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Review

Exergetic Life Cycle Assessment: A Review

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Abstract: Exergy is important and relevant in many areas of study such as Life Cycle Assessment (LCA), sustainability, energy systems, and the built environment. With the growing interest in the study of LCA due to the awareness of global environmental impacts, studies have been conducted on exergetic life cycle assessment for resource accounting. The aim of this paper is to review existing studies on exergetic life cycle assessment to investigate the state-of-the-art and identify the benefits and opportunity for improvement. The methodology used entailed an in-depth literature review, which involved an analysis of journal articles collected through a search of databases such as Web of Science Core Collection, Scopus, and Google Scholar. The selected articles were reviewed and analyzed, and the findings are presented in this paper. The following key conclusions were reached: (a) exergy-based methods provide an improved measure of sustainability, (b) there is an opportunity for a more comprehensive approach to exergetic life cycle assessment that includes life cycle emission, (c) a new terminology is required to describe the combination of exergy of life cycle resource use and exergy of life cycle emissions, and (d) improved exergetic life cycle assessment has the potential to solve characterization and valuation problems in the LCA methodology.

Keywords: exergy; life cycle assessment; sustainability; LCA; review

1. Introduction

Exergy analysis is useful to rationally and meaningfully assess and compare processes and systems [1]. These capabilities are reflected in the two key features of exergy analysis: (a) efficiency to provide a real evaluation of how actual performance tends to or deviates from the ideal, and (b) exergy loss to identify more clearly than energy analysis the types, causes, and locations of thermodynamic losses [1]. Exergy efficiency was included in the 2001 Swiss canton of Geneva as a new parameter for characterizing the energy performance of buildings [2]. As exergy describes the work potential of energy, exergy-based analysis is used in system design or process optimization [3]. Exergy is used for assessment, design, analysis, and improvement of systems; an example is an application of exergy analysis to integrated energy systems such as biomass, geothermal, and steam power systems [1]. Table 1 summarizes the importance of exergy, classified by topic. In life cycle analysis, exergy-based approach is relevant to quantify energy and material resources, determine consumption and depletion of natural resources, and as an indicator of resource utilization efficiency [4–9]. In production processes, exergy method is used to keep inventory of exergy losses and efficiencies on a single scale [10–12]. Exergy has been used in technological processes to achieve sustainability to reflect extent of use of renewable resources, to account for technological efficiency and conversion of waste products into neutral or harmless products [13]. Exergy is used to deepen the understanding of the built environment to develop low-exergy systems for the future [14,15] and for a scientifically based sustainable building assessment tool [16,17]. Exergy analysis optimizes the efficiencies of energy systems [18–21] and in this way, reduces global impacts [22,23].

Table 1. Summary of the importance of exergy classified by topic area.

Topic	Importance	References
Life cycle analysis	Exergy enables the analysis of cumulative consumption of resources	[5,6]
	Exergetic LCA is a more appropriate approach to quantify the environmental problem of the depletion of natural resources	[4,6]
	Exergy provides additional indicator for LCA, energy efficiency, and resource quality need	[7–9]
Production processes	Exergy analysis accounts for exergy losses and efficiencies and thus provides a more accurate inventory	[10]
	Exergy quantifies various results of manufacture, use and disposal of goods, and services on a single scale—exergy loss	[11,12]
Technological sustainability	Exergy enables both qualitative and quantitative evaluations of resource consumptions	[5,13]
Built environment	Exergy concept deepens the understanding of space heating and cooling to develop low-exergy systems for future buildings	[14,15]
Sustainability index	Exergy-based index overcomes the limitations of the subjectively defined weights used in other sustainability assessment tools	[16,17]
Energy systems	Exergy analysis evaluates the performance of energy systems to optimize their efficiencies	[18–21]
Global impacts	By improving the efficiency of a process, exergy analysis reduces global impacts related to the process	[22,23]

Although, most uses of exergy are in the area of metallurgical and chemical process analysis, thermal system design, and energy conversion system design [24], the use of exergy in life cycle analysis is currently emerging. The emergence of exergetic life cycle assessment is probably because of the importance of wholistic analysis of a system, a product or a process for resource accounting over a life span. Szargut et al. [25] first analyzed life cycle of a system based on exergy by developing the concept of cumulative exergy demand. Cornelissen and Hirs [4] further proposed the inclusion of the concept of exergy into Life Cycle Assessment (LCA) as exergetic life cycle assessment. They described exergetic life cycle assessment as a method to measure the depletion of natural resources in LCA and as a tool to evaluate the efficiency of resource use. There are also other studies on exergetic life cycle assessment [5,26–30]. The aim of this paper is to review existing studies on exergetic life cycle assessment to investigate the state-of-the-art and identify opportunities for improvement of the approach. Following the introduction, this paper describes exergy and exergy-based methods, introduces the use of exergy in LCA, analyzes studies on exergetic life cycle assessment, and provides discussion and conclusions from the findings.

2. Description of Exergy

2.1. Definition of Exergy

The capacity of doing work has been accepted as a measure of the quality of energy [31]. Energy quality in a system can be grouped into either available energy or unavailable energy. Exergy is a measure of the possible maximum useful work before a system reaches equilibrium with its environment [32]. Szargut [31] defined exergy as the work obtainable for a matter to be brought to a state of thermodynamic equilibrium with the common elements of the natural surroundings by mechanism of reversible processes, which involves interchange only with the elements of nature. According to Bejan et al. [33], exergy is available when an idealized system (called an environment) interacts to equilibrium with another system of interest, while heat transfer occurs only with the environment. The following can be deduced from these definitions:

- To calculate exergy, the idealized state is specified;
- Only common components such as atmosphere, hydrosphere, and lithosphere can be used as idealized systems because of thermodynamic disequilibrium in the surrounding nature;

- Being a measure of energy quality, exergy is used to investigate technological processes, in addition to analyze the processes of power plants and of other mechanical machines;
- Exergy losses occur from irreversible process, which either cause reduction of the useful results of the process or increase use of energy from whatever source of derivation.

