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Sustainability Assessment Techniques and Potential Sustainability Accreditation Tools for Energy-Product Systems Modelling

Valeria Selicati*, Nicola Cardinale

Department of European and Mediterranean Cultures, University of Basilicata, Via Lanera 20, 75100 Matera, Italy

* Correspondence: Valeria Selicati (valeria.selicati@unibas.it)

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Abstract: The modelling of complex technological systems serves as the foundation for enhancing process performance, including sustainability features (triple-bottom line). The European Green Deal, proposed in 2019, aims to cut greenhouse gas emissions by 2050 and foster a resource-independent economy. Such a change must be carefully planned. Comprehensive sustainability protocols and guidelines are necessary to describe the standardized methodological procedure, the environmental certification procedures that allow market comparability and identification of the best solutions, the databases, the calculation tools and software, and the benchmark and target with which to make comparison. Policies and regulatory or incentive instruments promote the broad adoption of these approaches and ensure that policies reduce environmental, economic, and social impacts. This paper consists in an overview of sustainability assessment tools' role in energy policy and short- and long-term modeling of more eco-friendly energy-product systems. Additionally, the paper explores these methods' pros and cons in planning, analyzing, and optimizing energy/product systems, also according to the circular economy paradigm. All of these strategies aim to help the decision-maker make more consistent judgments by taking into consideration essential objective, such as end user or stakeholder demands, and minimizing subjective elements. An extensive listing of Sustainability accreditation and communication tools is provided. Sustainability assessment is an evaluation and optimization method that promotes sustainable development in all political planning and decision-making. It examines the social, economic, and environmental effects, finds conflicting goals, and recommends early optimization. Potentially, sustainability assessment should be integrated into the political planning process and depend on domain-specific research and assessments that currently exist or are planned, such as in combination with decision-making. Sustainability assessment is not designed to be an extra analytical tool. A sector-specific environmental or economic study from a strategic environmental analysis or regulatory effect analysis may be crucial to a sustainability assessment.

Keywords: Sustainability assessment; Energy-product systems; Energy modelling, Policy tools, Circular economy

1. Introduction

In 2019, the European Commission unveiled the European Green Deal [1], a new plan that seeks to eliminate greenhouse gas emissions by 2050 and supporting a resource-independent economy. The worldwide global concerns, such as global warming and climate change, the Russia-Ukraine conflict, and the Coronavirus pandemic, all indicate the need for a shift from fossil-based systems to bioenergy and bioproducts in order to achieve our sustainable development goals. Such a shift must be meticulously planned, taking into account the long-term viability of the various components of these systems. Innovative sustainability tools are essential to achieving this crucial aim.

The tools are essential for making the existing practice's technique applicable. By tools, we mean the protocols and guidelines that describe the standardized methodological procedure (in greater detail than technical standards), the environmental certification procedures of building and product that allow comparability on the market and identification of the best solutions, the sources of the data (databases), the calculation tools (tools and software), and the reference values (benchmark and target) with which to make a comparison (especially of the building). Therefore, we can state that policies and regulatory or incentive instruments play a crucial role in promoting the widespread adoption of the approach, but they are also useful for ensuring that policies drive toward an effective reduction of environmental consequences [2].

Environmental policies frequently address environmental concerns in isolation, despite the need for a holistic perspective. Hence the significance of including the evaluation of sustainability (environmental, economic, and social) into the policies and using it to inform the subsequent improvement measures.

Sustainability assessment is an evaluation and optimization tool that aims to promote the integration of sustainable development in all areas of political planning and decision-making. It evaluates the social, economic, and environmental implications of political initiatives and actions undertaken by the Union, identifies competing objectives, and advocates early optimization.

In general, sustainability assessment evaluates projects prior to their implementation, in the sense of an ex-ante appraisal. The sooner sustainability evaluation is included into the political planning process, the higher the policy design flexibility and optimization scope, and the more efficient its utilization.

Sustainability assessment focuses on the strategic, planning, and programming levels and may be used to the evaluation of initiatives and projects from the widest variety of policy domains. As far as feasible, sustainability assessment should be incorporated into the normal political planning process and draw on domain-specific studies and evaluations that already exist or are planned as part of that process, such as in conjunction with the drafting of a decision. An evaluation of sustainability is led by the agency responsible for the relevant subject [3]. Sustainability assessment is not meant to be an additional kind of analysis in addition to current evaluation tools. Instead, it provides a detailed evaluation of effects from the standpoint of sustainable development. In essence, a strategic environmental analysis or regulatory impact analysis might be an important component of a sustainability assessment by providing a sector-specific environmental or economic review.

This paper discusses the significance of sustainability assessment techniques as an auxiliary tool for energy policies and the short- and long-term modelling of more eco-friendly energy-product systems. The objective is to answer as thoroughly as possible the question “to what extent do the presented evaluation tools meet the requirements for the assessment of sustainability?”.

This study examines these techniques, which include techno-economic, life cycle evaluation, emergy, energy, and exergy studies. Following a short explanation of the fundamentals behind these methodologies, their advantages and disadvantages in planning, assessing, and optimizing energy-product systems are explored. All of these methods share the objective of supporting the decision-maker in making more consistent decisions by taking into account important objective and reducing subjective factors, including the needs of end users or stakeholders.

2. Sustainability Assessment

The Methodology section should be written concisely, yet provide enough details to allow others to replicate and build on published results. The well-established methods can be introduced briefly with proper citations. Do not describe these published methods in details. In contrast, detailed descriptions are required for new methods. If multiple methods are adopted in the work, this section may be divided into several subsections, each providing details on a specific method. Note that the publication of your manuscript means all materials, data, codes, and protocols associated with the publication must be made available to readers. Remember to disclose restrictions on the availability of materials or information at the submission stage. If your manuscript uses large datasets deposited in an opensource database, please specify where the data have been deposited. If your study requires ethical approval, do not forget to list the authority and code of the ethical approval.

Sustainability is the capacity to ensure the continuation of production and variety while preserving human existence. In other words, sustainability is the potential for self-sufficiency without neglecting the needs of future generations. Sustainability is connected to the economy, society, and environment [4]. Economic sustainability focuses on ensuring prosperous economic development that does not hurt the environment. Social sustainability is concerned with the long-term viability of social circumstances such as education, health, happiness, a safe existence, and quality of life. Protection of natural resources is essential for environmental sustainability. The manufacturing system that meets all of these criteria may be considered sustainable. Sustainability criteria must be implemented in all activities in the contemporary world, notably in the industrial sector. These principles belong to the triple bottom line (TBL) [5] (Figure 1), of sustainability, which includes environmental, social, and economic concerns. Sustainability is also connected to the Sustainable Development Goals (SDGs) of the United Nations [6].

