yield facilities and long term contracts, while narrower tactical and operational decisions are taken to plan and operationalize the design in shorter timeframes.

The design of biorefinery projects is based on different engineering disciplines, including supply chain and process engineering. These areas have in common an engineering-based design approach that follows sequential stages: problem definition, conceptual and detailed design, and design specification and implementation (Goetschalckx, 2011). Differences in these steps may arise according to disciplines or design approaches.

2.4.1 Supply Chain Design

Supply chain design is approached as the strategic planning or synthesis of a supply chain network, heavily relying on the use of models. Common modelling approaches in supply chain design are linear programming (LP) as sets of linear equations with continuous variables, and mixed-integer linear programming (MILP) that also considers integer variables (Yan et al., 2012). Nonlinear programming (NLP) and evolutionary algorithms are less commonly used than MILP and LP, as illustrated in the review on supply chain design by De Meyer et al. (2014).

Design variables for biorefinery supply chains are related to biomass selection, the capacity and location of facilities, and transport means for raw materials and products (Sharma et al., 2013) (Goetschalckx, 2011; Sharma et al., 2013; Yan et al., 2012). Since some of these strategic variables often have little impact on the distribution and use of biorefinery products, these later stages are sometimes not considered in supply chain models (Giarola et al., 2012), which already require large computational capacities (Yue et al., 2014).

2.4.2 Process Design

The aim of process design is to strategically synthetize the chain of sub-processes and conditions that will result in a complete production process. This strategic designing often follows a sequence from less to more detailed stages, which may combine product, process and equipment design (Dieudonné et al., 2012; Seider et al., 2010).

Research on process design is often focused on three activities: process synthesis, integration and optimization. In process synthesis, the process superstructure and sub-processes are created, often through a hierarchical decomposition of the process (Grossmann and Guillén-Gosálbez, 2010;

Moncada et al., 2014) or other systematic approaches like the forward-backward approach (El-Halwagi, 2012) and synthesis algorithms for heat exchange and reactor networks (Grossmann and Guillén-Gosálbez, 2010; Seider et al., 2010). Integration, on the other hand, may relate to feedstock integration, process intensification, and energy and mass integration (Moncada et al., 2014). Optimization, on the other hand, can be approached by repeated simulations such as in sensitivity analyses, or with mathematical programming as for supply chain design. Combinations of mathematical programming with synthesis approaches have also been developed for optimization-based design (Grossmann et al., 1999; Grossmann and Guillén-Gosálbez, 2010). However, optimization algorithms integrated in simulation software, in combination with heuristics, are the most common way for process optimization in practice (Seider et al., 2010).

2.3 Sustainability

The Brundtland report (World Commission on Environment and Development, 1987) sparked the interest in sustainability by stating that "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (Hofer and Bigorra, 2008). From this classic definition it is derived that sustainable development does not impair the quality of life of future generations "here and elsewhere" (de Vries and Petersen, 2009). Sustainability, as a twin notion to sustainable development, has been considered to englobe the integral balance of three dimensions: economic, environmental and social, where poor performance related to one could hinder performance on the others (Kemp and Martens, 2007; Leadership Council of the Sustainable Development Solutions Network, 2013).

Biorefinery systems have often been considered inherently sustainable due to the renewability of biomass. However, this has been recently refuted given that sustainability is not founded exclusively on renewability or on the environmental dimension (Pfau et al., 2014). Therefore, it is acknowledged that for the development of sustainable biorefinery projects all dimensions of sustainability must be taken into account, which implies, for instance, considerations on by-product valorization, erosion, food security, land use, property rights, among others (Azapagic, 2014; Cambero and Sowlati, 2014; Rai et al., 2010).

The interpretation of sustainability remains a debatable subject even if definitions as the one presented above are widely accepted. This is largely related to: 1) the fact that environmental and economic aspects are quantitative, while social sustainability is often measured in qualitative terms; and 2) the flexibility of the sustainability concept, which is often reduced to subjective interpretations derived from the norms and values of individuals who seek to implement it (de Vries and Petersen, 2009; Hedlund-de Witt, 2013; Janeiro and Patel, 2014; Kemp and Martens, 2007; Van Opstal and Hugé, 2013). The latter relates to differences in worldviews, which has been studied in relation to the bioeconomy (see De Witt et al. (2015)). For example, the use of genetically modified (GM) crops for biomass production can be viewed as a technology allowing a production of low-input, high-yielding, "sustainable" biomass resources, while from a different perspective the same technology is seen as a threat to biodiversity, health or farmers self-sufficiency, and is hence considered a risk to "sustainability" (Hedlund-de Witt, 2014; Lotz et al., 2014). In biorefinery projects this subjectivity becomes highly relevant as a large diversity of stakeholders, including the chemical and agricultural industries, government and non-governmental organizations, is often involved in their development.

2.3.1 Concepts for Evaluating Sustainability

Evaluations of performance in relation to sustainability can be used as a tool for designing or assessing biorefinery projects. These evaluations are often based on the use of indicators that represent the severity of the project's impact on a specific aspect of sustainability according to the evaluation method. For instance, methods for the environmental life cycle assessment (LCA) methodology consider indicators like infra-red radiative forcing and phosphorus concentration for the climate change and eutrophication impact categories (Goedkoop et al., 2013; Institute for Environment and Sustainability, 2010). In some assessment methods, environmental or social mechanisms are used to relate so-called midpoint impact categories to endpoint impacts or damages. Thus, CO_2 emissions can be used directly as a stand-alone indicator for environmental performance, they can also be accounted together with other GHG emissions through their global warming potential as impacts on global warming (midpoint level). Additionally, global warming impacts can be further evaluated as damages on human health (endpoint-level) through mechanisms related to, for instance, alterations in disease frequency and population displacements, (Goedkoop et al., 2013). Furthermore, some impacts cannot be quantified or are better described by qualitative features, especially when dealing with impacts on society (Benoit and Vickery-Niederman, 2011). In these cases, indicators of qualitative nature may be used to relate the project to impact categories through semi-qualitative analyses, for instance with 1 to 10 scales (Wu et al., 2014).

Indicators, methods and methodologies can address one, two or three of the dimensions of sustainability (i.e. economic, environmental and social). Considering this dimensionality aspect, assessment tools can be considered as mono-dimensional (1D), bi-dimensional (2D) or tri-dimensional (3D). Thus, 1D relates exclusively to economic, environmental or social impacts; while 2D covers either socio-environmental, socio-economic, or economic-environmental impacts; and 3D relates to an integral sustainability in its three dimensions (Fermeglia et al., 2009; Sikdar, 2003). Furthermore, metrics based on mass and energy balances directly have also been used to describe the efficiency or technical performance of a project. These indicators are sometimes considered as a measure of economic and environmental sustainability impacts of a project given their relationship to resource use and operational cost, and are often used for sustainable process design or in energy analyses (Kalinci et al., 2013; Ojeda et al., 2011; Ruiz-Mercado et al., 2011; Wall and Gong, 2001; Zvolinschi et al., 2007).

3. Methodology of Literature Review

This systematic literature review is based on a literature search done in the multidisciplinary database web of knowledge. The search terms used as queries were biorefinery related (biorefinery, biofuels, bioenergy, bioproduct, bioplastics), design related (design, evaluation, assessment, optimization) and sustainability. The time period was defined from 2005 to present time (mid-2015). The mid-2000s is considered a reasonable point to start finding sustainability approaches, and a way to limit the number of papers that would otherwise be mostly focused on economic or environmental aspects only. The query results were screened through title and abstract analysis, yielding a sample of 78 papers related to the design of sustainable biorefinery projects, marked with an asterisk (*) in the reference list.

According to this systematic literature search, this review covers current practices for sustainable biorefinery design. Although not all existing approaches are covered in this literature sample, the analysis is enriched with references known in the field, identified through snow-ball sampling and expert recommendations and yielding 84 papers (the time frame of these was not restricted). Furthermore, this review is focused on methods and metrics for integrating sustainability in the design phase of biorefinery projects as applied or proposed in the reviewed literature. Therefore, research papers on the evaluation of existing biorefineries are not necessarily part of the reviewed literature.

The analysis on the incorporation of sustainability in the design of biorefinery projects is elaborated in two parts: first, methods and metrics for evaluating sustainability are analyzed according to sustainability dimensionality (*i.e.* economy, environment and society) and efficiency (i.e. energy, exergy and mass); then the incorporation of these method and metrics is analyzed according to the relevant design activities (e.g. as an assessment of a base case or as an objective of optimization) and stakeholder inclusion. From this analysis, the most important challenges and opportunities for sustainable biorefinery design are identified and discussed in Section 5.

4. Results and Discussion

The section covers the findings on the incorporation of sustainability in the design of biorefinery projects. In section 4.1, methods, impact categories and indicators of sustainability used in the reviewed literature are analyzed according to sustainability dimensionality and the use of efficiency metrics. Then, an analysis of how sustainability is, or is intended to be, incorporated in the designing of biorefineries is presented in section 4.2. Also a review on how different perspectives have been considered in the design for these projects is presented as part of section 4.2.

4.1 Sustainability in Biorefinery Project Design

Sustainability considerations have increasingly been incorporated in biorefinery design, as indicated by the number of publications in the last years (see Figure 2A.) However, most of the publications consider impacts on the economic and environmental dimensions of sustainability, while the social one is often omitted. Furthermore, efficiency indicators have also been used in combination with metrics that fall in the dimensionality classification (except in (De Meyer et al., 2015; Peralta et al., 2010) that use only efficiency metrics). These efficiency indicators are used to describe the efficiency of a project mostly in relation to energy, as presented in Figure 2B.

Incorporation of sustainability aspects in design of biorefinery projects has been done through different metrics and methods. In this review, these are categorized as stand-alone indicators, impact categories and methods that cover different dimensions of sustainability. Then, as schematized with line A in Figure 3, in some cases indicators are interpreted or used directly in design activities, e.g. CO_2 emissions as indicator in an optimization framework for the identification of optimal bioenergy sources (Iakovou et al., 2012). In some cases, several indicators are combined or analyzed through specific mechanisms to represent impact categories that are then used in design, (see line B in Figure 3). For instance, Cheali et al. (2015) use a process cost and environmental impact category (PCEI), calculated as a combination of efficiency and process specific indicators, in an optimization framework for the design of a lignin upgrading biorefinery. In the work of Tock and Marechal (2012), GHG emissions, normalized to CO_2 equivalents based on global warming potentials (GWP), are used for process design as a measure of the contributions to the climate change environmental impact category. Furthermore, in the studies where endpoint LCA methods were used, impact categories are further analyzed as endpoint impacts or damages to for instance, human health (Figure 3, line C). In this result section, we discuss midpoint and endpoint impact categories together to avoid further complications with the analysis, however, when necessary for discussion, this aspect is mentioned.