The choice and definition of the reference environment or state is necessary for exergy analysis. This is because the sensitivity of the results to different choices of the reference state might vary with the operative conditions of the system analyzed [20]. Correspondingly, when the state is significantly different from that of the chosen base conditions, its flows are not overly sensitive to the definition of the reference environment. This is the case, for instance, in the analysis of power plants. In turn, when the properties are close to those of the base conditions, results from the analysis have great variations depending on the definition of the chosen base state. This is the case of the analysis of space heating and cooling in buildings.

2.2. Brief Historical Background on Exergy

The historical background on exergy can be traced to the first and second laws of thermodynamics. According to Szargut et al. [25], in the 1840s, James Joule proved that there was an exact numerical equivalence between work and heat (also known as the conservation of energy), in accordance with the first law of thermodynamics. While the second law was based on Carnot's experiments, which demonstrated that the limitations of heat-to-work conversion depend on the temperature at which the heat is available or the 'quality' of the heat. Consequently, the internal energy and entropy functions were defined, followed by the enthalpy, the Helmholtz function, and Gibbs Free Energy [25]. These functions increased the capacity to understand the effects of the laws and their use to effectively solve practical problems. According to Szargut et al. [25], exergy function is introduced to improve our comprehension of thermal and chemical processes by enabling the investigation of processes, whether complex or not, to determine the theoretically most efficient way by which that process could be performed within the environment.

2.3. Relationship between Exergy and Other Energy Qualities

The terms entropy, exergy, and emergy help to articulate the important qualities of energy [32]. While exergy depicts the amount of work a system can exert on its environment, unavailable energy, also known as entropy, cannot be converted into work. According to Shukuya and Hammache [34], exergy measures the potential of dispersion of energy and matter in their environment while entropy quantifies the state of dispersion or the extent of dispersion of the energy and matter (Figure 1). In other words, exergy is used within the process or system to produce entropy. The terms exergy and entropy generation minimization [35] are common in the second law of thermodynamics.

Exergy is related to emergy in that the latter reflects all the exergy retrieved and used from the original state to the present state of a process. Odum [36] defined emergy as: "the available energy of single kind previously used directly and indirectly to make a product. Its unit is the emjoule (ej)" Solar emjoules (sej) are the solar energy equivalents required directly or indirectly to make a product with energy content. Bastianoni et al. [37] stated that emergy can be expressed as a function of exergy, although the goals and boundaries of the reference state differ. While the former retraces the embodied solar energy in a product, the latter assesses the quantity of primary resources that goes into that product. In addition, in the former, the system comprises the whole biosphere, with solar energy as the basic input. In the latter, however, the analyst defines the control volume, according to the goal of the study [37]. Among the major energy qualities, exergy is preferred for this study because of its flexibility in the choice of primary resources for analysis, and its capability to quantify the potential of dispersion of energy and matter into the environment of study.

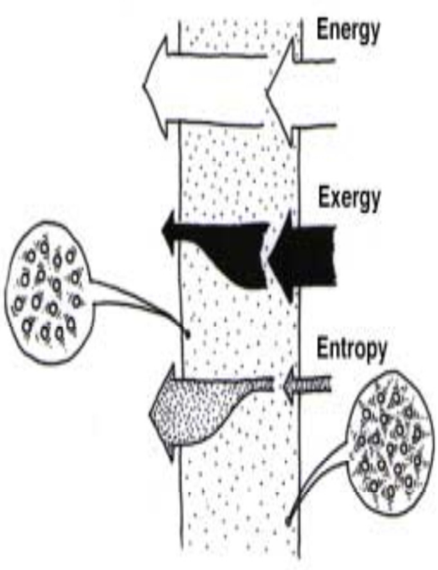

Figure 1. Illustration of energy, exergy, and entropy flow in and out of a building envelope system [34].

3. Exergy-Based Methods and Life Cycle Assessment

3.1. Exergy-Based Methods

Morosuk et al. [8] consider "exergy-based methods" as a general term that includes the conventional and advanced exergetic, exergoeconomic, and exergoenvironmental analyses and evaluations. Exergoeconomic analysis is a technique that combines both exergy and economic analyses to evaluate the costs of inefficiencies in a process, and it is referred to by other names such as thermoeconomics, second-law costing, and cost accounting [38]. Exergoenvironmental analysis combines exergy analysis and life cycle assessment, which is conducted at the component level, to identify the location, magnitude, and the causes of environmental impact [39,40]. Tsatsaronis and Morosuk [41] stated that exergy-based methods describe the situation, the quantity and the sources of inefficiencies, costs, and environmental impacts; and enable analysts to study the interconnections between them. In generic terms, the major exergy-based methods include the following:

3.1.1. Cumulative Exergy Demand (CExD)

The Cumulative Exergy Demand (CExD) was proposed by Szargut et al. [25]. It is defined as the sum of exergy of all supplies required to produce a product or provide a service [7]. CExD is related to Cumulative Energy Demand (CED), but unlike CED, it can account for materials and quality of energy inputs. In addition to this advantage, CExD analysis can provide insight into potential improvements and for comparing alternative products, by accounting for exergy use throughout the life cycle.

3.1.2. Thermo-Ecological Cost (TEC)

The Thermo-Ecological Cost (TEC) method accounts only for the cumulative consumption of non-renewable primary exergy resources. It is expressed in exergy units and not in monetary units. This method was developed with the premise that it is essential to determine and reduce the depletion of non-renewable natural materials in the field of ecological applications of exergy [42].