Sustainability science, according to Jerneck et al. [7], combines environmental science with economic, social, and development studies in order to better comprehend the dynamic, complex relationships between environmental, social, and economic challenges. However, for the transition to sustainability, objectives must be evaluated. This has presented significant hurdles to the scientific community in terms of developing efficient, but trustworthy, instruments. As a result of these obstacles, sustainability assessment has become a fast-growing field. The number of tools claiming to be able to be used for evaluating sustainability has increased, and many of these tools have evolved to provide improved application instructions, data, and case study experiences.

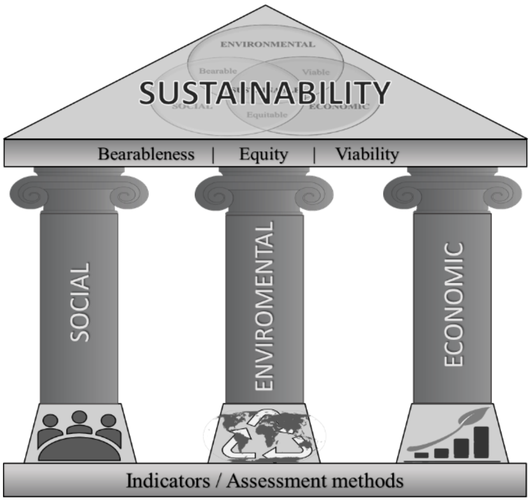

Figure 1. Three pillars of sustainability concept (TBL) [8]

Practitioners have a set of tools (certifications, labels, indicators, etc.) available to quantify the degree of sustainability of a system or a circular product, but there is little clarity on how a stakeholder could take advantage of it. The supplementary instruments for sustainability must be as unambiguous as its canonical definition. In particular, we refer to the systemic tools for the circular economy, the instruments for measuring and enhancing sustainability, the tools for the accreditation and communication of sustainability, UNI and ISO standards, and the Sustainability Framework's guiding principles [9, 10].

Environmental, social, and economic sustainability is not a qualitative slogan; rather, it is a measurable paradigm that guides choices and strategic decisions toward sustainable and circular business models. Therefore, it becomes essential for stakeholders to have official, recognized, and concrete tools for quantifying the potential of strategies and sustainability actions.

What is required for these practices to be as standardized as possible (locally and potentially globally) is a sort of essential toolbox for:

- always having under control the medium-to-long-term strategic path and the circular business results that you want to achieve;
- evaluating the strategic potential of a circularity path and its specific stages;
- providing evidence to its own stakeholders of the path taken towards a circular and sustainable business model.

We are discussing systemic environmental management tools or guidelines for the adoption of a circular economy, which offer the benefit of adopting a high-level, 360-degree perspective on the entire project.

The systemic tools for quantifying the sustainability of a project (especially a business) play an important role for an additional reason: they enable the incorporation of an organizational model capable of controlling the parameters, processes, and numbers associated with the development of circular processes.

However, an internal organizational model that permits a fundamental view of the outside world is also externally focused. That is, what stakeholders and partners are doing throughout the entire design process, both upstream (i.e., in the supply and supply phases) and downstream (i.e., the product/service fate).

A second advantage of these systemic tools is that they help outline a medium-to-long-term strategy to achieve objectives that are consistent with the policy (of sustainability, circularity) defined at the outset, thereby providing inspiration for any deviations or recalculations of the initial requirements.

A third benefit can be the establishment of well-defined objectives and deadlines. This enables the allocation of time and resources to strategic figures who will develop circular economy issues and the monitoring of the entire process via audit.

Lastly, when the study is intended to support the company's business, these standards and environmental management systems or the adopted specific guidelines are required to have an awareness of what is being done inside and outside the company: an awareness accompanied by detailed monitoring actions of what occurs along the supply chain and during the end-of-life phases of the product or process. UNI EN ISO 14001: 2015, UNI EN ISO 50001: 2018, BS 8001: 2017 and Italian UNI CEI 11352 are some of the most important systemic and environmental management standards, but the list is by no means exhaustive [11, 12].

In the literature, the connection between circular economy and sustainability is unclear [13]. The majority of scientific studies on the activation of circular processes do not evaluate their sustainability, and in practice, environmental evaluations to support circular strategies are not widely utilized [14].

The tools to measure and improve sustainability are designed to achieve a level of detail and concrete quantification that enables the stakeholder to respond to two objectives: a) “I want to evaluate the potential of the strategy for my path towards a circular business model” and b) “I want to determine whether my request is advantageous and brings the anticipated benefits”.

Numerous instruments and indicators are available for conducting analyses and evaluations of this nature.

The list and choice of which to adopt vary based on the focus of sustainability that is intended to be pursued (what is defined as a requirement and which forms the basis of the purpose and objective of the study), which may be social, environmental, or economic in nature [15].

An absolutely non-exhaustive example would be to divide the methods based on the nature of the analysis, i.e., measurement instruments and improvement of social impact, such as S LCA Social Life Cycle Assessment, Social Footprint - Product Social Identity, and specific KPI on social aspects; measurement instruments and improvement of environmental impact, such as Material Flow Analysis, LCA - Life Cycle Analysis, and specific KPI of an environmental nature (e.g. Carbon and Water Footprint); or measurement tools and enhancement of economic impact, thus Life Cycle Costing, Techno-Economic Analysis, and specific economic KPIs.

Energy-product systems rely on substantial quantities of materials, chemicals, and fossil fuels, and their creation is not carbon-free. Moreover, due of the time lag between carbon dioxide reductions and emissions, bio-based systems do not yield carbon neutral goods [16]. Accordingly, it may be concluded that energy-product systems continue to encounter obstacles that call their environmental sustainability into doubt. Consequently, these systems should be evaluated from an environmental standpoint in order to identify environmental hotspots and develop methods that would result in lowest environmental harm.

2.1 The Policy

Policies’ scope of application is continually being defined and is of increasing interest to public administrations. Policy refers to the strategic guidelines or action lines underlying the production of both direction documents and multi-year action programs, as well as (European) directives and cogent (national) regulations, building standards, and local planning tools [17].

In this case, the application mode is played on two levels: on the one hand, the methodology can be a tool for defining policies and verifying their effects (applied by policymakers), and on the other hand, the methodology can be incorporated into the policies as a means of mitigating impacts (therefore requesting the final operators to demonstrate a reduction in environmental impacts).

Critical to the affirmation of this path are, on the one hand, the preparation of public administration officials in applying the given tool to support the definition of the policies and in verifying the application if the LCA methodology is required by the policies, and, on the other hand, the preparation of market operators to meet regulatory requirements [18]. This necessitates finding levels of simplification in the application of the methodology, which typically translates into a reduction of the environmental indicators considered (to make the results and comparison between alternative options easier to read) or a simplification of the LCA evaluation (relying on secondary data from software and databases or by reducing the phases of the life cycle considered). Simplifications are always risky because they can lead to results that do not correspond to reality, despite their importance in the initial phase of the LCA methodology’s implementation. It is essential to expand the preparation of the operators and to avoid trivializing the application of the methodology.