4.1.1 Economic Sustainability

The economic dimension of sustainability is often considered in the design of biorefinery projects, mostly through profitability or techno-economic analysis (TEA) where technical aspects of engineering projects are analyzed in economic terms. Indicators used in economic analyses in the reviewed papers are numerous, as shown in Figure 4. However, these metrics are mostly related to three topics: costs, profits and margins, and value of investment. Out of these three, the most common economic indicators are production cost, gross profit and net present value (NPV), (Figure 4).

Costs indicators are a measure of economic performance often used to compare biorefinery alternatives for producing a given product or processing a particular raw material. For example, Coleman et al. (2014), compare the production cost of different microalgal fuel production systems and locations combining biomass assessment and logistics models. However, costs metrics per se do not reflect the economic performance of the project since expected revenues are not considered for their calculation.

Profit, on the other hand, is an indicator based on costs and revenues, and can thus be used for comparisons of systems with different products. For example, Ng et al. (2015) use gross profit as an objective function for optimization-based design, in which different systems of product alternatives and related processes are evaluated. Furthermore, when differences in capital requirements among different alternatives are expected to be minor or when capital costs are not yet known, a gross operating margin can be used as indicator of economic potential at the early-stage of a project. An example of the latter case is the study by Field et al. (2013), where an operational cost model is used to investigate design trade-offs and alternative uses of biochar for bioenergy production, where differences in capital cost are expected to be minimal. Evidently, this type of high-level analysis is suitable when exploring different concept alternatives and data availability is an issue, but it cannot be taken as a realistic indication of the economic potential of a project.

Other indicators are those related to the investment value of a project. For example, NPV is a measure based on cash flows of the project throughout a future period of time under a defined discount rate. This metric is useful for estimating the value of long term projects and can also be a communication tool with business teams. Although this type of metrics can be very sensitive to considered discount rates or other assumptions (Seider et al., 2010), it is still widely used in the reviewed literature (see Figure 4). For example, in the work by Karschin and Geldermann (2015), NPV is used as an economic indicator given the well-defined conditions of the system (i.e. fixed electricity prices). Another common metric for economic potential is the minimum selling price (MSP), price at which a product would yield a defined profitability. This metric has been used to evaluate the potential competitiveness of a process in the market, as part of their techno-economic analysis. For instance, Tan et al. (2016) conclude that their process for the production of high-octane gasoline from biomass is potentially cost-competitive to conventional fossil alternatives, making it an interesting option for further research. Zhu et al. (2013) also use MSP to evaluate the economics of processing algal biomass residues into liquid fuels, and find that it is competitive with conventional fuel prices only with large-scale centralized facilities supported by a neighboring large-scale algae production site.

Policy benefits or taxes on emissions and resource use are also considered for evaluating the economic performance of project alternatives under different policy scenarios. For example, in the optimization model developed by Kantas et al. (2015), penalty costs for water usage and CO_2 emissions are accounted as operating costs when these are higher than predefined limits. However, given the unpredictability of these measures, such analyses carry uncertainties with large impacts on the project set-up. For example, in the same study (Kantas et al., 2015) it was found that the optimal raw material mix for the biorefinery can change considerably under different CO_2 penalty costs, having significant impacts on biomass cost, supply contracts and processing technology.

These economic metrics used in the reviewed literature generally reflect the performance of the project on microeconomic terms, mostly to analyze costs and profits related to the project. Some authors have discussed that this type of analysis on its own does not represent economic sustainability, calling for analyses on the project's potential to add value to the economy (Keller et al., 2015; Wood and Hertwich, 2013; Zamagni et al., 2013). This macroeconomic benefit perspective is rarely addressed in the reviewed literature, and is included only in the assessment work by Gheewala et al. (2011), where the increase in gross domestic product and tax revenues to the region in relation are used for quantifying the human development and total value categories in their assessment of a biorefinery project.

4.1.2 Environmental Sustainability

Environmental sustainability has been included in the design of biorefinery projects through methods that indicate expected environmental impacts of the project. Interestingly, EcoIndicator99 (EI99) is the only LCA method referenced in the reviewed literature. This finding is in agreement with the fact that EI99 is a method based on endpoint damage functions presented as a single indicator, making it simple to implement (Goedkoop and Spriensma, 2001; Institute for Environment and Sustainability, 2010). For example, Santibanez-Aguilar et al. (2014) used the eco-indicator directly as environmental optimization objective for the planning of multiproduct biorefinery projects. As the authors discuss, by using this single indicator, the entire range of environmental impacts related to the project's life cycle, and an indication of social impacts through the analysis of damages to human health, are included in the analysis. However, this method has the limitation that most categories are modeled based on the European situations (except global categories like climate change and ozone depletion), and may thus not be adequate for cases with other geographical scope (Goedkoop and Spriensma, 2001; Institute for Environment and Sustainability, 2010). This method characteristic is not addressed in the reviewed papers, some of which are based on non-European contexts.

Another systematic approach for the inclusion of the environmental dimension in biorefinery design is the WAR algorithm. This method is used to determine the potential environmental impact of a chemical process (Li et al., 2011) through impact categories related to global atmospheric and local toxicological effects (Young et al., 2000). Some of the impact categories in the WAR and EI99 methods are similar, like ozone layer depletion in EI99 and the ozone depletion potential in the WAR algorithm (Goedkoop and Spriensma, 2001; Young et al., 2000). However, while in the WAR algorithm impact categories are directly normalized and weighed for obtaining a single index, EI99 impact categories are further analyzed as endpoint impact categories (*i.e.*, human health, ecosystem and resources), and are then normalized and weighted into a final indicator. This endpoint-midpoint difference has been discussed in relation to LCA methods and summarized as a trade-off between certainty at the midpoint level, and relevancy or ease of use at the endpoint level (Bare et al., 2000).

These methods for environmental assessment have also been applied in separate analyses along the main design method of the study. For instance, Gebreslassie et al. (2013a) and Wang et al. (2013) present economic-environmental optimization based on the combination of NPV and GWP as objective functions, where EI99 is applied only on found optimum design alternatives and is not part of the developed optimization framework itself. Thus, the design is synthetized considering climate change as the only environmental topic. Yet, given that the results of these optimization frameworks are presented as Pareto sets of solutions, the separate EI99 assessment is actually useful to analyze the trade-offs between different solutions, and thus include a broader environmental analysis.

However, environmental considerations have mostly been incorporated in biorefinery design through the inclusion of stand-alone indicators and impact categories, i.e. indicators and impact categories that are not part of an established method like the EI99 and WAR algorithm. These metrics are mostly related to the climate change topic. That is, from the papers that covered any environmental issue, about two thirds were related to GHG emissions and global warming (GW). This predominance of climate change related metrics is shown in Figure 5, where stand-alone environmental indicators used directly for biorefinery design activities are presented.

Global warming or climate change impacts are often considered in design as an impact category on environmental sustainability, derived from GHG emissions related to the biorefinery project. These emissions are accounted as CO_2 equivalents, often in reference to the IPCC global warming potential (GWP), and are sometimes estimated with the use of models and databases, like the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model. For instance, in the work by Zamboni et al. (2011), a life cycle GWP is used for a “life cycle optimization” design approach of biorefinery projects. Thus, the author includes environmental and economic objectives to optimize a biorefinery project, which are further analyzed regarding relevant legislation limits for biofuels, also expressed in GWP terms.

In some cases, CO_2 emissions are interpreted directly as impacts on environmental sustainability, and sometimes they are simplified by considering only CO_2 emissions in certain parts of the project. For example, Sharma et al. (2011) and Shastri et al. (2011) estimated GHG emissions from CO_2 emissions related to production, utility generation and transportation. This simplification approach might be handy for high level estimations; however it must always be taken into account that GHG emissions are relevant in all stages of the biorefinery project (Efroymson et al., 2013). Furthermore, emissions from agricultural stage can be far from negligible, with large GHG emissions due to, for instance, land use changes (Akgul et al., 2012) and high fertilizer dosages (Fan et al., 2013).

The pronounced incorporation of GHG and GWP in biorefinery design (Figure 5), may be due to the biofuels potential for reducing GHG emissions, considered one of the main drivers for biofuel development (Azapagic, 2014), with greenhouse emission criteria in policies like the EC Biofuels and Bioliquids Sustainability Scheme and the Renewable Fuel Standard in the US (United Nations, 2014). However, environmental sustainability is not only affected by global warming and climate change, but by many other phenomena, like biodiversity losses, soil erosion and eutrophication, which are often context specific and could be critical in the development of biorefinery projects (Efroymson et al., 2013). Although some metrics related to these topics have already been used to include these issues in biorefinery project design, such as the nitrogen losses and erosion indicators, the use of this type of metrics remains limited as shown by number of publications in which these are used (see indicators related to soil and water topics in Figure 5).

4.1.3 Social Sustainability

The social dimension of sustainability, in contrast to the economic and environmental ones, has been modestly considered in the design of biorefinery projects. That is, out of the 84 papers reviewed in this study, social sustainability was included at the indicator level in only three papers, as summarized in Figure 6 (Akgul et al., 2012; Kempener et al., 2009; Schaidle et al., 2011) (multidimensional metrics that include the social dimension of sustainability are similarly scarce and are discussed in the next section). This low regard for social issues in biorefinery design is in line with other engineering practices, which have only recently started to consider the social aspects of new product developments (i.e. the “who and why” of the social aspects, as complimentary to the “what and how” of the technical aspects in socio-technical engineering design (Seider et al., 2010)). This minor attention for impacts on society in biorefinery design might be due to the historically long disengagement between the social and the natural and engineering sciences. Yet, some of the review publications do cover topics in the social sustainability domain; food and energy security at the indicator level, and education and life expectancy at the category level, as discussed below (see Figure 6).