3.1.3. Cumulative Exergy Extraction from Natural Environment (CExENE)

The Cumulative Exergy Extraction from Natural Environment (CExENE) method is an extension of the boundaries of CExD to include land use. CExD accounts for energetic supplies and materials traditionally considered non-energetic such as mineral, water, and metal, but ignores land use. CED only accounts for materials, which may be used as energy carriers [43]. Therefore, CExENE is quantitatively the most comprehensive resource indicator of the three, because it evaluates energy carriers, non-energetic supplies, and land occupation. Conceptually and qualitatively, CExENE differs from CExD and therefore leads to a different evaluation. CExD measures the exergy that is transferred into the technological system from nature, while CExENE accounts for total exergy that is deprived of the natural system [43] which may or may not be transferred into the technological system.

3.1.4. Industrial/Ecological Cumulative Exergy Demand (ICExD/ECExD)

The Industrial/Ecological Cumulative Exergy Demand (ICExD/ECExD) method is an extension of the CExD method to emphasize on industrial and ecological processes, respectively [44,45]. ICExD reports the exergy of natural wealth consumed by each industrial sector both directly and indirectly, while ECExD reports the exergy used up in ecological systems to produce each natural wealth [46]. For a production chain, ECExD analysis improves on ICExD analysis by including exergy losses in the industrial as well as ecological stages [46]. This method defines the mathematical form of economic and ecological systems through fiscal and physical input-output tables. Like the economic input-output model, the main advantage of this method is probably the availability of the necessary macroeconomic data for each sector. However, there is lack of details of individual processes in these sectors, which can lead to aggregation error [46].

3.1.5. Extended Exergy Accounting (EExA)

As proposed by Sciubba [47], the Extended Exergy Accounting (EExA) method is used to compute a commodity value based on its resource equivalent value instead of its fiscal cost. This method is based on two essential assumptions: (a) that the cumulative exergy content of a product or service is the sum of the exergies of the product's constituents, in addition to a weighted sum of the exergies of the production process of the product, and (b) that non-energetic costs such as labor, capital, and environmental emissions can be reformulated in terms of exergy from global system balances. While (a) is a paraphrase of Szargut's CExD, (b) is the original contribution of EExA. A theoretical and practical advance in EExA can be found in Dai et al. [48].

3.1.6. Comparison of the Exergy-Based Methods

This section presents a comparison of the exergy-based methods. The comparison is based on deductions from the description of the exergy-based methods. Table 2 compares the identified exergy-based methods in terms of scope and limitations. The comparison was based on a desk study.

Table 2. Comparison of the exergy-based methods.

Exergy-Based Method	Scope	Limitations
Cumulative exergy demand	Measures energy quality, exergy losses of materials, and emissions	Limited to exergy losses of natural resource; excludes that of the ecological system
Thermo-ecological cost	Focus on cumulative consumption of non-renewable primary exergy resources	It does not include renewable primary exergy resources
Cumulative exergy extraction from natural environment	Measures quality of energetic and non-energetic resources, and land occupation	It does not track exergy transferred into the technological system
Industrial/ecological cumulative exergy demand	Focus on exergy losses in the industrial and ecological stages of a production chain	It is limited to production processes
Extended exergy accounting	Resource equivalent value of a commodity including labor, capital, and environmental emissions	It is intrinsically limited to time and region

While the scope column emphasizes the focus of each of the methods, the limitations column emphasizes their shortcomings.

According to Dewulf et al. [49], the CExD is by far the most applied method as a measure for environmental impacts. The limitation of CExD method, the exclusion of exergy losses in ecological system, is accommodated in ECExD method but the latter is limited to only production processes. On the other hand, although CExENE method appears to extend boundaries of CExD to include land use, the CExENE method is not designed to track exergy transferred into the technological system. An ideal exergy-method could be an extension of the CExD method to cover ecological systems.

3.2. *Life Cycle Assessment*

Life Cycle Assessment (LCA) is defined as the aggregation and approximation of inputted and outputted resources, and the potential environmental impacts of a product system, in addition to their processes and designs, over its life cycle [50,51]. This section will focus on the description of LCA methodology. A recent review of articles on "LCA of buildings" can be found in Nwodo and Anumba [52]. The methodology includes the goal and scope definitions, inventory analysis, impact assessment, and interpretation of results [50].

3.2.1. Goal and Scope Definition

The goal and scope definitions entail the aim of conducting the LCA study and expected application, the target audience, the results use, and the specification of system boundary and functional units [53]. During the scope definition process, the system boundary and functional units are determined, indicating the included and excluded processes and quantification of the product's function [53,54]. For example, the system boundary for LCA of a building may consist of either cradle-to-grave process (i.e., raw material production phase to end-of-life phase), cradle-to-gate process (i.e., raw material production phase to construction phase), or gate-to-gate process (i.e., within construction phase).

3.2.2. Life Cycle Inventory Analysis

The Life Cycle Inventory (LCI) is the calculation of the inputted and outputted resources such as energy, materials, carbon emissions, and wastes for each of the stages in the service life of a product [55]. An LCI analysis requires extensive non-duplicated data collection. Finnveden et al. [56] observed that setting up inventory data could be one of the most difficult stages of an LCA. According to ISO [50], the goal and scope definition of a study sets the plan for implementing the LCI phase. For example, with the specified system boundary, the data for each unit process are collected to be included in the inventory. The collected data are utilized to quantify the inputted and outputted resources of a unit process. The operational steps outlined in Figure 2 are performed when executing the plan for an LCI analysis, although some iterative steps are not shown [50]. Over the decades, several national and international databases have evolved, including Swedish SPINE@CPM database, the German ProBas database, the Japanese JEMAI database, the US NREL database, the Australian LCI database, the Swiss ecoinvent database, and the European Life Cycle Database [56].

3.2.3. Life Cycle Impact Assessment

Life Cycle Impact Assessment (LCIA) is the classification and characterization of the LCI results based on environmental impacts or human effects [53–55]. The main impact categories from these classification and characterization include human health impacts such as respiratory organics, respiratory inorganics, global warming potential, and climate change; ecosystem quality impacts such as eutrophication potential, acidification potential, and land use; and resources impacts such as energy and material or mineral use [57–60]. A simplified LCI model for a specific type LCA can be adapted from existing databases such as ecoinvent, Athena, Gabi, and OpenLCA, for calculating LCIA. Figure 3 illustrates the elements of an LCIA while Figure 4 illustrates a simple example of LCA calculation process [61].