2.2 Tools and Methodologies

2.2.1 Life Cycle Assessment - LCA

The Life Cycle Assessment (LCA) analysis is a standardized and internationally recognized method of calculation by UNI EN ISO 14040: 2021 and UNI EN ISO 14044: 2021 that allows to evaluate the direct environmental impact of innovative products and processes, while also taking into account the indirect impacts associated with the supply chain (upstream), the phases of use (core), and end of life (downstream).

LCA is an effective method for measuring the environmental impacts of diverse goods and systems. LCA is a distinctive method since it focuses on goods and systems from a life-cycle viewpoint and prevents issue shifting. This method analyses the possible environmental impacts of materials and energy consumed throughout the life cycle of a product, from the extraction of raw materials through waste management/disposal [19]. Consequently, it may quickly detect causes of non-sustainability at each step of a product’s life cycle. LCA is a defined approach based on the International Organization for Standardization (ISO, 2006) that evaluates a product or system in four phases, including aim and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and results interpretation, schematized in Figure 2.

Considering the general functional system model depicted in Figure 3, the structure of an analysis is always dependent on the circumstances under which it is conducted, i.e., the objective and scope, as well as the functional unit to be analyzed. It also depends on the type of streams to be analyzed, the available data, and the granularity of the study itself [20].

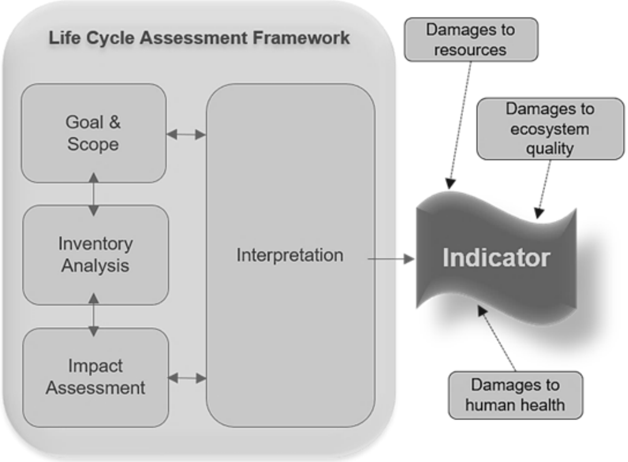

Figure 2. Scheme of the phases of the LCA [21]

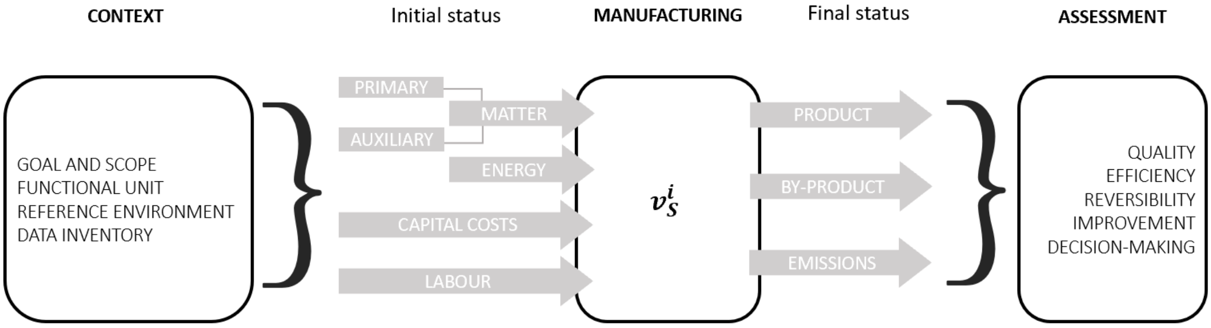

Figure 3. Generic functional system mode [20]

Inputs and outputs must be quantified based on a particular functional unit (FU), which might be input- or output-oriented depending on stakeholder interests. System boundary definition is another important decision when applying an LCA [22].

LCI is the second phase of an LCA, in which all inputs and outputs to/from the system are collected. This stage requires the careful collection of two types of data: foreground data and background data related with the life cycle of energy and mass fluxes.

Foreground statistics pertain to the kind and amount of materials and energy utilized in a product's life cycle. These are directly obtained statistics on the kind and amount of materials and energy used in production, treatment, production, transportation, consumption, and waste management. It also contains information on the environmental burdens of applying materials and energy to a system, which are mostly assessed using the current literature. Typically, background information on the environmental impacts of the production of materials and energy is gathered from databases such as Ecoinvent [23]. It should be highlighted that improper LCI leads to overestimation or underestimating of environmental costs, and that the findings of research are subject to substantial uncertainty. In addition, the extracted database data are often not given at the local and regional levels, which might increase the uncertainty of the findings. In the last phase of an LCA research, LCI leads to a huge list of compounds with vastly varied potentials to cause environmental harm, rendering LCI-based decision-making nonsensical. In other words, LCIA and LCI are transformed to a number of impact/damage categories.

It is a potent instrument due to its versatility and adaptability when investigating a sustainability strategy. It is adaptable because the LCA analysis permits you to shift the focus of the measurements:

- at the level of the entire system: that is, apply it to the entire organization, on all its assets, and conduct ex -doors and ex -post assessments regarding the adoption of a circularity strategy; - at the level of a portion of the system: that is, apply it to a particular product line or a single product component (Early Design Stage).

However, it is adaptable in that it allows you to focus on distinct product/process phases:

- in advance of the creation and production process (so -called upstream). For instance, if the intention is to

use new materials with a certain amount of renewability, then early-stage evaluations of the different impacts of the two types of materials must be conducted.
- phases of product/service use and consumption (so -called core).
- phases downstream of the production process (so-called downstream): for instance, if the modifications designed with an eco-design perspective determine a different end-of-life phase in terms of potential environmental impacts, and therefore if the transition from a product "Standard" to a product AS A Service Saas is actually advantageous.

Depending on the project objective, LCIA is based on a variety of methodologies, including CML 2001, Eco-indicator 99, EDIP 2003, IMPACT 2002+, IMPACT world+, and ReCiPe. If the objective is limited to traditional environmental issues, such as climate change, approaches that identify environmental effects based on midpoint impact categories, such as CML 2001, may be used. IMPACT 2002+, IMPACT world+, and ReCiPe are indicated for presenting environmental harms to human health and ecosystem quality.

Overall, it is possible to infer that LCA may aid in promoting and enhancing sustainability since it helps identify environmental hotspots. However, there are still problematic restrictions. Diversity in system boundaries, FU, allocation techniques, database, and LCIA approach, for instance, might not only make it hard to compare the findings of different research, but can also result in an overestimation or underestimating of environmental energy-product systems and hence biased conclusions. Ignoring some data, such as data linked to land-use change in feedstock production or data connected to garbage collection, may also result in unknown outcomes and, as a consequence, in the formulation of flawed policies and choices. In the interpretation phase of LCA, studies done on energy-product systems strive to justify the manufacture and use of these goods, which may result in the development of inappropriate suggestions and strategies. Future research should concentrate on these limits in order to attain more sustainability.

