Conventional and Exergetic Life Cycle Assessment Process and Applications of

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Abstract

This study presents the life cycle assessment of various power generation technologies based. The assessments cover impacts from extraction, processing and transportation of fuels, construction of power plants and power generation. Life-cycle assessment (LCA) to power generation technologies is very useful as the world seeks ways to meet growing electricity demand with less health and environmental impacts. LCA is an evolving methodology with several barriers and challenges but has helped in improving the understanding of the lifecycle energy, greenhouse gas emissions, air pollutant emissions, and water-use implications to power generation. The application of LCA tools facilitates an analytically thorough and environmentally holistic approach in assessment and comparison of power generation technologies. Most LCAs show that the best power plants are hydropower, both run-of-river and with reservoir, nuclear energy, and wind power. Fuel combustion directly leads to emissions and potential environmental harm. The cradle-to-grave approach considers all steps between material and fuel extraction from the environment until they are returned to the environment. The methodology used in lifecycle assessment (LCA) includes the effects of all the production phases, use and recycling on the environment. The complete LCA involves factors like water and air pollution, and noise. Exergy which is the maximum useful work that can be extracted from a system as it reversibly comes into equilibrium is used in various fields such as industrial ecology and environmental engineering, for efficient use of energy and to minimize harmful environmental impacts. Exergy analysis has been in application since the late 1990s and is extended into the realm of resource and environmental analysis, to develop integrated analytical frameworks. Exergy analysis can be used in decision-making by policy makers in making sustainable choices.

Key words: Energy payback ratio; emissions factor; exergy assessment; greenhouse gas emission; lifecycle assessment; LCA; sustainability assessment.

1. Introduction

Energy is an essential resource for modern society used for many applications like lighting, transport, communication, heating, air conditioning, manufacturing among others. The evaluation of energy production technologies considers all aspects like energy and raw-materials consumptions, energy efficiency, and environmental impacts must be considered. The environmental impact is an important factor in the evaluation of power generation technologies(Petrescu et al., 2017). Electricity systems account for 38% of primary energy use globally and are set to rapidly grow as demand for electricity-based services increases such as looking, lighting, sanitation, heating and cooling, and information and communications. The current global electricity mix is dominated by fossil fuels led by coal, natural gas, nuclear, and petroleum which are all nonrenewable (Edenhofer et al., 2013; Moses J. B. Kabeyi & Oludolapo A. Olanrewaju, 2022).

Assessment tools like the Life Cycle Assessment (LCA), Exergy Analysis (ExA), and Emergy Analysis (EmA) are used to account for sustainability indicators in social, environmental, and economic, dimensions, and hence are applied to carry out assessments under these three dimensions (Cano-Londoño et al., 2022). Life cycle assessment (LCA) is a holistic approach applied in evaluating the environmental impacts of products and systems through their entire life. Life cycle analysis is needed to foster the development of energy technologies in a sustainable manner (Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022c; Paredes et al., 2019). Life cycle assessment (LCA) is a decision support tool which assesses environmental burdens of products and processes right from materials extraction to disposal popularly referred to as cradle-to-grave or even cradle-to-cradle. For accuracy, the power generation life cycle assessments should better characterize spatial and temporal characteristics(Jordaan et al., 2021). A life-cycle assessment is regarded as an environmental assessment of all steps used in production and delivery whole goal is to present a holistic and inclusive picture of environmental impacts by considering all significant downstream "and upstream activities and their impacts(Gagnon et al., 2002; Moses Kabeyi & Oludolapo Olanrewaju, 2022).Selection of generation technologies is becoming complex and involves economic, operational, siting, social, and policy constraints, etc. (Edenhofer et al., 2013). Life Cycle Impact Assessment (LCIA) is applied to classify and characterize the lifecycle inventory (LCI) results based on environmental impacts or human effects. The impact categories based on these characterizations and classification include.

i.) Health impacts like global warming potential, respiratory organics, respiratory inorganics, and climate change.
ii.) Environmental/ ecosystem quality impacts like eutrophication potential, acidification potential, and land use.
iii.) Resources impacts like energy and material or mineral use.

A simplified life cycle inventory (LCI) model for a specific type LCA may be adapted from existing databases like ecoinvent, Athena, Gabi, and OpenLCA, to compute the LCIA. (M. J. B. Kabeyi & O. Olanrewaju, 2022; Nwodo & Anumba, 2020).