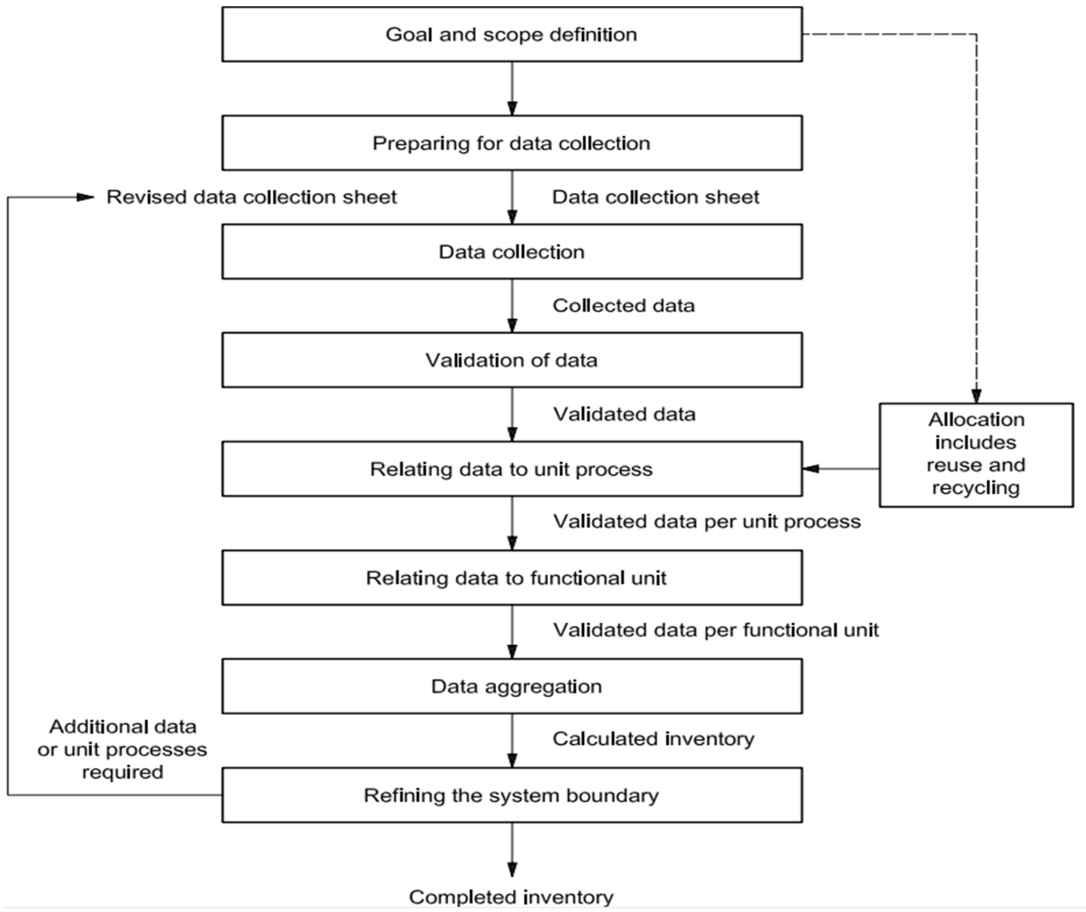

Figure 2. Simplified procedures for Life Cycle Assessment (LCA) inventory analysis [50].

3.2.4. Life Cycle Interpretation

The last process in standard LCA methodology is the interpretation of results. During the interpretation, LCA results are reported in such a way as to evaluate the need and opportunities to reduce the impact of a product on the environment [55]. The life cycle interpretation process comprises elements such as a highlight of essential issues based on LCI and LCIA results; an evaluation of comprehensiveness, sensitivity analysis, and consistency check; and conclusions, limitations, and recommendations. The findings of the interpretation can take the form of conclusions and recommendations to decision-makers, which is consistent with the goal and scope of the study [50]. The interpretation reflects the fact that the LCIA results are based on a relative approach, meaning they indicate likely environmental effects and do not claim to predict actual impacts. The interpretation framework may involve a review and revision of the scope of the LCA in an iterative way, as well as data quality in a manner that is consistent with the goal and scope definition [50]. Validation of results and sensitivity analysis may also be conducted during this process [54]. However, differences in the units of conventional LCA results make life cycle interpretation a difficult process. To avert this challenge, weighting, although optional, is usually employed, which introduces subjectivity to LCA results interpretation.