Since the LCA technique is one of the foundations of the Life Cycle Thinking approach, it must always be noted that economic and social assessments should be undertaken concurrently with environmental evaluations.

The system of the three dimensions of sustainability (environmental, economic, and social) and the ways of synthesizing the findings are a relatively unexplored and underutilized field. The evaluation of the LCSA Life Cycle Sustainability Assessment, which combines the evaluations.

The use of LCA Life Cycle Assessment (Environmental), LCC Life Cycle Costing (economic), and S-LCA Social-LCA (social) is not as widespread as it should be, and the crucial point is the synthesis of the three aspects [24]. Moreover, the theme of the synthesis between different indicators is also a crucial aspect of the LCA itself: the results frequently exhibit opposite trends when compared to different impact indicators, making it difficult to make a decision because it is impossible to determine which indicator is the most important. For this reason, evaluations are often streamlined by selecting the "most relevant" signal according to political norms (choosing the GWP or PEI). In practice, it would be desirable to do various sorts of analysis, such as normalization and methodological passages offered by LCA standards as optional, to determine which indication is most important. Normalization enables a comparison of findings to overall effects on a national or European scale, highlighting which indicator is more significant in terms of repercussions [25]. This application is very essential because it enables each sector (industrial, energy, agro-food, construction, etc.) to determine which sorts of effects are meaningful, i.e., how much each sector contributes to each impact indicator. This might also assist policymakers in determining which issues need intervention and which effect indicators must be evaluated in LCA sector analyses.

Life cycle costing (LCC) is an economic method that calculates the total costs of a product, process, or activity discounted over its lifespan [26]. LCC is not related with environmental costs as se, but with expenses in general. A conventional LCC is an investment calculation that ranks many investment possibilities to assist choose the best one. There are several life cycle costing analysis techniques, but only two of them incorporate environmental costs: Life Cycle Cost Assessment and Full Cost Environmental Accounting. For further information on life cycle costing tools.

2.2.2 Energy analysis

The most common approach for determining the resource utilization efficiency (sustainability) of energy-product systems is based on energy analysis based on the first law of thermodynamics. Additionally, this research may be utilized to minimize energy consumption in energy and material conversion systems and enhance their design solutions [27]. Energy analysis helps prevent possibly erroneous findings that standard economic feasibility and environmental impact assessment approaches may provide. This study takes into account all energetic flows and material streams (input energy/material, output energy/material, and energy/material generation) associated with the creation of a product or service. Note that material streams are converted into energetic terms using the relevant conversion factors. Performing energy balances to identify waste energy sources and find a solution to recover them is a common component of this study. Some dimensionless (e.g., energy efficiency) or dimensioned (e.g., specific energy consumption) metrics are also developed to evaluate various energy-product systems from a sustainability standpoint. Numerous researchers are able to evaluate the sustainability of systems using energetic indices due to the simplicity and convenience of application of energy analysis.

Despite the widespread use of energy analysis in the published literature for the evaluation of the sustainability of energy-product processes, this technique has significant disadvantages that impede its practical use. According to the first rule of thermodynamics, energy cannot be created nor destroyed (conserved for all processes). Therefore, energy analysis cannot provide light on energy deterioration (irreversibility) inside a process. The energy value does not account for the utility or quality of different energy flows and material streams entering and exiting a system as product/waste streams. The attribute energy relies exclusively on the qualities of energy flows or material streams (independent of environmental properties, it cannot successfully connect planned systems to their surroundings) [28]. The efficiency ratings derived from energy analysis do not account for ideal behaviour and, as a result, cannot give more significant information on the performance evaluation. Energy analysis excludes economic, environmental, and social elements, resulting in possibly erroneous information on the sustainability of energy-product systems. Given the inherent limitations of energy analysis, energy-based indicators seem inadequate for evaluating the sustainability and effectiveness of energy and material conversion processes.

2.2.3 Input-Output energy analysis

The primary purpose of the input-output model is to analyse the direct and indirect supply-demand relationships that exist among the numerous industrial sectors that make up the economy. This analysis plays an important role in the calibration of the characteristics of the industrial level of the economic structure as well as the interaction of these characteristics with energy, mineral resources, emissions, and other environmental factors.

Input–Output Analysis of energy based on Leontief’s economic input–output matrix, which analyses the trade between energy flows based on the conservation of embodied energy [29]. This establishes that the amount of energy that is embodied in an industry’s output is equal to the amount of energy that is embodied in its input products, plus any external energy that is input to the industry. It is devised to take into consideration the circulation of energy across the economy. The following are the typical applications that call for its use: 1) the direct and indirect energy needs of the economy, often known as the net energy analysis; 2) the energy cost of products and services for final demands; 3) the influence of alternative energy conversion technologies; and 4) changes in energy usage via the process of structural decomposition.

It has the same objective as LCA: to quantify the direct or indirect environmental consequences of a product or service, including its manufacture (but not always including the use or end-of-life phases).

When analysing the findings of input-output energy analysis, it is important to keep in mind the following assumptions:

a) It does not depict clearly the main, ultimate, useful, and service levels of energy use. These models solely account for the fundamental or ultimate level (the selection between them depends on the aim of the study).

b) The total energy need matrices are incapable of providing distinct information about energy conversion activities in the economy. These matrices combine all conversion efficiencies and energy usage efficiencies; hence, the majority of economic energy performance metrics cannot be identified. Consequently, they oversimplify the methods by which the economy uses energy.

c) The level of specificity with which the energy sector’s industries are represented is crucial to the quality of analysis of energy flows via input-output. In this regard, the energy sector is substantially aggregated in the majority of public input-output datasets.

d) Not all items in a particular sector have the same emissions when this technique is used to attribute environmental concerns. A median is used. However, in terms of power production, the emissions associated with coal-based power generating are significantly different from those associated with solar power generation. A presumption is made that the global mix is being used, but in reality just one source may be available for power production.

2.2.4 Exergy analysis

Exergy is the theoretical maximum amount of useful work that can be extracted from a system when it is brought to equilibrium via reversible processes [30]. According to the studies [31, 32], the application of exergy in manufacturing systems allows for the detection and evaluation of thermodynamic flaws as well as the identification of possibilities for improvement, because exergy, unlike energy value, takes into consideration both the quality and quantity of energy and material fluxes. Indeed, the exergy idea consolidates the first and second principles of thermodynamics in a systematic manner to address the shortcomings of energy analysis. This thermodynamic characteristic may objectively evaluate all energy flows and material streams based on the unit of energy without the requirement for expert assessment. The primary result of exergy analysis, irreversibility or exergy destruction, may provide essential information on the locations, causes, and sources of deviations from the ideal in a system. Notably, exergy depletion is directly related to economic loss and resource depletion. Notable correlation exists between exergy destruction and greenhouse gas emissions [33].