Food security is an important issue for the bioeconomy since both food and biobased materials are produced from biomass, and thus require land. Although recent studies state that food and biobased production do not necessarily compete for resources, and that there can even be synergies amongst both industries, this still depends on how bioeconomy research, projects and policies are developed (Souza et al., 2015). For example, food security is addressed by Schaidle et al. (2011) through a semi-quantitative indicator that considers the feedstock type used in the biorefinery project, based on the fact that cellulosic feedstock is considered to have a low impact on food prices relative to corn. Food security has also been incorporated in optimization-based design with the use of a sustainability factor constraint, which limits the use of domestic biomass for biofuel production (Akgul et al., 2012). Thus, the limitation on biomass for fuel is considered to address the competition for land that otherwise would take place between fuel and food production. These two metrics address the food security topic, which has been scarcely addressed in biorefinery design, in a simple manner. However, the simplification of complex situations, like in the case of the bioeconomy, should be complemented with other strategies for food security, as these metrics alone do not define possible synergies between food and biobased production (Osseweijer et al., 2015).

Energy has strong implications of economic and political importance related to, for instance, modern production means and technologies, and long distance transportation. Energy can also have an impact on social development, as illustrated by an increase in the Human Development Index (HDI, related to education, health and wealth levels) with increasing energy use up to about 100 GJ/person/year at 80% - 90% HDI (Souza et al., 2015). With its more distributed nature (in comparison to fossil resources), biobased production has the potential to increase energy security in regions that are currently dependent on foreign energy resources or regions that even today are energy deprived (Nuffield Council on Bioethics, 2011). Also, bioenergy is an alternative to fossil resources when other renewables are not an options, e.g. in marine and aviation transportation (Dale and Ong, 2014). However, as discussed in Souza et al. (2015), bioenergy developments need to be dealt with congruent policies and management practices that ensure sustainable energy access and affordability. This point can also be brought to the design stage of biorefinery projects, where feedstock, scales, product portfolios, etc., are decided. In the reviewed literature, energy security in the design of biorefineries has been included through the maximization of an energy self-sufficiency indicator. This indicator expresses energy provision by a biorefinery project relative to demand in the project's geographical region (Kempener et al., 2009). The inclusion of an energy security indicator can be perceived already as a step forward for including sustainability concerns related to the bioeconomy. However it should be noted that this metric does not address issues of involvement of local communities or industries that might perceive no difference in, for instance, a change from fossil to biobased energy. Interestingly, the authors use the metric in an optimization framework that is combined with an agent-based modelling approach to analyze and assess bioenergy networks, including local organizations responses along the duration of the project.

Other metrics used in the reviewed literature that are based on regional levels are the education and life expectancy measures (Gheewala et al., 2011), which contribute to the Human Development Index. These indicators are based on observations of differences between national and regional levels where the project is placed. Although these metrics based on existing cases can provide information for new biorefinery developments, they rely on already existing data that is not always available, or is not transferable to new projects. That is to say, data from previous biorefineries is not necessarily applicable in future cases as these might be based on entirely new processes and raw materials.

Despite the fact that social indicators used in the design of biorefineries cover diverse topics in contrast to those in the environmental domain, their use is still uncommon (see Figure 6).

Furthermore, from the papers reviewed in this study, these indicators were only used in the same studies in which they were defined, with the exception of the energy self-sufficiency indicator in the study by Kempener et al. (2009), which was initially described in (Beck et al., 2008). Also, it is relevant to remark that social impacts might require the inclusion of actors relevant to the project, which is rarely addressed in the reviewed papers (further discussion is presented in section 4.2.4).

4.1.4 Multi-dimensionality

The previous sections covered different approaches to address separately the three dimensions of sustainability in the design of biorefineries. This section discusses approaches that have been developed by academics and professional organizations to address multiple dimensions of sustainability at once in engineering projects. An example of such approaches are the metrics from the Institution of Chemical Engineers (IChemE), which consider environmental indicators related to resource usage, emissions and other outflows; economic indicators like profit, tax and investments; and social indicators related to the workplace and society (IChemE, 2002). However, these metrics are meant to evaluate the performance of equipment, unit operations and processes, and some are exclusively of operational nature. For instance, IChemE's Society Metrics are based on performance, e.g., on the base of employees who have resigned or been made redundant, which are not easily transferred to ex-ante evaluations (IChemE, 2002). In this review it was found that although these IchemE sustainability metrics are sometimes incorporated in the design of biorefinery projects, the social indicators were in all cases excluded (Kasivisvanathan et al., 2012; Ng et al., 2013; Shabbir et al., 2012).

Other approaches that combine metrics related to different dimensions of sustainability are for instance those presented by Cheali et al. (2015) (metrics originally published by Posada et al. (2013)) and Sacramento-Rivero (2012). In the first publication, different economic, environmental and efficiency metrics like costs, GHG emissions and energy efficiency are combined with more detailed process metrics for sustainable process synthesis (Cheali et al., 2015). These metrics, embedded in a superstructure optimization framework, were used to obtain biorefinery designs for production of ethanol derivatives that outperform fossil based approaches (Cheali et al., 2015). By contrast, the framework proposed by Sacramento-Rivero (2012) is based on four categories related to feedstocks, processes, products, environment and corporate themes. The author defines these themes and their metrics to assess impacts on sustainability, covering the dimensionality and efficiency classifications, intended for both monitoring and design phases. Although these two frameworks do cover impact categories along the three dimensions of sustainability and efficiency metrics, they are still limited with regards to the analysis of impacts to society. In the sustainability index of Cheali et al. (2015), health and safety, a socio-environmental aspect (discussed below) is the only topic related to society. On the other hand, in the framework proposed by Sacramento-Rivero (2012), the corporate category with relevance to society is not applicable at the design stage, similarly to the IChemE society metrics mentioned above (IChemE, 2002; Sacramento-Rivero, 2012).

Some impacts can be considered to relate to more than one single dimension of sustainability (see Figure 6 with an overview of multi-dimensional indicators used in the reviewed literature). This is the case of employment impacts, which have been used as part of the economic and social analysis of projects. For example, in the optimization studies by Cucek et al. (2014) and Kantas et al. (2015), labor costs are part of a single economic objective function to be minimized. In fact, labor requirements expressed as costs, are often accounted in the techno-economic analysis for estimating processing cost, and are thus considered an economic topic. Contrastingly, Santibanez-Aguilar et al. (2014) and You et al. (2012) use employment requirements (or jobs created) as a social objective function to be maximized as a benefit to society, illustrating them as opposed to the economic objectives (profit or costs) of their projects. Remarkably, in the work by Ayoub et al. (2009), a labor social objective function expressed as number of workers, is presented as objective function to be minimized or maximized depending on the project context, which in their case is in fact minimized according to discussed population issues in Japan. This labor requirement or job creation metric illustrates the importance of taking the context into consideration in sustainability analyses.

Impacts on human health are also found in relation to two dimensions of sustainability, the environment and society, which was briefly commented by Santibanez-Aguilar et al. (2014). In the reviewed papers, human health impacts are considered in widespread methods like EI99 and the WAR algorithm as environmental impacts, while these aspects are also accounted in the IChemE sustainability metrics as society impacts. Health and safety indicators are also sometimes proposed in combination with (techno-)economic and environmental indices as measures of sustainability, thus inferring a correlation between health and safety impacts and society (Cheali et al., 2015; Ng et al., 2012). In general terms, it is observed that human health impacts, considered as environmental impacts, are typically analyzed through measures of exposure to emissions as occupational health issues (like in the WAR algorithm) or as health effects related to global environmental phenomena (e.g. ozone depletion in EI99). In the cases where human health impacts are considered social impacts, besides accounting for occupational effects as mentioned above (like in (Cheali et al., 2015; Ng et al., 2012; Schaidle et al., 2011)) these impacts are in some cases measured through other indicators related to frequency of accidents (IChemE, 2002; Sacramento-Rivero, 2012), and the existence of occupational and environmental health and safety systems (Sacramento-Rivero, 2012). However, it is clear that the latter measures are not available at the early design stages of a project.

It is remarkable that some studies included a combination of indicators from different dimensions of sustainability, thus attaining multidimensional analyses. However, in some of these studies, this multi-dimensionality is only achieved through the use of limited aspects in these dimensions, particularly in relation to social sustainability as mentioned above. For instance, in the 3D works of You et al. (2012) and Golberg et al. (2014), employment creation is the only social sustainability impact considered, while in the works by Gebreslassie et al. (2013b) and Wang et al. (2013) it is health impacts that take this role. This is further illustrated in Figure 7, where impact categories used in the reviewed literature are placed in a dimensionality scheme (circles as dimensions, and their overlap as multidimensional areas) and topics related to these categories are explicit. For instance, the Crop Sustainability metric (CSI) (Golberg et al., 2014), is an impact category composed of water efficiency, polluting chemical release and employment metrics that place it in the overlap of economic, environmental and social dimensions. However, social and economic dimensions are represented solely by the employment metric and thus allow a limited analysis of social and economic sustainability. However meritorious it is that engineering projects consider sustainability beyond the more common economic and environmental aspects only, there is clearly a need for improving the integration of social sustainability aspects for sustainable biorefineries

Interestingly, in a recent study, Dale and Ong (2014) proposed a design framework considering a broader sustainability view based on objectives (related to economic, environmental and societal dimensions of sustainability) and not on particular sustainability indicators. Thus, by defining sustainability through objectives, the authors avoid limiting the concept to any particular set of metrics and leave it open to those of interest in a given context (although it can be discussed that by defining sustainability objectives the concept is already restrained at some level). Although some indicators are indeed suggested, the question remains if the same issues related to social IChemE metrics (discussed earlier in this section)**,** would be faced following this approach, and how trade-offs in conflicting situations are to be dealt with.

4.1.5 Efficiency Metrics

Efficiency metrics indicators have been used to refer to the efficiency of the system with respect to mass and energy inputs and outputs. Efficiency indicators are often used in the process engineering domain, where they can be useful for identifying improvement opportunities in the design, for instance, through energy or mass integration at early stage design (Ruiz-Mercado et al., 2013). Furthermore, indicators in this category have also been useful to compare different systems beyond the production process, like the use of energy efficiencies when comparing different bioenergy system alternatives (Ayoub et al., 2009).

Energy efficiency indicators have been predominant in biorefinery projects, as illustrated in Figure 2. These energy indicators provide information regarding the efficiency of energy resources use, sometimes considered indirectly related to environmental and economic sustainability, and also to socio-economic issues as mentioned in section 4.1.3. Also, given that most biorefinery products are energy products themselves, these metrics also provide information regarding the systems efficiency to convert raw materials into the target product without the need of a second indicator, like mass yields. Thus, energy efficiency indicators are often used to both compare and improve a production process based on the energy balance of a system. For instance, Caliandro et al. (2014); Tock and Marechal (2012) used the energy content of the product over energy inputs to assess the efficiency of process alternatives. This efficiency indicator, in combination with other economic and environmental metrics, was then used for heat and energy recovery as part of optimization frameworks used to improve the design.