Since the environmental impacts and benefits tend to occur at different phases of the power plant life cycle, it is very important to consider the entire lifecycle. When comparing two options, important phases may not be the same for e.g., technology option. Therefore, the life cycle approach, i.e., Life Cycle Assessment (LCA) methodology is preferred. The LCA is a methodology for evaluation of environmental impact of a product, process or an activity in the course of its life cycle by quantitatively and qualitatively identifying and describing energy and materials requirements , and associated emissions and wastes generated and released to the environment(Rentizelas & Georgakellos, 2014).

As a power decision support too, Life cycle assessment (LCA) evaluates the environmental burdens products cross the life cycle. LCA is increasingly being used to address environmental impacts of energy systems and technologies. A typical Life cycle analyses is neither spatially explicit nor temporally resolved (hence they represent a snapshot in space and time or with general data that is not representative of a location at a particular time. Occasionally, LCA results are impactful to the energy sector evolution through knowledge improvement of energy systems and influence policy decisions(Jordaan et al., 2021). LCAs are however challenged by economically powerful and highly innovative energy sectors, more so high regional and temporal variability of operations. These variabilities contribute to unresolved problems in LCA notably the highly diverse generation technologies leading to different regional mixes which are highly influential on LCA results. Therefore, life cycle assessment for power generation should adequately characterize spatial and temporal characteristics for accuracy and reliability(Jordaan et al., 2021).

This study assesses the state of the art of LCA applied in power generation technologies and systems with emphasis on areas like methodological issues, challenges associated with for power generation technologies, quantitative results obtained from the literature, improvement opportunities for LCA applied in power generation. In this study, a review of both conventional and exergetic life cycle assessment was undertaken in a systematic approach to investigate their state-of-the-art, relevance and establish opportunities for application as well as improvement s to the methods in modern energy systems. The paper is structured to introduce and describe LCA, exergy, introduce exergy-based methods and LCA, review and present benefits, processes, and applications of traditional and exergetic life cycle assessment, and improvements. The methodology applied involved literature review, that entailed a systematic selection of journal articles, reports and other published literature from various databases/ databases like Web of Science Core Collection, Scopus, and Google Scholar (Nwodo & Anumba, 2020).

1.1. Problem statement

Life cycle analysis for power generation technologies has increasing continued to addressed the environmental impacts of energy technologies. As LCA role continues to grow as a decision support tool for energy policy, lingering questions remain on how results can be applied in the face of uncertain assumptions in an ever-evolving energy sector. Typical LCA is neither spatially explicit nor temporally resolved and therefore it represents a snapshot in space and time or with general data that do not represent a location and particular time. Although the life cycle results are impactful to the evolution of the energy sector through enhanced knowledge of energy systems and influence policy, the assessments are challenged by economically powerful, fast-paced, and highly innovative energy sector mainly by high regional and temporal variability of operations. The variability contributes to unresolved problems in life cycle analysis LCA. Different regions have different regional energy mixes since the power grid consists of highly diverse power generation technologies (Jordaan et al., 2021).

1.2. Rationale of the study

The transition to renewable energy sources and "green" technologies for power generation and storage should mitigate the climate change from greenhouse gas emissions. The main sustainability challenge for the transition is the dependency on critical materials, processes and other resources that have significant environmental impacts. Beyond the global warming concerns, we have serious sustainability concerns like loss of biodiversity, water scarcity , environmental pollution, and energy security that should equally be addressed during the transition (Ciacci & Passarini, 2020; Kabeyi & Olanrewaju, 2020). The issues of energy and environment are seriously interconnected and need comprehensive analysis and understanding of resource management strategies and their consequences. As an example, vital water resources depletion and contamination is related to possible shortages in power generation, distribution and use while at the same time the supply of water needs energy(Ciacci & Passarini, 2020; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022a).

There is therefore need for a system perspective to locate, locate, and quantify the impact of human activities and processes on the environment. The Life cycle assessment (LCA) is one of the most inclusive analytical techniques to analyze sustainability tradeoffs and benefits resulting from complex energy and environmental systems(Ciacci & Passarini, 2020; Kabeyi & Olanweraju, 2022).

For accuracy, power generation LCA should better characterize spatial and temporal characteristics [2]. The comparison of power generation technologies is considered generic because it presents a general overview of environmental and economic impacts that are generally expected. Specific impacts can be smaller or greater based on site specific conditions or mitigation measures(Gagnon et al., 2002) The comparisons help decision makers as follows :

i.) Policy decisions may be needed before site specific information is available hence the "generic" comparisons can be used in decision making.
ii.) Many energy system analyses do not consider the impacts of entire energy systems from extraction and processing, operation, and disposal.
iii.) Many assessments neglect sustainability and reliability aspects yet they are important in sustainable development.
iv.) There is a need for generic data at the planning level for power generation technologies but is not a substitute for detailed and careful analysis of site-specific conditions. However, it provides indication of impacts and choices that need more careful detailed consideration(Gagnon et al., 2002; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022d).