Figure 4 depicts a generic open system in equilibrium, the state of which is characterized by specific values of its physical and chemical attributes. The system interacts with its reference environment, which has certain physical and chemical features.

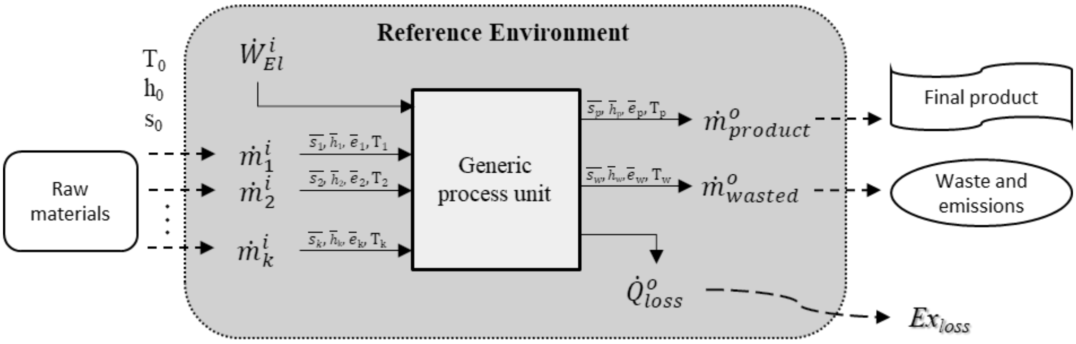

Figure 4. Generic open system control volume [34]

The foundation of EA is stated by the first and second principles of thermodynamics. The first law deals with energy conservation, while the second deals with the quality of energy and materials. These thermodynamic rules underlying the EA are critical for tracing the set of parameters that must be measured and monitored throughout the process, as well as the variables that may be derived. According to Szargut's research [35], reference flows can be uniquely recognized in the balancing equations of mass, energy, and then exergy.

Given the triple approach to sustainability (TBL), even exergetic analysis bridges well this concept; in fact, reference [36] graphically depicted some conceivable interdependencies among exergy, economics, and environment already in 2012.

The following are the primary benefits of using exergetic analysis: a) the ability to compare different energy systems, such as direct cycles and inverse cycles; and b) the possibility of locating and quantifying the real sources of system inefficiency, giving helpful information, and properly resolving the resource expenditure to improve the system's effectiveness. However exergy, like other sustainability evaluation methodologies, has several drawbacks. Reference environment parameters (temperature, pressure, and chemical composition) may alter exergy-based assessments [37]. The cut-off criteria for energy and material conversion system boundaries affect exergy-based analysis accuracy. Different papers describe exergetic markers, making it difficult or impossible to compare study findings.

Exergy-based assessments for energy-product system sustainability evaluation have advanced, however they may be improved. Exergy-based assessments, especially those with economic and environmental restrictions, may exceed other sustainability assessment techniques in accuracy and reliability.

Additionally, exergy analysis has been extensively used to assess and enhance energy-product processing systems for sustainability, efficiency, and productivity due to its unique conceptual properties. The exergy concept's capacity to incorporate economic and environmental restrictions is crucial [38]. These combined methodologies, named exergoeconomic and exergoenvironmental, may discover, measure, and analyse energy-product system component-level economic losses and environmental costs. By accounting for thermodynamic losses, exergoeconomic analysis may improve technoeconomic analysis. By distributing component-level environmental loads and quantifying intermediate product environmental burdens, the exergoenvironmental technique may consistently overcome LCA analysis' shortcomings in energy-product system sustainability evaluation. This combination of exergy, economy, and environment can accurately analyse the thermodynamic productivity, economic feasibility, environmental safety, and sustainability of energy and material conversion processes. This combination may help interpret exergoeconomic and exergoenvironmental data and discover a global optimum point. Advanced analysis improves exergy-based findings. Advanced analysis may identify energy-product processing unit interactions and assess the preventable fraction of thermodynamic inefficiencies, economic losses, and environmental costs. Advanced exergy-based studies may divide exergy destruction and component-related costs and environmental consequences into avoidable/unavoidable endogenous/exogenous portions. Extended exergy accounting [39], is an approach to performing design and configuration optimization of a system evaluating overall resource consumption because it enriches the energy and matter flow with some other "externalities" [40] as capital flow, environmental damage remediation costs flow, and labour flow, always in exergetic terms. Exergy can be combined with economic and ecological concepts, such as cumulative exergy consumption [41], thermo-ecological cost [42], and thermoeconomics [43].

However, integrated exergy-based strategies for detecting and measuring economic and environmental indicators are arbitrary, imprecise, and fraught with uncertainty. The precision and dependability of these procedures must be enhanced via the development of economic accounting and environmental impact assessment techniques. The exergy idea has its own shortcomings, which severely impact the quality of findings generated by exergy-based integrated approaches. In addition, some theoretical assumptions and simplifications in integrated exergy-based techniques may impact their outcomes' dependability and precision. Future research should concentrate on addressing these difficulties using cutting-edge scientific methodologies.

2.2.5 Material-flow analysis

Material Flow Analysis (MFA), which seeks to quantify the material streams and reserves of a certain substance in the anthroposphere, is a well-established tool for evaluating resource-use efficiency.

MFA defines a system based on the input and output physical fluxes of materials in space and time [44].

MFA begins with the establishment of system boundaries. Then, all important system operations and flows are modeled. A process might include transformation, transport, or storage.

This analysis takes into account all the material flows associated with a specific product or service, including the so-called ecological rucksack. The ecological rucksack represents the actual material intensity of a given product and consists of all the materials required for the entire production process minus the actual weight of the product. The analysis allows for the identification of the source of the environmental impact and, consequently, the direction in which the environmental burden can be reduced. It could be used to analyze a product's life cycle, but it is typically applied to industries [45]. Applied to a product's life cycle, it can be used to support the Life Cycle Inventory (LCI) component of life cycle assessment (LCA). MFA allows for careful observation of mass balances, but MFA indicators are restricted to a material flow basis. However, when LCA is used in conjunction with additional indicators, the scope is typically limited to environmental implications.

2.2.6 Ecological Footprint

The Ecological Footprint [46] is an accounting technique that calculates the resource consumption and waste absorption needs of a particular population or economy in terms of an equivalent geographical area. The calculation of the Ecological Footprint involves many steps. The yearly consumption of food, housing, transportation, consumer goods and services is calculated for the typical individual. Next, the land area required for the production and environmental effect of each of the consumption items is computed, and then the required land areas are added together. The outcome is a land area per person for yearly consumption of goods and services. It is stated in terms of global hectares (gha) or planets. Numerous nations and areas have implemented the Ecological Footprint. Changes at the city or urban-region level, as well as aggregated indices, have also been analysed. It has mostly been used to measure sustainability at the national level.