Exergy, a measure of energy quality defined as the “maximum amount of work that can be extracted from a stream as it flows towards equilibrium” (Li et al., 2011), is also a common efficiency metric for biorefinery design, as shown in Figure 2. Like energy metrics, exergy has been widely used to analyze and improve processes (Ng et al., 2012; Peralta et al., 2010). Furthermore, exergy indicators have been discussed to provide more relevant information for environmental and economic analyses than energy metrics, given that exergy is a measure of the usability of energy, not just quantity (Kalinci et al., 2013). For example, Cohce et al. (2011) used both exergy and energy measures to identify sub-processes and parameters that had a strong impact on the efficiency of a hydrogen production process. Although both metrics indicated similar efficiencies for the evaluated process, exergy analysis allowed to identify sub-processes where energy quality was lost, which is not possible with energy analysis only. Regardless of the broader scope that exergy analysis allows, in biorefinery project design this is not yet a common practice, which may be in part due to the historical place of energy balances in process engineering.

In addition to energy and exergy, other topics are also addressed through efficiency metrics, typically in reference to mass losses. For instance, water use is an indicator mostly used in relation to the efficiency of the conversion process (Bernical et al., 2013; Schaidle et al., 2011), although crop water use efficiency related to the evotranspiration phenomenon has also been applied for analyzing biomass production configurations (Eranki et al., 2013). Also, efficiency metrics are used to analyze how much (potential) product is lost in the system through metrics like carbon efficiency (Bernical et al., 2013) or product losses (de Figueiredo and Mayerle, 2014). Clearly these metrics address topics of interest for each case, i.e. water efficiencies related to water availability concerns, carbon yield and product losses related to emissions or maximum use of raw material. Thus, their use depends on the project's context, and may add strength to a sustainability analysis.

4.2 Sustainability Incorporation in Design Activities

The sustainability methods and metrics discussed in the previous sections have been incorporated in design activities through assessment, optimization and design approaches. In this section, sustainability incorporation in these design activities is reviewed. Moreover, given the importance of stakeholder's perspective for sustainability in the biobased economy, an analysis of perspectives inclusion for biorefinery design during design activities is presented at the end of this chapter.

4.2.1 Assessment Approaches

In the design of engineering projects, design alternatives are typically evaluated or assessed based on performance indicators related to certain topics of interest. Thus, assessment methods are used as a tool when designs are already available, either for selection of most sustainable process alternatives or for their improvement. Furthermore, research for the design of biorefinery projects focused on performance assessment have been mostly related to the analysis of the conversion process or facility, with few studies related to the supply chain, like (Coleman et al., 2014; Eranki et al., 2013; Nguyen et al., 2014). For instance, Kalinci et al. (2013), present an assessment for the analysis of solar-assisted biomass gasification though GHG emissions, energy and exergy indicators. These metrics are used to compare the process performance under different conditions, like gasification temperature or feedstock type, in order to draw recommendations for future technology developments.

Assessments frameworks for sustainable biorefinery design are based on specific methods and metrics to evaluate certain aspects of sustainability. For instance, Li et al. (2011) present an explicit assessment framework that combines efficiency and economic metrics like exergy efficiency and NPV with methods for environmental and social analysis like the WAR algorithm, and the so-called EISI impact category (representing impacts on health and safety, referred to as impacts on society by the authors). Interestingly, this framework is based on a combination of process parameters and known chemical indices, like heat of main reaction and flammability, which are available at an early design stage. However, these metrics are limited to impacts directly related to the conversion process only, and do not cover upstream processes like raw material production or transport, which can be highly relevant in biobased conversions.

In contrast, the LCA methodology, with well-known methods like those discussed in previous sections, covers the entire life cycle of the products. However, LCA is limited to the environmental dimension of sustainability only. In the reviewed literature, few authors propose or apply integral assessment approaches, i.e. approaches that aim to integrate all dimensions of sustainability in a single analysis. Exceptions include the frameworks proposed by Li et al. (2011) and Sacramento-Rivero (2012), however, these lack a life cycle approach or consider limited topics regarding environmental and social sustainability, as discussed in depth in sections 4.1.2 and 4.1.4. In the recent years there have been developments towards life cycle sustainability assessments (LCSA), mainly through the combination of LCA with life cycle costing (LCC, a form of economic assessment like TEA) and social life cycle assessment (sLCA) (Kloepffer, 2008; Zamagni et al., 2013). Although this LCSA approach faces difficulties related the harmonization of different boundaries and units, and the adequacy and measurability of social indicators in sLCA (Schebek and Mrani, 2014), some authors have published practical approaches for this LCSA approach (Zamagni et al., 2013). However, according to the reviewed literature, LCSA is not yet applied for biorefinery design. Interestingly, the assessment framework recently published by Keller et al. (2015) extends on this LCSA concept for ex-ante evaluations of biorefineries, complementing it with sustainability and scenario analyses to face the methodological difficulties discussed above and analyze possible barriers to the projects.

Large data requirements are common difficulty to these assessments methods, particularly during early design stages. Therefore, shortcut assessment models are promising alternatives for this type of analysis. Karka et al. (2014) present a short-cut statistical model to assess environmental impacts of multiple product and process systems from knowledge on environmental impacts related to known products and production processes. The proposed statistical model relates molecular indicators and minimal process characteristics to potential environmental impacts and is suggested as a tool for selecting best alternatives for environmental sustainable design. However, given its limited accuracy, the model is proposed for high level estimations only, related to GWP and cumulative energy demand (Karka et al., 2014).

In some cases, assessment frameworks and methods include a normalization step, in which a reference value is used to harmonize results in a common scale. This normalization can be dependent or independent of the results of the analysis itself. For example, in the assessment framework by Li et al. (2011) the maximum and minimum values of each indicator are as limit values to further normalize them into a 0 to 1 scale. Hence, this type of normalization is only applicable when the assessment framework is used to compare multiple alternatives. Another type of normalization found is through the use of a value that is independent from the results obtained in the analysis itself. This type of normalization can be seen in the assessment framework proposed by Sacramento-Rivero (2012), where results are normalized based on “critical values” that represent the limit after which the considered system is no longer sustainable and is doomed to collapse. Given that this type of normalization is independent from the obtained results, it is also suitable for non-comparative assessments (e.g. to identify improvement opportunities in a design). However, the use of predefined “critical values” may subject the analysis to a normative perspective of what a sustainable state is.

Normalization is used to either ease the comparison of values or to allow aggregation of results by having the values in common units. However, this is an extra step that adds complexity to an assessment framework, and may also reduce the clearness of the analysis as real values are presented behind a normalized scale. In line with this reasoning, it is found that publications dealing with impacts related to one or two dimensions of sustainability do not normalize metrics to a common scale but rather present un-aggregated results in their absolute values. By contrast, all studies dealing with assessments that include the three dimensions of sustainability have a normalization step (Gebreslassie et al., 2013a; Gheewala et al., 2011; Golberg et al., 2014; Li et al., 2011; Sacramento-Rivero, 2012; Schaidle et al., 2011; Wang et al., 2013; Ziolkowska, 2013) . In order words, these more complex assessments involving more numerous and diverse indicators, rely on normalized values to allow an easier analysis of results.

Besides normalization, weighting can also be part of an assessment framework in order to express the relative importance of various results or result categories. Studies related to the assessment of impacts on the three dimensions of sustainability often use weighting factors to emphasize the importance of these dimensions or impacts related to them. For instance, in the study by Schaidle et al. (2011), weighting factors are given to different metrics related to economic, environmental and social dimensions of sustainability. Moreover, given that these weighting factors are subjective representations of the decision maker’s opinion, their influence on results can be further studied with a sensitivity analysis. For instance, Schaidle et al. (2011) arbitrarily gave equal values to the weighting factors, afterwhich different “perspectives” were defined with higher importance given to either the economic, environmental or social metrics. This type of analysis allows comparing benefits and drawbacks of the evaluated alternatives, and in their case studies, identifying a compromise with a biorefinery alternative that scores best in 50% of the analyzed perspectives. By contrast, weighting factors for different sustainability criteria can also be defined by a group of experts on the field, as in the work by Ziolkowska (2013). Although this expert approach allows for more educated insights on what can be considered as more relevant in the analysis, care should be taken in participant selection to avoid one sided inputs (see perspective inclusion in section 4.2.4).

4.2.2 Optimization Approaches

Optimization approaches have also been a common way for integrating sustainability concerns in the design of biorefinery projects, particularly related to sustainable supply chain optimization. For example, Giarola et al. (2011) present an optimization framework to find an optimal hybrid 1G+2G biorefinery and related supply chain, considering biomass production yields, demand centers and horizons, as well as technical, economic and market information. Optimization-based design has been also included process structure design in few cases. Tay et al. (2011b) present the optimization of the superstructure for an integrated biorefinery, based on raw material availability, processing technologies and related data on yields and economic performance. However, often in these optimization cases, the process stage, modelled with or without its supply chain, is reduced to only yields and black box models that are blind to, for instance, integration possibilities. From the reviewed literature, few studies use optimization approaches for process integration (Caliandro et al., 2014; Tock and Marechal, 2012), parameter optimization of already defined process structures (Vlysidis et al., 2011), or a combination of both (Ng et al., 2012).

Regardless of the main focus of the optimization approach, i.e. process or supply chain, sustainability issues are typically integrated through the use of indicators, mostly as objective functions. For example, a design can be optimized to meet the objective of the highest possible NPV or the lowest possible GWP. Therefore, optimization problems are mostly approached through mathematical programming modelling like linear and non-linear programming. An exception to this tendency is the use of evolutionary algorithms to find faster solutions of order-based combinatorial problems. However, the use of the latter approach is limited to a couple of papers (Ayoub et al., 2009; Caliandro et al., 2014), perhaps due to increased computational requirements that are commonly avoided with heuristics in classic optimization approaches.