2. Generation Options

Power generation systems do not have equal capability to provide energy services which are variable and time varying. Reliable power systems cannot rely on the "must-run" power systems such as geothermal and nuclear energy or on intermittent power systems like solar and wind alone, but rather an optimized mix of different sources. Energy sources like hydropower with storage could service all electricity needs and maintain system balance. Likewise, is oil or diesel, or gas fired power plants which have desirable flexibility, because of ability to store the energy resource for later use without loss. Intermittent sources constantly require a "backup" system to compensate for fluctuations and storage to store excess when generation for use during high electricity demand(Gagnon et al., 2002)..

2.1. Analysis of Intermittent Sources

Two approaches can be applied for analysis of intermittent generation systems: for fair comparison.

i.) The systems can be combined for analysis with a typical backup system, which provides the same reliability as other standalone systems. Though technically challenging, it can be done hence adding wind energy to hydropower.
ii.) Where the system does not consider the required backup, then can be recognized clearly that the assessment is not at par with other "stand-alone" systems(Gagnon et al., 2002).

2.2. Main Types of Electricity Generation Systems

Power generation technologies vary greatly based but can be grouped on their ability to meet fluctuating. electricity demand. Table 1 shows the different power plants and their applications.

Table 1: Classification based on expected service level.

	Power plant technology	Application	Remarks
1	Hydropower with reservoir	Base and peak load	Very efficient and flexible systems
2	Runoff river plants	Base load	Less flexibility
3	Pumped storage	Peak load	Can enhance use of variable renewables
4	Diesel power plants	Base load and peak load	Expensive and polluting but highly flexible

5	Natural gas	Base load	Less flexible
6	Coal	Base load	Have some flexibility for peak and variable load supply
7	Heavy oil	Base load	Some flexibility and highly polluting
8	Biomass	Base load	Less flexibility
9	Nuclear	Base load	Very little flexibility

From table 1, it is noted that different power plants have different roles to play on the grid and hence their performance characteristics are important.

3. Life Cycle Inventory Analysis

The Life Cycle Inventory (LCI) involves the computation of inputs and outputs of resources like materials, energy, ,emissions, and wastes from each stage in the service life of a product(Nwodo & Anumba, 2020). An LCI analysis requires extensive non-duplicated data collection. LCI involves the compilation and quantification of natural resources consumed and substances released into the environment. In the life cycle inventory (LCI) analysis, the life cycle is drawn with all energy and material requirements like air, water, soil, land, etc.; as well as their environmental releases which are quantified. The steps in an LCI analysis are the development of a flow diagram, collection of data, multi-output processes, and results reporting(Nieuwlaar, 2013). Life cycle inventory (LCIs) are generally based on average data of energy and material inputs and outputs collected from the site or estimated from literature or from modeling studies. To construct an LCI, all inputs and outputs for all processes should be identified and quantified. An LCI process should be at an industrial scale for the modeled system to be as close as possible to a real process. In the case of an ongoing development and low technology readiness level (TRL) of a new process, there should be a scale-up modeling to determine material and energy flows for the desired real scale.(Angoy et al., 2019).Figure 1 shows the steps followed a lifecycle inventory asseement.