2.2.7 Strategic Environmental Assessment and Sustainability Impact Assessment

Impact Assessment has been used to evaluate the potential environmental implications of significant development projects ever since it was developed in the 1960s. This is done in an effort to lessen the detrimental effects of these projects. The Environmental Impact Assessment (EIA) gave rise to the Strategic Environmental Assessment (SEA) in the 1990s. SEA is a method that examines the environmental repercussions that may result from strategic actions. The difference between SEA and EIA can be broken down into two key categories. SEA is required to be carried out before EIA, and it is carried out in circumstances in which there is less knowledge, more uncertainty, and less concreteness, which is frequently the case with political choices. In contrast, EIA is carried out in the definitive circumstances of a particular project. In spite of these differences, the two methods have a great deal in common in terms of ideas and procedures. Participation from the general public is an essential component of both the EIA and the SEA processes, and representatives of a wide range of interests should be given the opportunity to express their opinions concerning the recommendations.

Evaluation of the Impact on Sustainability (SIA). The goal is to move away from sectoral evaluations, which are frequently incomplete, and toward integrated evaluations that take into account environmental, economic, and social criteria. This new tool has been developed with the intention of improving the ability to recognize "the anticipated positive and negative implications of proposed policy initiatives, thereby enabling more informed political judgements about the proposal and the identification of trade-offs in the pursuit of conflicting goals". An evaluation of the impact on sustainability was carried out for the first time in 2003 and is now a requirement for all of the major activities carried out by the Commission. During the course of their investigation into the preliminary SIAs, Wilkinson et al. [47] came to the conclusion that not a single assessment had adhered strictly to the standards established by the Commission. This study also discovered that the range of consequences that were measured was limited, and that environmental and social factors continue to receive less attention than economic ones. It is anticipated that there will be additional adjustments and development of guidelines in the near future.

2.2.8 Techno-economic analysis

It is common practice to conduct a techno-economic analysis in order to evaluate a process in terms of both its technical and economic viability (performance indices, costs, and revenues). This potentially useful framework could be applied to the analysis of costs and benefits, as well as the actual implementation of energy and product systems in the real world. The purpose of conducting a techno-economic analysis is to determine if there is a correlation between the technical characteristics of energy or product systems and economic indicators [48]. The payback time analysis, the return-on-investment analysis, and the cash flow analysis are typically the three economic methods that are utilized in techno-economic analyses of energy and material conversion systems. Cash flow analysis using several indices (such as minimum selling price, internal rate of return, and net present value) is the most common method for evaluating the economic performance of energy or product operations. Other methods include net present value analysis and internal rate of return analysis. Both the net present value method and the internal rate of return method are utilized in situations where the selling price of the product is either known or can be anticipated. Using the minimal selling price method involves methodically determining the price at which a product is offered for sale. Capital expenditure (CAPEX), which refers to the cost of equipment, piping, warehouse, and service facility, and operational expenditures (OPEX), which refers to the cost of transportation, raw material cost, utilities, maintenance costs, labour and overhead, and taxes. In general, the methodology for cost estimation relies on these two major items. The annual cash flow takes into account all production costs (the total of CAPEX and OPEX) as well as project revenues (for example, annual product sales) over the course of a project's lifetime, which is typically between 20 and 30 years. It is essential to reduce CAPEX and OPEX while simultaneously raising the production volume of bioenergy carriers and bioproduct streams in order to achieve the highest possible level of profitability from the project. As a result of its capacity to evaluate energy and product systems from both a technical and an economic perspective, techno-economic analysis has emerged as an interesting method for academics to use in assessing the performance of sustainable sustainability of energy and product systems [49]. In addition, this prospective strategy may involve conducting an in-depth analysis of the benefits, dangers, and unknowns associated with the process. In contrast to LCA and energy analysis, this study has the ability to accurately determine the economic viability of energy projects, as well as their short-term and long-term economic success. This approach to determining whether or not something is sustainable does have some drawbacks, despite the fact that it has the potentially very exciting benefit of being techno-economic. For instance, the findings of technoeconomic analysis may be misleading due to the assumptions, simplifications, and approximations that are frequently used in the modelling of the processes. This is because the modelling of the processes frequently relies on approximations, simplifications, and assumptions. In order to improve the accuracy and dependability of techno-economic analyses, it is helpful to provide specific details regarding the thermodynamics, kinetics, and transport phenomena of processing units.

This strategy pays no attention to the thermodynamics or environmental impacts of the energy or product systems it examines. It may be possible to find a solution to this issue by combining the LCA and exergy methodologies with techno-economic analysis. The application of techno-economic analysis to determine whether or not a project will be profitable is extremely dependent on the scope of the project. As a result, studies focusing on sensitivity and uncertainty should be carried out in order to improve the transparency and trustworthiness of the results of technological and economic research.

2.2.9 Hybrid approaches

Each approach for assessing sustainability has its own advantages and disadvantages; thus, the optimal method relies on the research purpose, process complexity, and required degree of accuracy. It is noteworthy to note that integrated solutions may also remove the bulk of the disadvantages associated with singular approaches.

Throughout the multidimensional notion of sustainable development, a range of assessment methodologies are utilized alone or in conjunction with one another to gather precise information about a manufacturing process in terms of productivity, performance, quality, and reversibility. Another feasible alternative for blending bottom-up and top-down assessment techniques is hybrid modelling.

Due to the scientific rigor of the exergy idea and the comprehensiveness of the information included in an LCA, combined LCA+exergy-based techniques have gained substantial interest from the scientific community. LCA+EA-based assessments, especially those augmented by economic and environmental variables, may provide more useful indicators than conventional sustainability assessment methodologies. See the studies [20, 21] for two systematic reviews of the potential additions between LCA and Exergy, the derived techniques and synthetic indicators. For completeness, the following methods must be mentioned: the Cumulative Exergy Demand (CExD) by Bösch et al. [50], Exergetic Life Cycle Assessment (ELCA) and Zero-Exergy Emission ELCA (Zero-ELCA) methods were developed by the Cornelissen [51] the Emergy Based-LCA, and it is formally provided by Reza et al. [52], who say that Emergy is a beneficial supplemental tool to LCA rather than an alternative technique, the Life Cycle Exergy Analysis (LCEA) by Wall and Gong [53], the Hybrid Exergy-based Input-Output Analysis (H-ExIO), the studie of Rocco [54] and the most integrated method Thermodynamically Based-Life Cycle Analysis [55].