Optimization of multiple objectives related to different sustainability dimensions can be done one at a time, where the model is optimized for one objective and subsequently for others, lie the optimization tests by Eranki et al. (2013) in relation to fuel, soil, water and emission category topics. Alternatively, non-economic impacts can be monetized or transformed into economic terms so that they can be added to economic metrics, and then the model can be optimized based on a single objective. This monetization is often based on expected CO_2 or GHG emission penalty costs or savings (Ayoub et al., 2009; Cobuloglu and Bueyuektahtakin, 2014; Kantas et al., 2015; Sharma et al., 2011; Vlysidis et al., 2011), although other indicators (e.g. soil erosion prevention and water use) have also been monetized in some studies (Cobuloglu and Bueyuektahtakin, 2014; Kantas et al., 2015). These approaches are practical given that the multi-objective problem is simplified and units are harmonized. However, monetization is based on either volatile market values or on expected values and costs, which inherently add uncertainty to the analysis.

Multi-objective optimization approaches have been more frequently used to handle several objective functions related to diverse aspects of sustainability in the design of biorefinery projects. Most commonly, one of the conflicting objectives is defined as a constraint and the problem can be solved for a single objective. For example, Cucek et al. (2014) simplifies the profit-food security multi-objective problem already at the mathematical problem definition by setting a food security criterion as constraint for biomass conversion into energy. Subsequently the problem is treated as single-objective from this point on. The epsilon-constraint solution method for multi-objective optimization, which also relies on the re-definition of one of the objectives as inequality constraint, has also been widely used as a solution approach (Gebreslassie et al., 2013b; Giarola et al., 2011; Kempener et al., 2009; Santibanez-Aguilar et al., 2014; Wang et al., 2013; You et al., 2012; Yue and You, 2014a, b; Zhang et al., 2014). The results of the epsilon-constraint method can be further collected in Pareto curves where the trade-offs between both objectives can be analyzed. For instance, You et al. (2012) compare the trade-offs between production cost vs. GHG emissions, and production cost vs. employment creation for cellulosic biofuel supply chains. On the other hand, to obtain a single result of optimization, fuzzy logic can be used to solve for multiple objectives by defining a degree of satisfaction or a value range for the objectives. Shabbir et al. (2012), define this degree of satisfaction by defining the fuzzy goals or limits for both objectives according to the optimal solution found for each objective individually. Another optimization approach through bi-level optimization, where a part of the problem is initially optimized to be used as input for the second part (Andiappan et al., 2015). All of these methods involve inherent limitations, either by not having a solution as a single result with the Pareto sets, by possible missing a global optimum or by having to define a compromise for two conflicting objectives.

Similarly to assessment approaches, optimization approaches often rely on normalization and weighting methods. Typically, these methods are used to combine different metrics related to a single sustainability dimension, which can be used to optimize multi-objective problems as discussed above. An exception is the optimization work by (Cheali et al., 2015), in which various metrics related to different sustainability dimensions are directly combined into a single objective through normalization and weighting factors. In the reviewed optimization studies, result-dependent normalization is a common practice. Also, the hierarchy, egalitarian and individualist modes of the EI99 used for environmental optimization, are in few cases also considered for normalization and weighting (Gebreslassie et al., 2013a; Santibanez-Aguilar et al., 2014).

4.2.3 Design Approaches

Sustainability aspects have been modestly incorporated in design of biorefinery projects (i.e. 10 out of the total 84) through design approaches that combine indicators, impact categories and methods.

In these design approaches, sustainability can be considered as a guiding principle, like the study of Kolfschoten et al. (2014), where identified improvement opportunities for farming, processing and transport activities are used as guiding principles to design an integrated sugar and ethanol production value chain in The Netherlands. These opportunities included, for instance, the local processing of sugar beets to recycle nutrients and water to the soil, and avoid hampering transportation costs related to centralized plants. However, these types of approaches do not yield a design itself, but rather set constraints or criteria for further design. Then, the designing itself can follow for example knowledge-based approaches like in (Kolfschoten et al., 2014), or optimization approaches like those discussed above.

Most reported design approaches, however, present explicit frameworks for design that differ on the focus of design and on design methods included therein. For instance, de Figueiredo and Mayerle (2014) present a framework for designing anaerobic digestion supply networks that breaks down the design task into subsystems, i.e. planning of routing, logistics network design, and processing plant location. According to the authors, this breakdown approach allows for a better understanding of sustainability trade-offs, although the approach, in this case, is mostly focused on costs. Ng et al. (2015) present a design framework that integrates customer needs in a combined product and process design framework. Activities in their framework include product design through molecule prediction models, and process design through optimization models based on profits and efficiency metrics, which overall satisfy customer requirements. In general, design frameworks, regardless of their different emphasis, include a sequence of steps that lead to a “sustainable” design, often through optimization and assessment of defined sustainability criteria, like efficiency metrics.

Frameworks with a process design focus commonly combine process modelling with TEA, LCA and/or process integration tools, thus considering economic and environmental dimensions of sustainability, and efficiency metrics. Mayumi et al. (2010), present a design framework with a model of the process concept, which includes process routes and candidate products, to generate inventory information for an LCA. The assessment results are to be used as feedback for the improvement of the process concept. Jenkins and Alles (2011) includes an additional economic evaluation in their proposed framework, which is used for selecting promising process alternatives in combination with LCA results. PSE methods for process integration have been also used to provide additional insights for the design of biorefineries, by combining, for example, LCA results with process integration models (Chouinard-Dussault et al., 2011). Mansoornejad et al. (2014) further combined in a hierarchical design framework, market and techno-economic analysis with LCA and supply chain analysis. However, in most of the reported frameworks, the supply chain in which the process is to be embedded is not taken into account, missing a large part of the scope of biorefineries.

In contrast to the strongly process oriented frameworks, de Santoli et al. (2015) present a design framework that deepens on the analysis of the project context for developing a bioenergy production process and its related supply chain network. Interestingly, the context analysis is characterized as a territorial energy vocation that considers available resources, established socioeconomics and historical productions in the geographical area of the project. This territorial vocation, together with an analysis of energy needs, is used to develop scenarios for bioenergy production, and is further assessed through economic analysis. Sustainability considerations are integrated in this framework by defining the project constraints and basis of design related to the territorial vocation. This vocation, related to resource potential, waste exploitation and the recovery of traditions (through to the consideration of historical production), may be said to cover to some degree the economic, environmental and social dimensions of sustainability. However, in the framework, the evaluated alternatives are only evaluated through economic metrics.

4.2.4 Perspective Inclusion

Throughout this review of biorefinery design it can be observed that no single optimum sustainable biorefinery design, or method for attaining it, exists. That is, a sustainable design is not only context dependent but it also relies on the designer or decision maker’s input on how to define, assess or select what sustainable is for each case, for example when a degree of satisfaction is defined as a compromise of opposing objectives. In the reviewed papers this understanding is in few occasions acknowledged, and often the “sustainable” biorefinery design is a product of mathematical, computational models based on hard data only.

In few works, the need for further input for finding a solution is addressed, particularly for the selection of weighting factors (Cobuloglu and Bueyuektahtakin, 2014; Xie and Huang, 2013), and the definition of fuzzy objectives for optimization (Andiappan et al., 2015; Tay et al., 2011b). Tong et al. (2014a) propose an alternative to balance these subjective choices by defining two measures for uncertain values in an optimization framework, which represent optimistic and pessimistic views. In the EI99 method, subjective inputs are presented through three idealized cultural perspectives, i.e. egalitarian, hierarchic and individualist (Goedkoop and Spriensma, 2001). Thus, from these cases it is clear that not only external knowledge is needed, but that the input also depends on subjective specific points of views. Thus, the worldviews of those involved in the design activity can have large impacts on global outcomes of the analysis.

Diverse stakeholders or perspectives have been considered in few cases. For example, Slade and Bauen (2013), consulted several experts to validate previous studies on microalgal systems and compare their energy use and environmental impacts. Through expert workshops, the authors discuss the validity of previous LCA studies for their meta-analysis, finding, for instance, that these are often outdated, superficial, or over optimistic. Similarly, Ziolkowska (2013) incorporates diverse stakeholder inputs into a framework to rank uncertain economic, environmental and social criteria. Thus, diversity in expert inputs is handled as uncertainty through fuzzy set theory, further analyzed with a multi-criteria method. These two works are based in participatory approaches that acknowledge subjectivities and imprecisions in decision making, and although the latter is intended for design at the policy level, the approach could be applicable for design of biorefinery systems as covered in this review. A noteworthy study is that by Dale et al. (2015) in which a high level conceptual framework is presented for the selection and evaluation of indicators for bioenergy systems (thus no metric or indicator is directly proposed). Dale et al. (2015) bring this approach for sustainability assessment considering that the selection of indicators is related to stakeholder's objectives and values (section 2.3). Although not particularly presented for design, this framework brings forward relevant points for sustainable biorefinery design, such as the inclusion of all relevant stakeholders, articulation of their objectives, and trade-offs between conflicting goals. Furthermore, as the authors discuss, such an open procedure allows for transparency and legitimacy, which can have a positive effect on the support for such projects.

5. Challenges and Opportunities

Biorefinery design has passed the times when biomass was considered sustainable solely due to its renewability characteristic. Nowadays, published methods, models and databases are used for estimating possible impacts related to the three dimensions of sustainability, and shortcut models have been identified as an interesting approach to perform these analyses at the early-stage design. However, there is still the challenge to strengthen the incorporation of sustainability in the design of biorefinery projects, as discussed throughout this review.

Some authors, for example, have defined and applied a number of society related metrics for the design of biorefinery projects; however these are often limited to human health or employment metrics, as discussed in section 4.1. Although these bi-dimensional impacts are important aspects of sustainability, using these as only social sustainability metrics means that some relevant impacts to society might be completely by-passed. Thus, there is a need for a widespread application of social sustainability analysis in the designing of biorefinery projects that also considers the context of the project.

Environmental sustainability, on the other hand, is often taken into account for the design of biorefinery projects. However, it is often reduced to global warming related impacts only. Regardless of the significant global importance of this topic, it is by no means the only relevant environmental aspect for biorefinery projects. Some studies address other environmental impacts, like those related to soil and water quality, or include broad environmental methods and metrics, like the WAR algorithm and IChemE sustainability metrics, but these cases are few and the methods are not always fully incorporated for design. Furthermore, the latter approaches still face some shortcomings for biorefinery design, like geographical validity, uncertainty or the process-centered scope of the WAR algorithm and the IChemE metrics.

Sustainability analyses often consider the economy dimension. However, the analysis is generally focused on enterprise sustainability through metrics like NPV and production cost. Although relevant for assessing the feasibility and sustainability of a project from a microeconomic perspective, there is still a need to include macroeconomic views that reflect the impacts on the economy in which the project will be embedded.