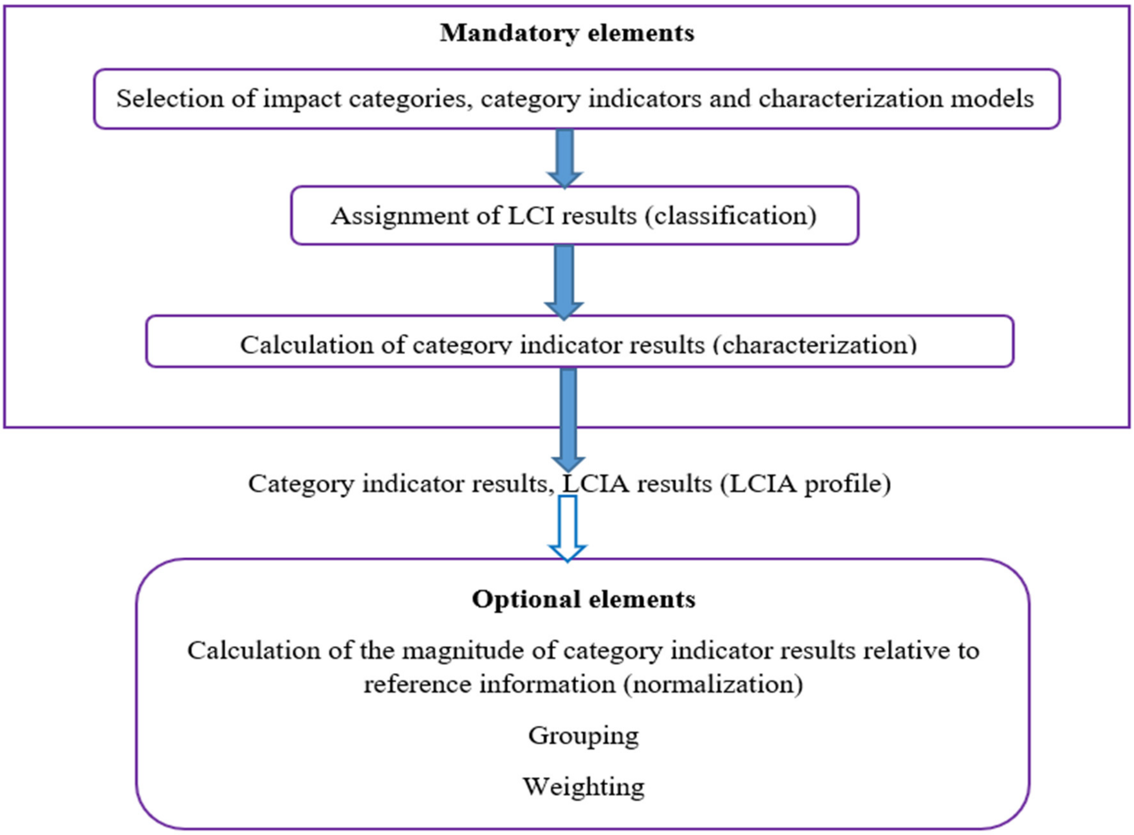

Figure 3. Illustration of the elements of a Life Cycle Impact Assessment (LCIA) [50].

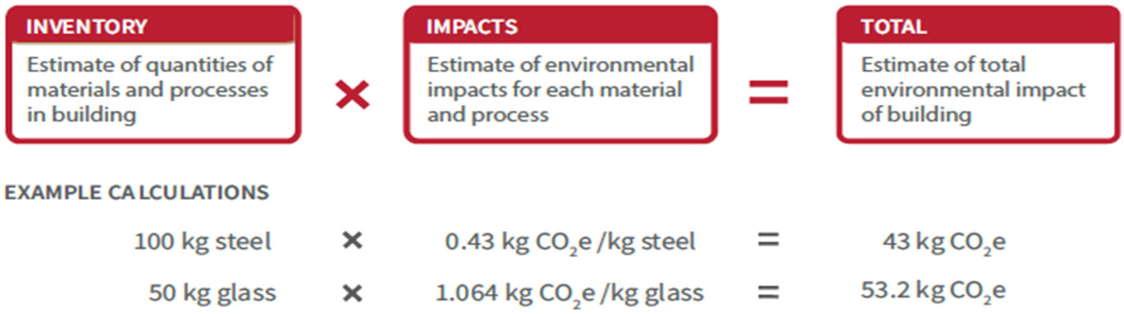

Figure 4. Simple example of LCA calculation process [61].

3.3. Use of Exergy-Based Method in Life Cycle Assessment

An exergy-based method is relevant in LCA since the latter also measures life cycle resource use and corresponding life cycle environmental impacts. De Meester et al. [5] opined that exergy enables the natural energy and material resources to be simultaneously quantified. According to Finnveden et al. [6], a thermodynamic approach based on exergy can be used to measure the use of resources in LCA and in other sustainability assessment methods because the approach can account for energy resources, metal ores, and other materials using their chemical exergies, which are expressed in the same unit. Exergy can complement LCA as an additional impact category indicator [14]. Cornelissen and Hirs [4] demonstrated that, besides LCA, life cycle exergy analysis has value in quantification of the environmental issue of natural resources being depleted.

As mentioned previously, the method of cumulative exergy demand can be used to express the summation of exergies of natural resources expended in all the stages of a technological system or process. Unlike cumulative energy demand, it also measures the chemical exergy of the non-energetic raw materials, which are extracted from the environment. As a result, the CExD method has the capacity to be used in LCA. Currently, CExD method is used in exergetic life cycle assessment for resource accounting by applying any of the following three techniques [25]:

- Process analysis which traces and evaluates exergy for the processes in the manufacturing of a product;
- Balance equations of cumulative exergy demand which utilizes a system of equations to express the CExD of products outcome as a summation of the cumulative exergy of the intermediate products and that of the natural resources extracted directly from the environment;
- Extension from cumulative energy consumption which calculates the CExD based on CED, which, in turn, can be obtained conveniently from commercial LCA tools.

The following section provides a review of previous studies on exergetic life cycle assessment.

4. A Review of Exergetic Life Cycle Assessment

4.1. Methodology for Articles Selection

The procedure involved an analysis of systematically selected articles to investigate the extent of exergy use in LCA and in other sustainability assessments. The reviewed articles were selected from a set of journal articles, which were published for a specified duration between 1990 and December 2018, in addition to recent articles (published since 2019 till date) collected from Google Scholar and/or Scopus. The Web of Science Core Collection is maintained by Clarivate Analytics, and it is a multiple-database platform that includes SCI-Expanded, SSCI, A&HCI, and ESCI. This platform holds more than 12,000 high-impact international journals and it is frequently used by researchers throughout the world [62]. A design was created to search for the articles. To retrieve the articles, three title "TI" record fields and one topic (TS) record field were created as follows:

- TI = "exergy life cycle assessment";
- TI = "exergetic life cycle assessment";
- TI = exerg* life cycle assessment;
- TS = "exerg* life cycle assessment".