2.2.10 Multi-criteria analysis

Sustainability is characterized by a dynamic multidimensionality, and it does not seem that any single solution is capable of addressing its whole complexity. Multi-Criteria Analysis (MCA) is used in instances where competing evaluation criteria are comprised of many and complex indices and indicators. MCA sets basic goals or objectives and then attempts to discover the trade-offs between them; the ultimate purpose is to determine the best strategy. This methodology has the benefit of combining both qualitative and quantitative data [56]. With the multi-criteria assessment technique provided in the previous sections, the performance of an energy conversion system can be evaluated from several perspectives, and the available solutions for meeting energy demands may be compared from multiple perspectives. It is recommended that such an approach be used to supplement the conventional energetic, exergetic, economic, or thermo-economic study. Even though social factors were discussed in the previous section, insufficient data prevented the inclusion of social indicators in this study.

MCA has been used in the selection of the most effective alternative energy management strategies and the formulation of energy and environmental policy.

2.2.11 Other tools

Various methodologies and procedures have been evaluated and used to test cases in the literature to disclose the sustainability needs. In this post, we have selected the most often used terms that, to date, have room for refinement and optimization, as well as applications in numerous sectors. See Sarıkay et al. [57] for more ideas and methodologies not covered in this article. These authors provide and analyze many methods, models, and review papers. Also St Flour and Bokhoree [58], whose work seeks to identify the many sustainability evaluation methodologies at the national level, taking environmental, economic, and social elements into account. Chang et al. [59] have categorized thirty different techniques. Moreover, sustainability indicators and composite indexes are increasingly recognized as a useful tool for policy making and public communication in conveying information on country and corporate performance in areas such as the environment, economy, society, and technological advancement; a comprehensive review of these has been conducted in the studies [60, 61]. The critical review of Walzberg et al. [62] defines methodologies based on six criteria: temporal resolution, scope, data needs, data granularity, the ability to measure material efficiency potentials, and sustainability completeness. Another fascinating endeavour is that of Turkson et al. [63], who cluster policy sustainability evaluation methodologies.

3. Sustainability Accreditation and Communication Tools

These tools come into play once a circular economy strategy is adopted. Obtaining labels and official certifications signifies the ability to transparently and consistently spread the culture of a good practice to the outside world. Receiving and communicating an accreditation of a receipt certification - national or international - represents a plus of recognition towards the entire market (public, private, B2B and B2C) and enables you to access tenders or obtain rewarding scores in this regard [64].

Obtaining a label, certification, or sustainability label is the appropriate external evidence of one’s own efforts and concrete actions along a business circularity path [65].

Utilizing them as resources that are frequently requested by the group of which your company is a part, or by stakeholders and customers, could be a wise strategic decision.

In actuality, these two documents are required by Legislative Decree 254/2016, which implements EU Directive 2014/95 [66]. Within the matrix of UNI ISO standards and official programs, in particular two standards that allow to determine how much the carbon footprint of a product, organization, or individual has been reduced. In addition, the company may request the registered trademark of Carbon Footprint by registering with the Italian Program Operator Carbon Footprint Italy for the release of a registered trademark.

Registration for these portals was created with the intention of conveying solidity and credibility to those who implement it, thereby avoiding the risk of conveying false information and expiring in Greenwashing; ISO 14025, if a company desires to develop a genuine environmental product declaration (similar to EMAS as an approach) with an EPD environmental declaration. It is a type of certification based on the LCA analysis of an infrastructure, a product, or a company service, within which circularity-related indicators can be included. Specifically, by indicating the amount of second-generation renewable material present in a product and whether or not the company has embarked on a circular economy path in accordance with the BS 8001 guidelines.

The primary labels and certifications, but not UNI ISO Matrix, of national and international significance and credibility are as follows:

3.1 Certified Carbon Neutral

This accreditation is designed to make enterprises carbon neutral. The protocol is a framework that provides a number of initiatives that may be utilized to decrease emissions via different means, such as the adoption of more energy-efficient office equipment.

Businesses that achieve carbon neutrality should enjoy the distinction of being climate leaders, lower expenses associated with energy efficiency and less travel, and a reduced chance of being taxed on their carbon footprint size.

To achieve Certified Carbon Neutral accreditation from Natural Capital Partners, must evaluate its carbon footprint and take steps to decrease it to zero via a mix of internal efficiency measures and external emission reduction efforts. The Carbon Neutral Protocol is a 2002 framework that organizations may use to become carbon neutral with the assistance of outside consultants [67]. The procedure involves the following steps: define what emissions are included for each Carbon Neutral (Company, Product, Department); external evaluators are brought in to measure emissions, which have been categorized; target company is dedicated to achieving carbon neutrality from its current level; reduce conduct (such as the implementation of energy efficiency measures, the use of renewable energy, the reduction of business travel, etc.); and communicate the progress towards carbon neutrality at each phase to the principal parties involved.

3.2 Degree of Circularity – BS8001

Calculate the degree to which companies adhere to the principles outlined in the British standard BS8001:2017 [68]. This is the standard that identifies the six factors that can lead to a reduction in the application of the idea of a circular economy in actual business settings. The tool evaluates the efficiency of business procedures, which makes it possible to acquire a particular indicator that attests to the organization's dedication to incorporating the circular economy. In addition to this, it identifies areas in which improvements can be made and boosts your reputation by conveying your potential in an objective manner to external stakeholders like investors and partners. The final report can be incorporated into a Sustainability Report, and an analysis of the context can be added to it in accordance with ISO 14001:2015.

3.3 Energy Star

Developed in 1992 by the Environmental Protection Agency (EPA) in the United States, the certification helps companies and people save money and preserve the environment via greater energy efficiency. Products will be lab-tested by an independent lab certified by the US EPA, and certification will be issued if they meet the EPA's energy efficiency requirements [69]. Energy Star certified items are more energy-efficient; thus, they contribute less to the emissions and global warming generated by electricity production and the various detrimental blow impacts, including climate change, droughts, wildfires, floods, and habitat loss. Energy Star-certified items are identical to other comparable products, except they are more energy efficient. To quantify the energy consumption of a product, rigorous scientific tests are conducted. It is evaluated yearly. Energy-efficient products are better for the environment, thus obtaining this accreditation is a method for companies to become more sustainable. Reduced energy consumption reduces environmental impact since, by definition, the items will produce less emissions than equivalent non-energy star certified products.

This accreditation is well-known only in North America, and the site provides a directory for users to purchase for energy star-certified items. Notably, items sold outside the United States and Canada also have this certification, indicating that it is worldwide recognized.

3.4 Cradle-to-Cradle

Very well-known on the British and American markets, taking into account not only the environmental elements of sustainability, but also the ethical, social, and circularity concerns. The accreditation evaluates the circularity, sustainability, and safety of the product's materials. There are five areas related to the product's sustainability, and each is graded on a scale from Basic to Platinum [70].