Although some approaches that include a combination of metrics related to the dimensions of sustainability have been reported in the literature, they were found to have strong limitations like reduced applicability at the design stage, or at different contexts, or they have a narrow consideration of sustainability topics. Thus, there is a need for a holistic integration of broad and integral sustainability that is in-line with the context of given projects, and that is practical at the design stage when data availability is limiting.

Multi-objective optimization approaches and integral sustainability assessments have shown to be useful methodological tools to integrally incorporate sustainability aspects in the design of biorefinery projects through the combination of metrics related to the economy, environment and society dimensions. However, most of these approaches have been particularly limited by their disciplinary focus, designing processes that are blind to their supply chain, or by the contrary, designing supply chains that over-simplify the conversion process, and thus do not consider integration opportunities related to this supply chain stage. Thus, there is a challenge to overcome a discipline barrier to integrate supply chain and process knowledge for the design of sustainable biorefinery projects.

In this review it is observed that often process and supply chain research have a common mathematical programming approach, sometimes combined with, for instance, simulation and other tools. Thus, an obvious opportunity is the use of this mathematical approach to bridge disciplinary differences. Also, if different modelling approaches are used for supply chain and process design, a higher level design or assessment framework can be proposed to handle and harmonize these different approaches, as already practiced for product and process design.

Some approaches or concepts from other disciplines have already been used to enrich the sustainability incorporation in design practices. For instance, the inclusion of a territorial vocation as part of the context analysis of the project is regarded as an interesting option to incorporate context specific integral sustainability. Thus, multi- and transdisciplinary design approaches are identified as opportunities to successfully consolidate integral sustainability in biorefinery design practices, while also considering the broad scope of biorefinery projects, the process and its supply chain.

Finally, throughout this review it is observed that sustainable design is not only based on absolute values, but that it also relies on subjective input to approach sustainability. Although sustainability problems in the engineering field have been addressed as wicked problems (Azapagic and Perdan, 2014), social and sustainability science approaches can bring light on how to include diverse and relevant perspectives from different stakeholders. For instance, studies like those by Ziolkowska (2013),Slade and Bauen (2013) and the conceptual framework of Dale et al. (2015), illustrate the use of participatory methods to consider different perspectives for weighting or validation of criteria, and indicator selection. Even more, Dale et al. (2015) propose with their framework to consider the objectives and values of the stakeholders in the selection of evaluation metrics. This inclusion of different perspectives may simultaneously attain the integral incorporation of sustainability in design, while possibly shedding light on reconciliation strategies for conflicting objectives.

6. Conclusions

Sustainability has increasingly been incorporated in the design of biorefinery projects; however, some challenges have been identified in relation to this design practice. For example, social sustainability is generally omitted in design practices, while environmental sustainability is often reduced to the analysis of global warming impacts, and macroeconomic effects are hardly taken into account. Efforts have been made to develop integral sustainability analyses for biorefinery design, but these have often been limited by the scope mostly related to conversion processes or to supply chains, while being blind to contextual settings or stakeholder perspectives. Namely, it is found that sustainability incorporation for biorefinery project design faces the following challenges:

- Inclusion of an integral sustainability analysis that considers societal impacts and goes beyond the micro-economy and global warming issues.
- Applicability during early design stages when data availability is limited.
- Disciplinary boundaries that limit the scope of analysis.
- Sustainability subjectivity, typically disregarded through the use of normative approaches.

Based on the analysis of these shortcomings and challenges, some prospects for improvement have been discussed in this paper. Overall, we identified the following opportunities towards the design of sustainable biorefineries:

- The analysis of the contextual setting for the project can be convenient to identify relevant sustainability issues related to the biorefinery projects.
- Common approaches and tools can be used to overcome disciplinary boundaries, like mathematical programming, simulation tools and databases.

- Incorporation of sustainability in design and assessment frameworks can allow the combination of different methodological approaches from different disciplines.
- Social and sustainability methods can be useful for considering sustainability subjectivities, particularly through the inclusion of stakeholder perspectives. Taking the phrase by Lou Reed (Reed, 1972) for emphasis, we encourage biorefinery researchers to "take a walk on the wild side" towards multi- and trans-disciplinary approaches by integrating social and sustainability sciences in their future developments.

Acknowledgments

This work is carried out within the BE-Basic R&D Program, which was granted a FES subsidy from the Dutch Ministry of Economic Affairs.

Appendix

Table A.1 Stand-alone indicators used in the reviewed literature.

Name (Other Names)	Description	Unit Dimensions	Sources
Economic			
Actual Sequestration Cost	Cost minus revenues of sequestration and utilization of CO2	Money/Time	(Gong and You, 2014a, b)
Capital Costs (Capital Expenditures, Investment Cost)	Sum of capital costs, depending on the case, it may include installation and start-up costs.	Money	(Caliandro et al., 2014; Coleman et al., 2014; Kalnes et al., 2007; Tock and Marechal, 2012)
Operating Costs (Operational Expenditure)	Sum of operating cost.	Money/Time	(Coleman et al., 2014)
Production Cost (Cost of Production, Least Expected Cost, Total System Cost, Total Supply Chain Cost)	Sum of capital and operating costs, when applicable biomass and product transportation costs, import penalty costs and credits are considered.	Money/Time	(Akgul et al., 2012; Baliban et al., 2013; Bernical et al., 2013; Coleman et al., 2014; Correll et al., 2014; Gong and You, 2014c; Huang et al., 2010; Iakovou et al., 2012; Michels and Wagemann, 2010;

			Sadhukhan and Ng, 2011; Slade and Bauen, 2013; Tong et al., 2014a; Tong et al., 2014b; Tong et al., 2014c; Xie and Huang, 2013; You et al., 2012; Yue et al., 2013; Yue and You, 2014b; Ziolkowska, 2013)
Transport Cost	Cost of transportation of biomass and/or product	Money/ Product Unit	(de Figueiredo and Mayerle, 2014)
Total Savings	The sum of utilities/mass savings and emission credits minus implementation cost	Money	(Chouinard-Dussault et al., 2011)
Gross Operating Margin (Financial Return)	Sales minus cost of raw material and utilities	Money/Time	(Field et al., 2013; Martinez-Hernandez et al., 2012, 2013; Rizwan et al., 2015; Tay et al., 2011a)
Credited Gross Operating Margin (Bioenergy Cost)	Sales and credits minus cost of raw material, utilities and penalties if applicable.	Money/Time	(Ayoub et al., 2009; Kantas et al., 2015)
Gross Profit (Annualized Expected Profit, Overall Profit, Total Profit, Earnings Before Interest, Depreciation, Taxes and Amortization)	Sales minus operating and capital cost (excludes taxes but may include overhead), when applicable biomass and product transportation costs, import penalty cost and credits	Money/Time	(Andiappan et al., 2015; Cheali et al., 2015; Cucek et al., 2014; Ng et al., 2015; Osmani and Zhang, 2014; Sammons et al., 2008; Santibanez-Aguilar et al., 2014; Shabbir et al., 2012; Shastri et al., 2011)
Internal Rate of Return	Calculated (interest) rate at which the NPV of the project equals zero	%	(de Santoli et al., 2015; Laser et al., 2009; Li et al., 2011)
Minimum Selling Price	Minimum Selling Price of the Product to fulfill profitability requirements	Money/ Product Unit	(Biddy et al., 2016; Dutta et al., 2012; Laser et al., 2009; Sen et al., 2012; Tan et al., 2016; Zhu et al., 2013)
Net Present Value	Sum of discounted revenues and costs in the life-time of a project	Money	(Gebreslassie et al., 2013a; Gebreslassie et al., 2013b; Giarola et al., 2011; Karschin and Geldermann, 2015; Kempener et al., 2009; Li et al., 2011; Vlysidis et al., 2011; Wang et al., 2013;

			Zamboni et al., 2011; Zhang et al., 2014)
Payback Time	Expected time in which the investment cost is payback from the projects cash flows.	Time	(de Santoli et al., 2015)
Return on Investment	Net profit over investment costs	%	(Schaidle et al., 2011; Sen et al., 2012)
Stakeholder Value	Weighted sum of future cash flows and terminal value of the enterprise minus the overall debt	Money	(Sharma et al., 2011)
Total Economic Value	Sum of revenues plus monetized (GHG and soil erosion) environmental impacts	Money/time	(Cobuloglu and Bueyuektahtakin, 2014)
Environmental			
Greenhouse Gases Emissions	Sum of emissions as CO2 equivalents per unit of product.	Mass/Product Unit	(Barnes et al., 2011; Bernical et al., 2013; Iakovou et al., 2012; Kalinci et al., 2013; Kempener et al., 2009; Sharma et al., 2011; Shastri et al., 2011)
Nitrogen Oxides Emissions	Sum of nitrogen oxides emissions over the system boundary.	Mass/Product Unit	(Schaidle et al., 2011)
Sulfur Oxides Emissions	Sum of sulfur oxides emissions over the system boundary.	Mass/Product Unit	(Schaidle et al., 2011)
Mitigation of GHG	The mitigation value is estimated from the half-life of the product in soil in a 100 year time horizon.	Mass/Mass	(Field et al., 2013; Laser et al., 2009)
Net GHG emissions reduction	Difference between total CO2eq emissions displaced and total CO2eq emissions form the feedstock, transport and processing systems of the proposed design	Mass/Product Unit	(Eranki et al., 2013)
Change in Soil Organic Carbon	Total change in solid carbon after growing feedstock	ns	(Eranki et al., 2013)
Erosion	Average soil eroded over the watershed land area	ns	(Eranki et al., 2013)
Nitrogen Losses	Total mass amount of nitrogen losses over the system boundary.	Mass/Product Unit	(Eranki et al., 2013)
Phosphorus Losses	Total mass amount of phosphorus losses over the system boundary.	Mass/Product Unit	(Eranki et al., 2013)
Oil Displacement	Petroleum use displacement.	Energy/Mass	(Laser et al., 2009)
Social			
Energy Self-Sufficiency	Energy generated relative to estimated demand in the region	-	(Kempener et al., 2009)
Food Price Increase	Semi-quantitative potential for	%	(Schaidle et al., 2011)