The first record field found articles, which have in their titles, the precise phrase "exergy life cycle assessment". Similarly, the second query found articles in which the precise phrase "exergetic life cycle assessment" shows in the title. The third query has a broader scope and found articles that contain at least one of the inputted keyword terms in the title. The "exerg*" term found different forms of that term such as exergy and exergetic. Finally, the fourth record field has the broadest scope and found articles that contain at least one of the inputted keyword terms in the topic field. Table 3 presents an overview of the input data used to search and collect the articles from Web of Science Core Collection database. The combination of the search result sets using the "OR" Boolean operator amounted to 43 articles set for further sorting and manual check. During sorting, some of the articles were found to be irrelevant to the subject and removed, in addition to manually seek for and add relevant cross-referenced articles. A total of 25 articles were finally selected for the tabular analysis.

Table 3. Overview of input data for search of articles on exergy LCA.

Parameter	Setting
Keywords	Exergy, exergetic, exergies, life cycle assessment
Type	Article or review
Time Span	1990–2018 (December)
Citation Index	SCI-EXPANDED, SSCI, A&HCI, ESCI
Language	All languages

4.2. Analysis of the Selected Articles

The 25 articles that discussed the use of exergy or its method in LCA and in other sustainability assessments were analyzed. Table 4 shows the summary of the analysis in terms of aim, method, result/discussion, and relevant conclusion. The result/discussion and conclusion from the collected articles are not limited to those shown in Table 4. However, those presented are deemed the most pertinent to identify the state-of-the-art and relevance of exergy in life cycle analysis. The presented articles essentially investigated the application of exergy methods to sustainability assessments for which LCA is a state-of-the-art technique.

Table 4. Analysis of articles on use of exergy methods in sustainability assessments.

Article	Aim	Method	Result/Discussion	Conclusion
[24]	To develop a multi-objective optimization model for green building structure design	Case study; life cycle analysis methodology; expanded cumulative exergy consumption	The expanded cumulative exergy consumption method enabled LCA to be classified into one objective function	The multi-objective optimization model can be used to locate optimum or near optimum green building designs
[43]	To initiate an extensive resource-based life cycle impact assessment method based on exergy concept	Cumulative Exergy Extraction from the Natural Environment (CExENE)	Fossil resources and land use had high CExENE scores when applied to materials in ecoinvent database	Although they differ in concept, CExENE is like CExD but further includes land use
[7]	To apply CExD indicators to ecoinvent database	CExD; use of resources in the ecoinvent database	In comparison to CED, non-energy resources are likely weighted more strongly by the CExD method	CExD is a more in-depth indicator than CED
[42]	To optimize thermo-ecological cost of a solar collector	Thermo-ecological cost; case study	The depletion of non-renewable natural exergy resources is the objective function for thermo-ecological optimization	The formulated objective function could also be used in economic optimization by introducing purchase prices
[46]	To develop a thermodynamic input-output model of the 1997 U.S. economy	Thermodynamic Input-Output Analysis; Industrial (I)CExD; Ecological (E)CExD	ICExD/money and ECExD/money ratios are useful to perform thermodynamic LCA at economy and ecosystem scales	The model and data encourage the development of sustainable engineering
[5]	To quantify the embodied and operational energy and materials for a family dwelling in Belgium	Case study; CExD; use of resources in the ecoinvent database	Findings show that annual CExD is around 65 GJ_{exergy}/year, with a minimal reliance on the construction type	Reduction of heating requirements is necessary to make family dwellings less fossil resource dependent
[63]	Use of exergy LCA model to assess a 2 × 300 MW coal-fired power plant	Cumulative Exergy Demand (CExD)	Direct exergy (i.e., operational fuel consumption) input accounted for about 93% while indirect exergy input accounted for about 7%	Using exergy as the basic physical parameter made the assessment more objective and reasonable

Table 4. *Cont.*

Article	Aim	Method	Result/Discussion	Conclusion
[23]	Exergy analysis and LCA of solar heating and cooling systems in the building environment in Greece	Exergy model; LCA framework; case study	Solar cooling system has high environmental impacts because of the fan coil units and the cooling tower	The environmental impacts of the systems are significant only at the production phase of their life cycle
[64]	Proposes and implements a framework for exergy-based accounting for land as a natural resource in LCA	Framework; case studies	Site-dependent characterization factors allow for spatial differentiation in exergetic LCA	Using exergy, the framework was able to account for more comprehensive land resources
[48]	To present the sustainability perspective of ecological accounting based on extended exergy	Extended Exergy Accounting (EExA); case study	An extended exergy-based sustainability index system was established to assess the performance of flows in the system	EExA can be used to rate the sustainability level of a place or process
[65]	To determine the environmental effects of a heating system at various stages in building using exergy and LCA	Advanced exergo-environmental analysis	Environmental effects of the exogenous and preventable exergy destruction rates are low	Advanced exergo-environmental analysis provides information not included in the conventional exergy analysis
[66]	To determine the efficiencies of recovering resources from household waste based on exergy analysis and Exergetic LCA	Exergy flow analysis; CExENE for Exergetic LCA	The exergy flow analysis showed scenario efficiencies of between 17% and 27% while Exergetic LCA had about 14%	Cumulative exergy consumption measures in waste LCA should be complimented by other impact categories
[67]	To conduct an optimization of thickness of insulation in a building wall based on Exergetic LCA	Case study	Sensitivity analysis shows that temperature affects total exergetic environmental impact	Walls with lower optimized insulation thickness show increased net savings and fewer payback periods
[6]	Use of case studies to illustrate and compare exergy-based thermodynamic approach with other approaches	Case studies	Different methods produced strikingly different results; this shows the need to be clear about the scope and limitations of the methods	There is a solid scientific base for thermodynamic approach based on exergy; results can be relevant for decision-making
[68]	Exergetic LCA of electricity production from waste-to-energy technology	Hybrid Input-Output method; case study	Primary non-renewable exergy embodied in electricity is non-negligible for both the construction and the operation phases	Joint application of exergy analysis and Exergetic LCA improved the overall thermodynamic performances of the system