Material health (Can the materials used adversely impact the environment or the health of the users? For example, the usage of the dangerous metal lead). Product circularity (Can the product contribute to the circular economy by using materials and components that can be reused, mended, recycled, etc. in order to minimize the use of virgin raw materials? Clean air and climate protection (Does the product's production process prevent or minimize emissions and use renewable sources of energy as opposed to fossil fuels?) Water & Soil Stewardship (Does the product's production use a great deal of water and discharge polluted wastewater?) Social justice (Does the corporation pay a fair salary, refrain from violating human rights, and support an equitable society?) In order to get certification, impartial Cradle to Cradle inspectors review and rate each case.

Acquiring this accreditation does not restrict a product to using solely materials and components with zero environmental effect. After certification is attained, it is anticipated that the organization would engage in a process of continuous improvement in which it minimizes the bad in favour of the good over time.

Cradle-to-cradle is an elitist name, since it needs minimally severe requirements that, if not met in all of the factors examined by the organization, render its attainment impossible.

3.5 Green Touch – ISO26000

The certification that was designed specifically for Circularity by the organization RINA that is responsible for certifying businesses to the ISO 26000 standard for ensuring that their business operations are sustainable. Your organization's image and credibility will dramatically improve if it pursues and achieves Green Touch accreditation; as a result, it will become known around the globe as a socially responsible business [71]. There are a variety of advantages that certified businesses are able to obtain, some of which are listed below:

- Improved performance
- Improved partnerships
- The formulation of a strategy to deal with environmentally responsible investments
- An enhanced grade with regard to finances
- A growing reputation.

3.6 Remade in Italy®

It is a national scheme to certify the use of reuse/recovery material in products: numerous international relations have established that the current economic system - of the linear type (take, make, arrange) - is no longer sustainable and, if not altered, will result in the depletion of natural resources.

In this context, the concept of recycling is fundamental: the challenge and goal of the coming years is to give waste and by-products new life by reusing them in the production cycle. This certification focuses on traceability, or the evidence of the amount of reused/recycled material present in the artifact (finished or semi-finished) via a traceability scheme of the materials used to make it. Remade in Italy® is the first environmental certification of product under accreditation, developed in the context of the homonymous association, that allows a company to declare the percentage of recycled material (or by-products) within a Material, semi-finished or finished product, of any type (also composed of different materials) and belonging to the supply chain. It stems from the desire to transfer the high value of "made in Italy" to recycled products [72].

Possession of the Remade in Italy® certification confers tangible benefits on the company, as it is an increasingly prevalent material/product compliance requirement within the CAM. In addition, Remade in Italy® certification can provide access to incentives, tax relief for certified products (such as plastic tax), and reward factors within public calls.

Remade in Italy® is a pattern that straddles the line between a product label and a system, as it also incorporates a procedure to be followed.

The Remade in Italy® certification is valid and must undergo at least an annual review. The certification body's inspection includes not only a review of the pertinent documentation, but also a site visit to examine the company's materials, products, and production process.

3.7 UL ECOLOGO®

Products and services that have been awarded certification have been demonstrated to have a lower environmental impact. ECOLOGO® Certifications are voluntary, multi-attribute, life cycle-based environmental certifications that signify a product's conformity with stringent, third-party environmental requirements [73].

These certifications are awarded on the basis of a product's environmental impact throughout its entire life cycle.

These standards establish measurements for a wide variety of criteria that may or may not fall under any or all of the following categories: materials, energy, manufacturing and operations, health and the environment, product performance and usage, and product stewardship and innovation.

The ECOLOGO® Certification program is recognized by Amazon's Climate Pledge Friendly Program in addition to third-party certification that your products satisfy high environmental criteria.

4. Conclusions

It can be asserted with absolute certainty that LCA is one of the most effective and widely used tools for environmental sustainability.

The assessment of sustainability focuses on strategic, programmatic, and conceptual activities. These include legislative goals and legislative drafts (strategies), ideas, programs, and plans. It is meant to assist the political process in ensuring that all three components of sustainability are considered.

Decision-making for sustainable development needs scientific assistance in the form of (a) predicting the potential effects of management alternatives and (b) developing enhanced management solutions. Ex-ante impact assessment combines scenarios of future trends with different management alternatives, evaluates environmental, social, and economic implications using indicators, and performs an integrated valuation and trade-off analysis against set development objectives.

The most current findings also support the theory that biodiversity loss and climate change are responsible for the recent increase in zoonotic illnesses, including Coronavirus. All of these results emphasize the necessity of decarbonizing the global economy and reducing global temperature rises to far below 1.5 degrees Celsius. It is commonly considered that a rapid yet successful transition from fossil-based energy and product production systems to energy-product systems provide a chance to achieve the aforementioned goals. Therefore, it is essential to utilize advanced sustainability assessment tools, such as techno-economic analysis, LCA, energy analysis, emergy analysis, exergy analysis, and the combination of these techniques, such as exergoenvironmental and exergoeconomic analyses, to determine the overall sustainability of these systems and to provide solutions to mitigate the environmental hot spots and energy sinks. Overall, it can be stated that despite the promises represented by these tools, they cannot be seen as complete solutions for addressing all the challenges associated in energy-product systems, and integration of various tools may produce more dependable and accurate results than individual techniques.

In order to answer the question posed in the introduction, three crucial factors must be considered: 1) whether the tools are able to integrate with the nature-social system; 2) in the defining of spatial elements, if the tools are able to assess multiple stairways or spatial levels; and 3) if the tools are able to handle both short-term and long-term viewpoints.

There is still a heavy emphasis on environmental characteristics, especially among product-related evaluation techniques, while, with the exception of LCC, social and/or economic considerations are often disregarded. Even while certain types of tools have transitioned to more integrated techniques, they are not widely used. There is still a paradox in the future development of methods for assessing sustainability. On the one hand, there is a desire for methodologies with more specific assessment performance, which includes case- and location-specificity. Concurrently, there is a desire for tools that are more inclusive in order to make them available to a large user base in a variety of case scenarios. Additionally, more standardized instruments that provide more clear outcomes are required.

The contribution emphasizes that the current trend to provide user-friendly software to practitioners for the evaluation of sustainability impacts (bottom-up approach) must be supported by regulatory revisions (top-down approach). The original principles of the circular economy, as formulated in the 1960s by Walter Stahel, are not always implemented; Circular economy is often trivially interpreted as a recycling of waste and strategies to solve the waste problem, rather than having a broader perspective on the efficient use of resources. In order to activate a circular and sustainable economy, it is necessary to evaluate the actual Life Cycle sustainability of circularity on a regular basis. Incorporating environmental sustainability assessment tools, such as the life cycle assessment, throughout the various phases of the building process is, therefore, more important than ever. To implement the transition to a circular and sustainable building process, the participation of political managers, who must modify the legislative framework, and all construction industry actors, who must modify their organizational and business models, is essential.

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