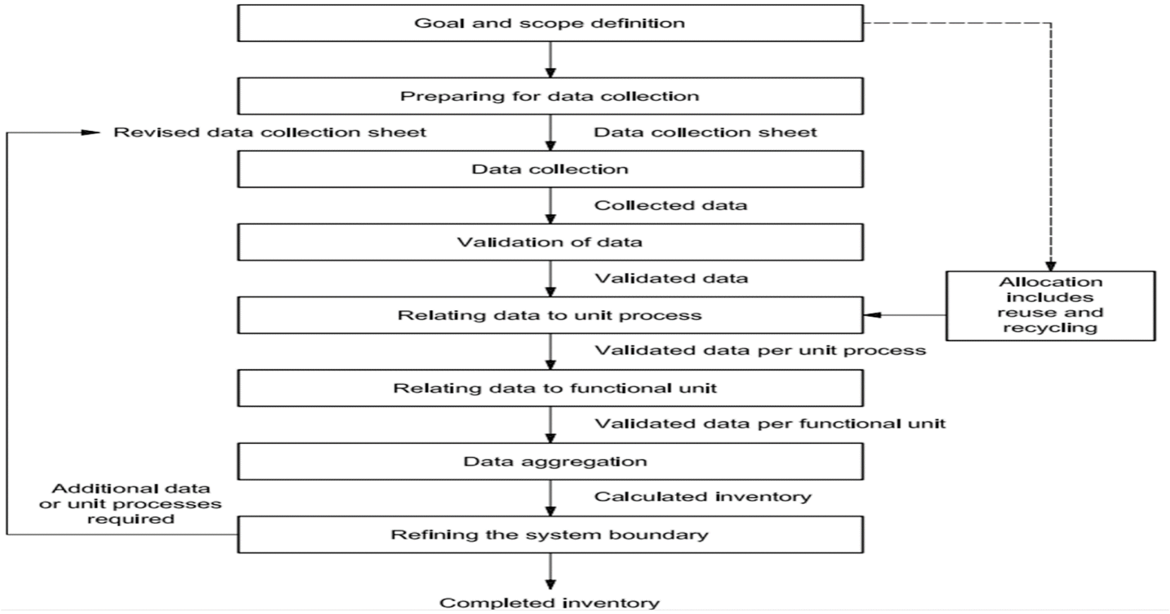

Figure 1. Simplified procedures for Life Cycle Assessment (LCA) inventory analysis

From figure 1, it is noted that lifecycle inventory analysis begins with goal and definitions followed by preparation for data collection, actual data collection, and validation and establishment relationship between data and unit process and the functional unit, before data aggregation and refining of system boundaries.

3.1. Development of a Flow Diagram

A flow diagram is used to reflect processes making up the product system and the inputs and outputs of the processes within the system. The boundaries are defined by the scope and goal of the analysis. Almost all processes in a system involve a form of transport between processes which requires energy. Processes relate to flows of intermediate products while elemental flows are shown to and from the environment. The elemental flows are material or energy flows entering or leaving the system drawn from the environment or discarded to the environment. Therefore the elemental flows originate directly from the environment e.g., energy and material resources, land use or they are discharged directly to the environment like emissions, heat, radiation, sound(Nieuwlaar, 2013).Figure 2 demonstrates a product system under life cycle inventory analysis.

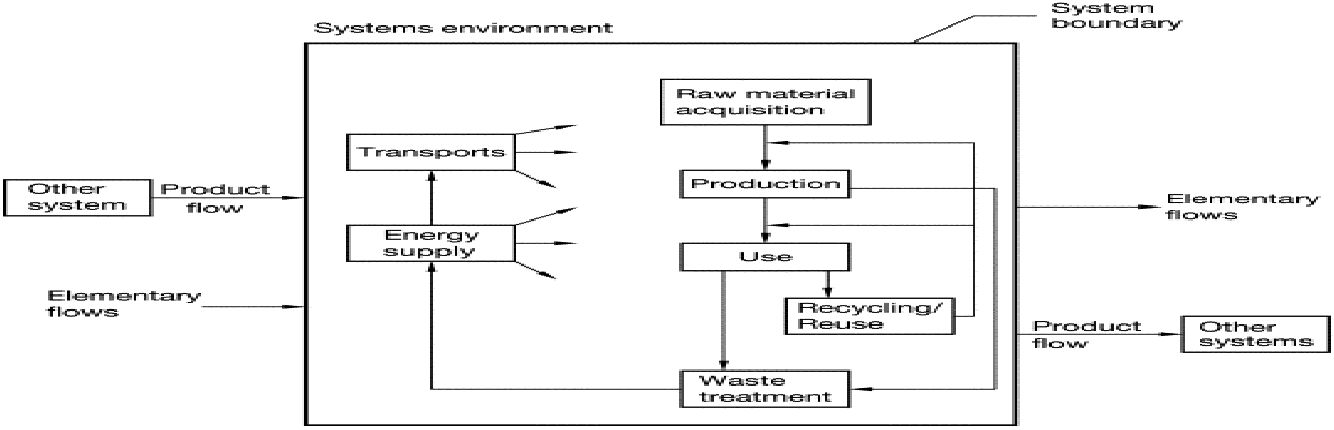

Figure 2. A product system for life cycle inventory analysis.