Table 4. *Cont.*

Article	Aim	Method	Result/Discussion	Conclusion
[69]	Comparative exergy-based LCA of conventional and hybrid base transmitter stations	Cumulative Exergy Demand	The results elaborated the means of development and sources of environmental impacts during the systems' life cycles	Such details provide the basis for the evolvement and production of sustainable products and processes
[70]	In production phase, to evaluate energy, exergy use, and CO_2 emission of building materials	Thermodynamic method; case study	Although life cycle energy use and life cycle CO_2 emissions are correlated, the latter was higher than the former in production phase	Thermodynamic method practically and significantly improves sustainable building evaluation tools and in making energy policies in building sector
[71]	Environmental sustainability evaluation of an ethylene oxide manufacturing process using CExD and ReCiPe	CExD and ReCiPe	Reduction in environmental impacts expressed in MJ (CExD) and dimensionless (ReCiPe)	CExD is useful in sustainability evaluation of process technology
[72]	Exergy-based study of coal-fired power generation	Case studies	Exergy-based method was successfully used to evaluate the thermal, economic, and environmental benefits	Exergy-based method can improve efficiency of systems
[73]	Exergy-based quantification of resource use during cement clinker production	CExD method	Chemical exergy provided an improved understanding of the resource use	Theoretical gap is needed to be filled in CExD characterization models
[74]	Environmental and economic optimization of insulation thickness	Exergy-based life cycle integrated economic analysis	The approach enabled comparative analysis between environment, economy, and both effects	Exergy-based method enables optimization of environmental and economic effects
[75]	Exergy-based LCA of water injection into hydrocarbon reservoirs	Exergy-based method	Exergy quantified efficiency and CO_2 emission during the process	Exergy method is important even in water driven recovery of oil
[30]	Exergetic LCA of hydrogen production	CExD method	Exergy measures deviation levels of emissions from the reference environment	Exergetic life cycle environmental model is based on LCA and exergy theory
[76]	A thermodynamic assessment with a cradle-to-cradle view	Second law of thermodynamics (Exergy law)	Energy and materials dissipate and deteriorate, and quality is lost irreversibly	Exergy explains the need for global management of the earth's resources
[77]	Assessment of manufacturing sustainability	Hybrid analysis (LCA and Exergy)	While LCA can estimate resource use, exergy includes quality of resource use	Exergy predicts ideal solution, which informs process improvement

4.3. Findings from the Reviewed Studies

The following is a summary of the findings from the reviewed articles:

- There is a solid scientific basis for thermodynamic approach based on exergy [6,70];

- The use of exergy method enables a sustainability assessment to be more objective and reasonable [63];
- The exergy indicator enables LCA to be expressed as a single objective function [24];
- The various exergy-based indicators have unique applications in various disciplines depending on the aim and objective of study [6];
- The CExD provides a more in-depth assessment than the conventionally used CEC [7];
- Use of exergy methods in LCA provides a more comprehensive measure of sustainability by accounting for non-energetic costs such as labor and capital [46];
- Existing studies use exergetic life cycle assessment as a supplement to conventional LCA [4,66].

In addition, the following were observed while studying the bibliometrics of the reviewed articles in Web of Science:

- The use of the term "Exergetic LCA" was more popular than the use of the term "Exergy LCA" to describe the depletion of natural resources in terms of exergy loss over a life cycle;
- Exergetic LCA, as a field of study, is multi-disciplinary;
- The existing number of articles about exergetic life cycle assessment is few relative to the searched timeline, which implies that the subject is still emerging;
- Exergy analysis is most popular in disciplines such as environmental engineering, environmental sciences, energy fuels, thermodynamics, and mechanics;
- In terms of location, most of the publications are based in European countries.

5. Discussion

5.1. Exergetic Life Cycle Assessment and Benefit

Currently, exergetic life cycle assessment, as a thermodynamic approach based on exergy, is utilized to measure resource use in LCA and in other sustainability assessment methods [6]. In other words, exergetic life cycle assessment supplements LCA with a deeper life cycle environmental impact assessment by including the impact of non-energy resources such as mineral ores. One of the categories of environmental impacts that needs consideration is resource use [50], especially, non-energy resources. Exergetic life cycle assessment solves the problem of characterization of non-energy resources in conventional LCA. The exergy-based methods, which were described in Section 3.1, are employed to characterize and quantify the impact of resource use. A review of the current methods to characterize resource use category in LCA can be found in Finnveden et al. [6]. The following two paragraphs state the resource use characterization problem in conventional LCA and the benefit of exergetic life cycle assessment to overcome this methodological problem in LCA.

The resource use characterization problem is encountered in conventional LCA at the LCIA stage in the estimation of environmental impacts for each material and process. Essentially, factors are assigned to each material unit depending on the environmental impact category in consideration. For example, as illustrated in Figure 4, the characterization factor of steel for the global warming potential category is 0.43 per unit mass of steel. Similarly, the characterization factor of glass for the global warming potential category is 1.064 per unit mass of glass. However, these characterization factors mainly depend, amongst others, on the following conditions:

- Fate—the amount of emissions released and the duration of the emitted substances in the environment;
- Exposure—determination of the species in the ecosystem exposed to the emissions;
- Effect—the resulting impact on the species in the ecosystem.

The calculation of characterization factors used in databases for LCIA requires that systematic modeling procedure be followed, which includes multimedia fate and exposure models, in addition to derivation of resulting impacts from experimental toxicity data. Calculation of these factors are localized and complex, even for a controlled study. Exergetic life cycle assessment can be an alternative solution to bypass the complex modeling needed to calculate these characterization factors. As already stated, resource use can be energy or non-energy resources such as mineral ores and materials. For a given energy source, the exergetic life cycle assessment, in form of cumulative exergy demand, can be calculated from the cumulative energy demand and gross calorific exergy-to-energy ratio [24]. For each material (e.g., aluminum, brick, concrete, steel, etc.), exergetic life cycle assessment, in the form of material exergy demand, utilizes the unit exergy of the material to estimate the resource depletion (such as chemical elements, compounds, and ores) due to the material use. Unit exergy of a material is a cumulative of the standard unit chemical exergies of the substances that make up the material. Standard unit chemical exergy of a substance is the unit chemical exergy of the substance when the reference environment is composed of air at 298.15 K of temperature and 101.325 kPa of pressure. Table of values for standard chemical exergies of substances can be found in literature [25].