	increasing food prices in **relation to feedstock type**, and a measure of food security		
Sustainability Factor	Sustainability factor that represents the fraction of biomass production that can be used for biofuel production, to ensure food security, based on a defined set aside land	-	(Akgul et al., 2012)
Socio-environmental			
Human Exposure Risk	Semiquantitative risk for human exposure to polluting emissions in relation to feedstock type	%	(Schaidle et al., 2011)
Socio-economic			
Employment Creation	Employment Creation	No. created jobs	(Santibanez-Aguilar et al., 2014; Schaidle et al., 2011; You et al., 2012)
Labor requirement	Employee time of labor requirements	Employee-time	(Ayoub et al., 2009)
Efficiency and Process			
Bioenergy Efficiency (Cold Gas Efficiency)	Energy in the product over energy in biomass	-	(Cohce et al., 2011; Kalinci et al., 2013; Tock and Marechal, 2012)
Energy Efficiency (Bioenergy yield, Net Energy Balance (NEB), Fossil Energy Consumption)	Energy in product(s) over energy inputs	-	(Bernical et al., 2013; Cohce et al., 2011; De Meyer et al., 2015; Eranki et al., 2013; Golberg et al., 2014; Jenkins and Alles, 2011; Kalinci et al., 2013; Kalnes et al., 2007; Li et al., 2011; Ojeda et al., 2011; Schaidle et al., 2011)
Net Bioenergy Efficiency	Energy output (product minus process requirements) over energy in biomass	-	(Caliandro et al., 2014)
Energy Use	Total energy use	Energy/Time	(Ayoub et al., 2009; Shastri et al., 2011)
Specific Total Energy Use (Cumulative energy demand)	Total energy use per amount of product	Energy/ Product Unit	(Kalnes et al., 2007; Karka et al., 2014; Tan et al., 2016)
Specific Fossil Energy Use	Total fossil energy use per amount of product	Energy/ Product Unit	(Kalnes et al., 2007)
Heat of reaction (Biorefinery Energy	Sum of enthalpy of reactions, or main reaction	Energy/Time	(Andiappan et al., 2015)

Consumption)			
Net Energy Ratio	Used energy over energy in biomass product	-	(Slade and Bauen, 2013)
Exergy Efficiency	One minus the ratio of exergy losses and exergy inputs; exergy in product over exergy inputs	%	(Cohce et al., 2011; Kalinci et al., 2013; Li et al., 2011; Ojeda et al., 2011; Peralta et al., 2010)
Exergy Losses	Exergy Balance	Exergy	(Peralta et al., 2010)
Carbon Efficiency (Carbon utilization)	Carbon in product streams over carbon in biomass	-	(Bernical et al., 2013; Tan et al., 2016)
Crop Water Use Efficiency	Ratio of biomass yield to evapotranspiration resulting from a particular feedstock	-	(Eranki et al., 2013)
Water Efficiency	Mass or volume water requirements over mass, volume or energy amount of product	-	(Bernical et al., 2013; Laser et al., 2009; Schaidle et al., 2011; Ziolkowska, 2013)
Mass Losses (Methane Loss)	Mass losses that reduce the production yield	ns	(de Figueiredo and Mayerle, 2014)
Production Rate (Ethanol Production)	Production rate as a function of process parameters like conversion yield and biomass inflow.	Mass/Time	(Eranki et al., 2013; Ng et al., 2015; Ziolkowska, 2013)
Biofuel Yield	Product outflow over biomass feedstock inflow	Product Unit/Mass	(Rizwan et al., 2015; Tan et al., 2016)

ns – not specified in reference(s).

Table A.2 Impact categories used in the reviewed literature.

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Results from the literature search are indicated with an asterisk (*) before the author's name.

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Azapagic, A., 2014. Sustainability considerations for integrated biorefineries. Trends in Biotechnology

Category Name	Category References
Economic Constraint	(Cheali et al., 2015)
Environmental Impact of Raw Materials	
Process Cost and Environmental Impact	
Global Warming	(Andiappan et al., 2015; Ayoub et al., 2009; Baliban et al., 2013; Chouinard-Dussault et al., 2011; Cucek et al., 2014; Eranki et al., 2013; Gebreslassie et al., 2013a; Gebreslassie et al., 2013b; Gheewala et al., 2011; Giarola et al., 2011; Gong and You, 2014a, b, c; Jenkins and Alles, 2011; Kalnes et al., 2007; Karka et al., 2014; Martinez-Hernandez et al., 2012, 2013; Mayumi et al., 2010; Michels and Wagemann, 2010; Nguyen et al., 2014; Sadhukhan and Ng, 2011; Schaidle et al., 2011; Tan et al., 2016; Tock and Marechal, 2012; Vlysidis et al., 2011; Wang et al., 2013; Xie and Huang, 2013; You et al., 2012; Yue et al., 2013; Yue and You, 2014a, b; Zamboni et al., 2011; Zhang et al., 2014; Ziolkowska, 2013)
Human Development Index	(Gheewala et al., 2011)
Total Value Added	
Crop Sustainability	(Golberg et al., 2014)
Enhanced Inherent Safety Index	(Li et al., 2011)
Economic Potential	(Kasivisvanathan et al., 2012; Ng et al., 2013; Tay et al., 2011b)
Economic Performance	(Ng et al., 2013)
Total Safety Impact	
Total Health Impact	
Feedstock Adequacy	(Sacramento-Rivero, 2012)
Transformation-process Performance	
Oil-displacement Capacity of Products	
Environmental Load	
Corporate Commitment to Sustainability	
Eutrophication Potential	(Schaidle et al., 2011)
Health Effects	

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Figure 1. Schematic example of a biorefinery project (supply chain and biorefinery system): As part of the supply chain (SC), feedstock from several locations is transported to distributed and centralized conversion centers, from which products are distributed to reach the final consumer and be used (A). In the biorefinery system (BRS), it is illustrated that feedstock preprocessing is mechanical (MP), and that chemical (CP), biochemical (BCP) and thermochemical (TCP) conversions are used to process two platforms (P1: Platform 1, P2: Platform 2) into two products (B).

Figure 2. Overview of the 84 reviewed publications. **A**: Number of publications per year. The dashed bar represents the number of publications only until mid-2015 when the search was performed. **B:** Number of reviewed publications according to the dimensionality and efficiency metrics. The frequency of efficiency metrics is not exclusive as they are often used in combination with others (*e.g.* a 1D publication that considers environmental sustainability, energy and exergy efficiency metrics is accounted in the "1D En", "Exergy" and "Energy" bars). Ec: Economic, En: Environmental, Sc: Social, EES: Economic, Environmental and Social. See section 3. Methodology of Literature Review for details on the search.

Figure 3. Schematic representation of how project interventions (i.e. emissions, resource use, products) are analyzed for the incorporation of sustainabiltiy for biorefinery design. The impact of project interventions on different aspects of sustainability has been analyzed and expressed as (A) direct stand –alone indicators (e.g. CO2 carbon emissions, total energy use), (B) impact categories that combine different indicators or use mechanisms to express emissions as midpoint impacts (e.g. global warming impact as the sum of greenhouse gas emissions' global warming potential relative to that of CO_2 in a given time frame), and (C) as impact categories that combine different impacts at the midpoint level (e.g. human health impacts estimated from impacts on climate change, particulate formation, human toxicity, etc.). Typically, studies following the approach described in C are based on well-known assessment methods like the LCA Ecoindicator-99.

Figure 4. Frequency of use and topic of economic indicators found in the 84 reviewed papers. Economic indicators used as part of impact categories are excluded from this figure. ASC: Actual sequestration cost, CC: capital cost, OC: operating cost, PC: production cost, TC: transportation cost, TS: total savings, GOM: gross operating margin, GOM_cr: credited gross operating margin, GP: gross profit, IRR: internal rate of return, MSP: minimum selling price, NPV: net present value, PBT: payback time, ROI: return on investment, SKV: stakeholder value, TEV: total economic value. See the appendix for the list of indicators and their definition.

Figure 5. Frequency of use and topic of stand-alone environmental indicators found in the 84 reviewed papers. E_GHG: Greenhouse gas emissions, E_NOx: nitrogen oxides emissions, E_SOx: sulfur oxides emissions, MGHG: mitigation of greenhouse gases; NGER: net greenhouse gas emission reduction; CSOC: change in soil organic carbon; Er: erosion; L_N: nitrogen leaching; L_P: phosphorus leaching; D_oil: Petroleum oil use displacement. See the appendix for the list of indicators and their definition.

Figure 6. Frequency of use and topic of stand-alone social, socio-economic (Sc-Ec) and socio-environmental (Sc-En) indicators found in the 84 reviewed papers. ES: Energy security index, FPI: food price increase, SF: sustainability factor, R_HE: human exposure risk, EC: employment creation, L: labor requirements. See the appendix for the list of indicators and their definition.

Figure 7. Overview of impact categories in the reviewed literature, according to dimensionality (impact categories group multiple indicators, or are defined through specific mechanisms for their calculation, see section 4.1 for more details). In this figure, impact categories used in the reviewed literature are grouped according to common topics. For instance, GW, EIRM and EnL are impact categories based on environmental metrics that cover the climate change topic; EnL additionally addresses land use. 1: health, social investment; 2: pollutant emissions, employment. An asterisk (*) indicates that efficiency metrics are also part of the relevant impact category. No frequency is presented in this figure as almost all categories are used once; the outstanding exception is GWP potential referenced in 35 papers. See the appendix for the list of impact categories, their definition and authors that cite them.

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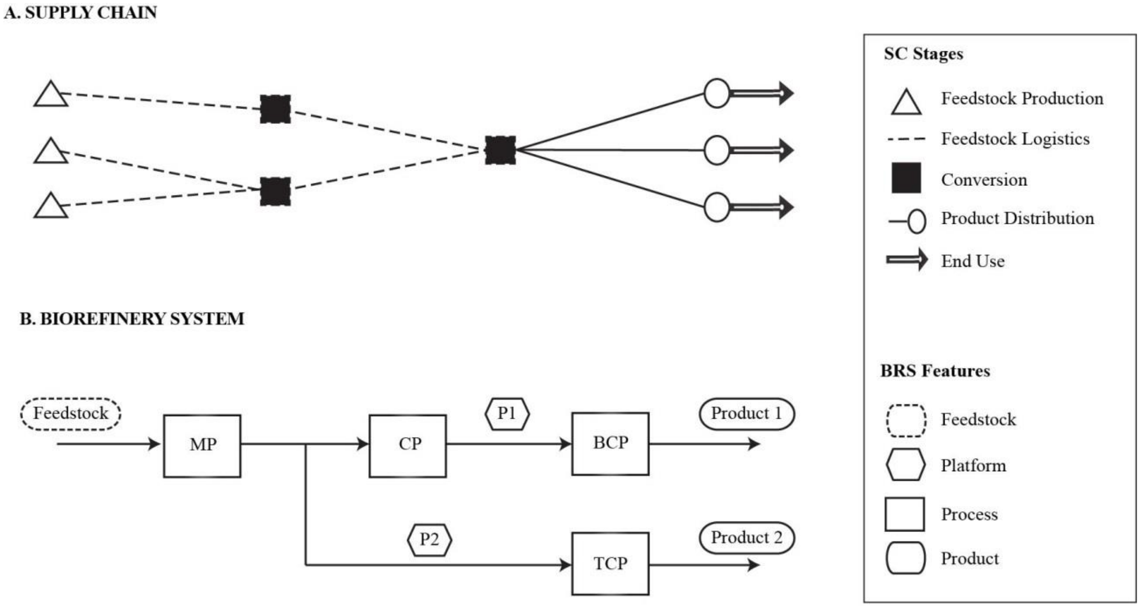
Figure 1.