From figure 2, it is noted that a system has boundary with product inflow from other systems and direct elemental flow from the environment. Main processes in the energy system are transportation, energy supply, waste treatment, production, acquisition of raw materials, material, recycling, and consumption. The system outputs include product flows to other systems, elementary flows to the environment.

The elementary flows originate from processes within the energy system boundary, as is shown in Figure 3.

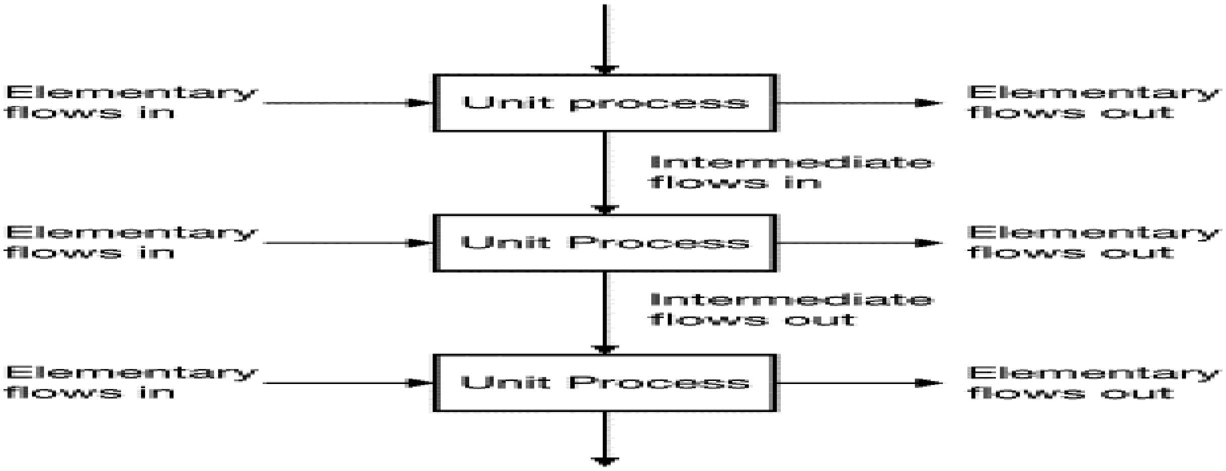

Figure 3. Unit processes within a product system.

From figure 3, it is noted that there are elementary flows specific unit processes that have their own elementary flow outs. Intermediate flows occur between various units in the system Data Collection

The most time-consuming stem in the life cycle inventory assessment is data collection. Data collected should be accurate and relevant for this purpose. Quite often, data is a mix of site-specific data which is obtained by measurements and calculations from measurement and generic, non-site-specific data which is obtained from databases or expert estimates(Nieuwlaar, 2013).

3.2. Multi-Output Processes

Energy systems have many processes that have a single useful output. In such multi-output processes, just one of the outputs may be used in the life cycle. The systems can also have outputs useful to other life cycles that are not under investigation. Material and energy inputs and the elementary flows of the processes under study are allocated among the useful outputs. An example of a multi-output process is cogeneration processes and products where fuel input in combined heat and power (CHP) plants is divided between electricity generation and heat production. In this case, the system can be extended by introducing reference technology for either product, e.g., for heat production, fuel input for heat production can be computed as the fuel required for heat production in a reference boiler. **The fuel consumption for power generation is** then determined by deducting the fuel input for heat production in the cogeneration system. The reverse can also be done where a reference electricity plant is introduced instead of a reference boiler and the process repeated. In another approach, physical properties of products like mass or energy content are applied as the allocation factor. Mass allocation may not however work for **a** CHP plant, instead energy content either on a heat/enthalpy basis or on an exergy basis is more realistic and s more meaningful. In the third approach, the economic value of the individual products can be applied for proper allocation factor. The three approaches have been widely used in LCAs (Nieuwlaar, 2013).

3.3. Reporting

The LCI outcome is a list of all elementary flows to or from the environment for each energy system study resulting from the functional unit provided by the energy systems. They can be organized based on the stage of life cycle stage and/or media like air, water, or land. These results can be used in further analysis like comparison of energy alternatives and identification of life cycle stages with significant environmental releases. These releases do not however express the potential environmental impacts**(Nieuwlaar, 2013).**.

4. Life Cycle Impact Assessment Method

A life cycle impact assessment provides a more meaningful basis for comparisons e.g. we may know that know that 8500 tons of carbon dioxide (CO_2) and 5000 tons of f methane are released to the atmosphere both being potentially harmful greenhouse gases, it is through a life-cycle impact assessment (LCIA) that we can determine has a greater impact. In terms of smog formation? Or which is worse than the other? Or what are the potential impacts on global warming? The LCIA uses science-based characterization factors, to determine the impacts of each emission to the environmental (Curran, 2008).