5.2. Opportunity for a More Comprehensive Exergetic Life Cycle Assessment

Exergetic life cycle assessment describes and measures resource use in LCA and in other sustainability assessment methods. However, in LCA, environmental impacts of both life cycle resource use and life cycle emissions are estimated or predicted. There is, therefore, the need to advance the exergetic life cycle assessment to include the impact of life cycle emissions. The reasoning is that since exergy is a measure of the degree of disequilibrium between a substance (in this case, emission) and its environment [78], then exergy of emissions can also be a measure of the environmental impact potential [24].

In this paper, the term "Exergy-based life cycle assessment (Exe-LCA)" is proffered to describe a measure of both life cycle resource use and life cycle emissions. Full development of the method for Exe-LCA is beyond the scope of this review paper and is discussed elsewhere [79]. Like material exergy demand, which was discussed in Section 5.1, the exergy of life cycle emissions can be estimated using emitted substance, instead. This is the exergy that is lost to the environment due to the emission of substances that cause environmental impacts during the life span of a product or process. Exergy of life cycle emission is a function of emission mass, standard chemical exergy of emission, and molar mass. For example, global warming potential is a measure of the potential of greenhouse gas emissions, such as carbon dioxide and methane, to cause global warming environmental impact. Therefore, the exergy of life cycle emissions that cause global warming environmental impact is a cumulative of the exergies of life cycle carbon dioxide emission, life cycle methane emission, and those of the other greenhouse gas emissions. The same procedure can be followed for other environmental impact categories.

In conventional LCA, the environmental impacts are quantified relative to one selected emission per category. For instance, global warming potential is in carbon dioxide equivalence, and acidification potential is in sulfur dioxide equivalence, etc. Such representations do not portray the contributions of the other underlying emissions e.g., contributions of methane and nitrous oxide to global warming, and the contributions of nitric and hydrochloric acids to acidification. One main advantage of using exergy of life cycle emissions is that the contributions of all the identified chemical emissions during the inventory analysis can fully be included as a cumulative. In addition, exergy of life cycle emissions, as well as exergy of life cycle resource use, express their measurements in the same unit of exergy. This unification capacity results in ease of comparison and other benefits that can make the exergy-based method suitable to achieving life cycle sustainability assessment [80], in addition to being a viable solution to a major methodological problem in LCA.

6. Summary and Conclusions

A review of exergetic life cycle assessment was conducted, using a systematic approach, to investigate the state-of-the-art and relevance of exergy in LCA, and to identify opportunity for improvement of the method. The paper was structured to describe exergy, introduce exergy-based methods and LCA, review and analyze studies on exergetic life cycle assessment, and to discuss the benefits of exergetic life cycle assessment and highlight opportunities for improvement. The methodology involved a literature review, which entailed a systematic selection of journal articles through search of major databases such as Web of Science Core Collection, Scopus, and Google Scholar. The databases were assumed to be comprehensive enough for the collection of the most relevant articles in exergetic life cycle assessment.

The review has shown that exergy-based method can improve on the conventional LCA method. Both exergy and LCA can be used to assess resource consumption and environmental impacts. However, exergy-based LCA goes deeper to assess the quality of resource consumption and environmental impacts. For instance, exergy assesses efficiency of resource use, resource recovery factor, and/or emission rate. Additionally, characterization factors, which are developed using exergy-based method, will be more accurate and robust than that from the conventional LCA method. This is because the former is based on standard thermodynamic properties (e.g., of temperature, and pressure) while the latter is dependent on subjective factors such as fate, exposure, and effects.

In addition, both exergy-based method and LCA can estimate potential environmental impacts from life cycle emissions but report or interpret them in different ways. In conventional LCA, each impact category is reported relative to one reference emission e.g., carbon dioxide equivalence for global warming potential, while in exergy-based method, each emission can uniquely be quantified and summed up. The advantage is that both absolute and relative values can be obtained using exergy-based method for a more robust comparative analysis and decision-making opportunity. It is recommended that exergy-based LCA method, instead of the conventional LCA, be utilized especially in cases where quality of evaluation, single objective values, combined environmental and economic assessment, robust inventory of characterization factors, and benchmarking are required. The critical issues in performing exergy-based LCA include the assumptions in determination of the exergies of the resources and emissions such as standard thermodynamic conditions, pure state of resources and emissions, and difficulty in determination of the individual emission mass. These issues should not be confused with those unique issues in performing exergy analysis of energy systems such as sensitivity of reference environments, choice of exergy efficiency type, unavoidable nature of irreversibility, boundary definition, and choice between steady state and dynamic state conditions, as reported in [20,81].

The following conclusions are deduced from the study:

- Among others, exergy has importance and relevance in life cycle analysis, sustainability, energy systems, and built environment;
- Exergetic life cycle assessment is used for resource accounting in life cycle assessment;
- Exergy-based methods provide a more comprehensive measure of sustainability by accounting for both energetic and non-energetic resources such as labor, and capital;
- The existing studies use exergetic life cycle assessment as a supplement to conventional LCA in resource accounting;
- There is an opportunity for a more comprehensive exergetic life cycle assessment that includes exergy of life cycle emissions;
- A new terminology is required to describe a combination of exergy of life cycle resource use and exergy of life cycle emissions; "Exergy-based Life Cycle Assessment (Exe-LCA)" is proffered;
- Improved exergetic life cycle assessment has the potential to solve characterization and valuation problems in LCA methodology;
- The unification capacity of exergy-based method is a promising technique to achieving life cycle sustainability assessment.

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