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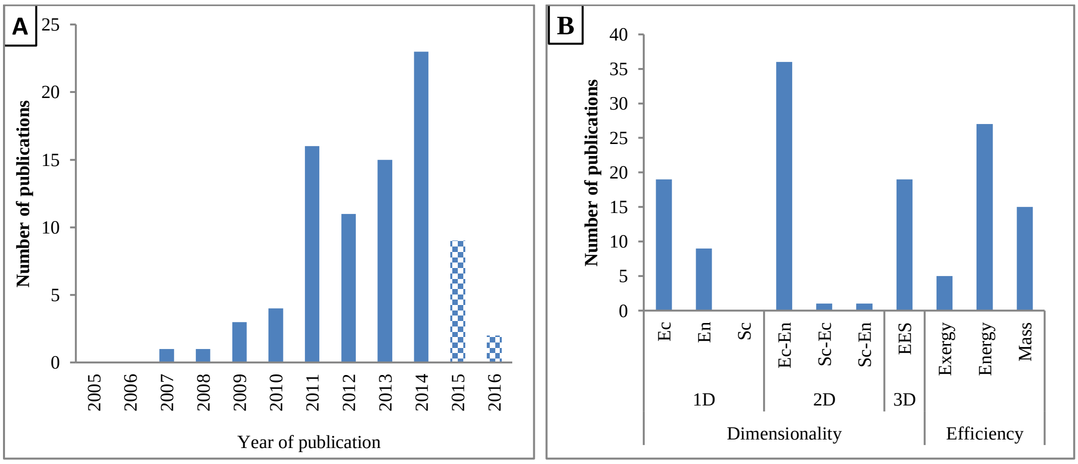

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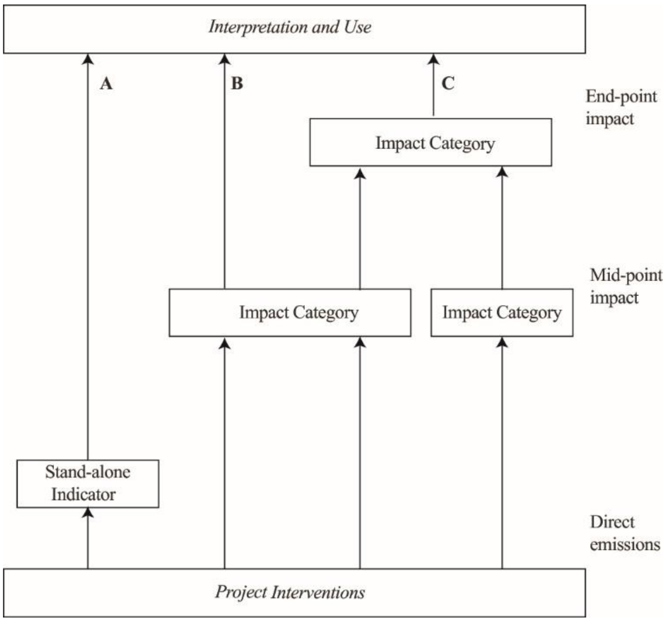

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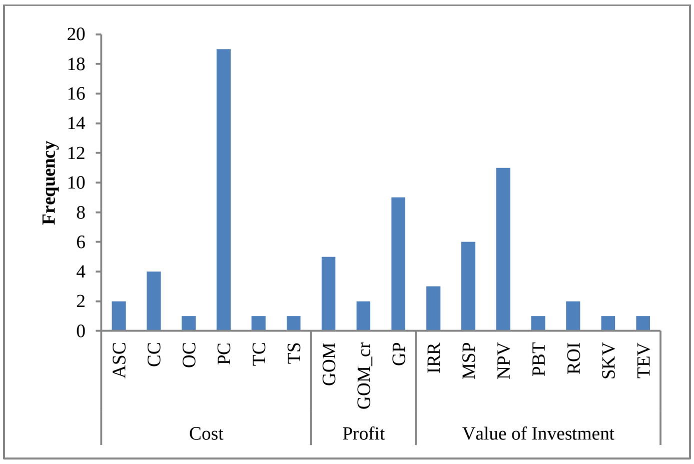

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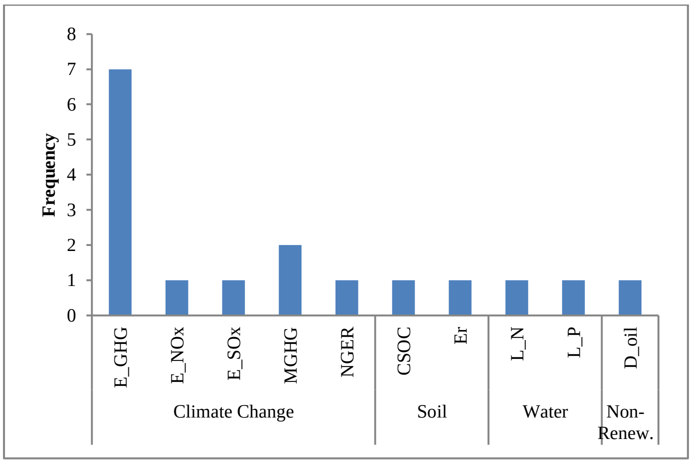


Figure 6.

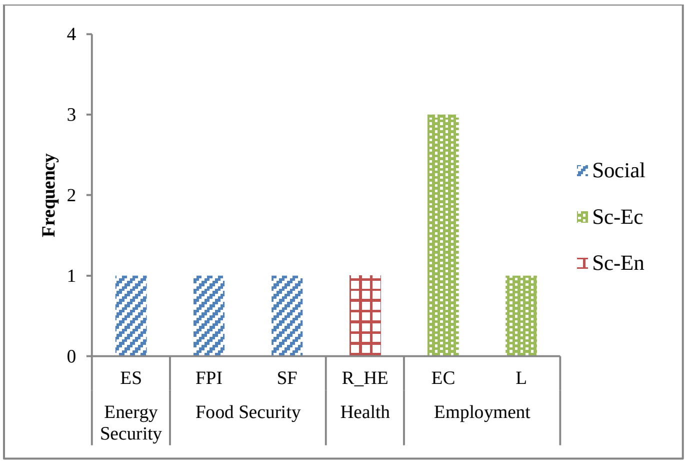
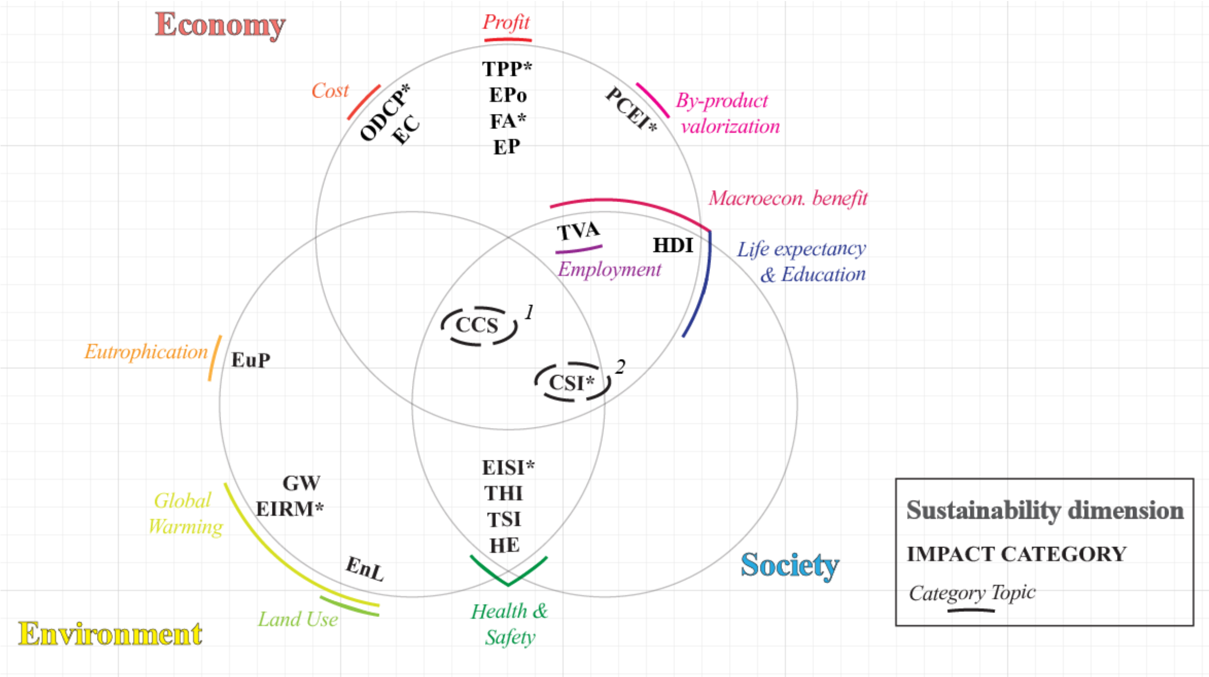


Figure 7.


Economy
Profit
TPP*
EPo
FA*
EP
Cost
ODCP*
EC
PCEI*
By-product
valorization
Macroecon. benefit
TVA
HDI
Life expectancy
& Education
Employment
CCS
1
CSI*
2
Eutrophication
EuP
GW
EIRM*
Global
Warming
EnL
Land Use
EISI*
THI
TSI
HE
Health &
Safety
Society
Environment
Sustainability dimension
IMPACT CATEGORY
Category Topic