Life cycle impact assessment (LCIA) is part of life cycle assessment (LCA) whose objective is to evaluate and understand the magnitude and significance of environmental impacts for a product system across its life cycle(Zhu et al., 2022). Life cycle impact assessment involves characterization of impacts and selection of impact assessment categories based on their contribution to the normalized and weighted analysis results. There are two basic approaches that can be used to characterize environmental impacts, namely.

i.) The midpoint approach and midpoint indicators recommended by the EC Environment Footprint Guidelines [12, 13] or
ii.) The endpoint approach and endpoint indicators.

These e approaches are different in terms of objectives and robustness, a comprehensive LCA may display the results using both. midpoint and endpoint approach and the endpoint and endpoint indicators approach but the conclusions remain the same. The term “impact” is generally used as the shorthand for “potential impact”, as it is defined in the ISO standards. Therefore, in the lifecycle assessment (LCA), “impact” associated terms like “impact assessment” or “impact category” is associated with the potential detrimental effects that a substance or a stress can leave on the environment, resources or human health or resources. Therefore, only potential environmental impacts are regarded as real impacts influenced by factors usually not included in the study. “The LCIA does not have to quantify any actual, specific impacts associated with a product, process, or activity, but seeks to establish a linkage between a system and potential impacts(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022e; UNECE, 2022).

Although much can be learned about a process by considering the life-cycle inventory data. An impact assessment is used to provide a more informed basis to make comparisons. It is through an impact assessment that we can establish the environmental releases with greatest impact**.** A life cycle impact assessment is used to compute impacts of the environmental releases like global warming and smog(Curran, 2008). In this regard, the LCI is converted in environmental impacts by category. The impact categories include toxicity, climate change, respiratory effects, acidifications, ozone layer depletion, acidification, eutrophication, natural resources depletion, etc. The substances in the Life Cycle Impact assessment have one or more impact category, e.g. NO_x is responsible for respiratory effects, acidification, and eutrophication(Angoy et al., 2019). Environmental models can be used to establish specific parameters that quantify effects of a substance. The result of the impact is proportionally linked to the mass of the substance released to the environment(Angoy et al., 2019). The environmental gains of energy technology substitution can be determined through complete analyses of LCA and LCI using data from pilot and industrial scales studies (Angoy et al., 2019; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022f)

5. Exergetic LCA Studies

Exergy is defined as the maximum useful work that can be extracted from a system when it reversibly reaches equilibrium with its environment. Exergetic LCA analysis can be applied many fields like industrial ecology, and environmental engineering, to enable more efficiently use of resources and minimize negative impacts i on the environment(Salehi et al., 2019). Exergetic analysis has been in use since the late 1990s, with applications being extended to into resource and environmental analysis, to establish an integrated analytical frameworks(Kabeyi & Olanrewaju, 2023a). The exergy analysis can also be used in decision-making by policy makers in making sustainable choices. In energy analysis, the ability to work is generally accepted as a measure of energy quality. The energy quality of a system is either available energy or unavailable energy. Exergy is used generally as a measure of the possible maximum useful work before a given system reaches equilibrium with the environment. Exergy is said to be available when an idealized system or an environment interacts in equilibrium with another system of interest, while heat transfer takes place with the environment(Salehi et al., 2019)..

5.1. Characteristics of Exergy

Based on the various definitions of exergy put forward, the following are features or characteristics of exergy.

i.) An idealized state is stated to calculate exergy.
ii.) Common components like the atmosphere, lithosphere, and hydrosphere, can be used as the idealized systems due to thermodynamic disequilibrium in their surrounding nature.
iii.) Exergy is used to investigate technical processes and analyze power plants and other machines since exergy is a measure of quality.
iv.) By reducing useful results of the process, energy consumption is increased from whatever source of derivation.

Exergy is quite useful in many areas of study like LCA, energy systems, sustainability, and the built environment. As interest grows in life cycle analysis mainly due to growing interest in global environmental impacts, studies have been conducted on exergetic lCA for resource accounting(Nwodo & Anumba, 2020). Exergetic life cycle assessment (ELCA) enables the assessment of the natural resources depletion by analyzing the exergy loss encountered during the entire life cycle. ELCA is therefore used to evaluate and establish processes through which natural resources are lost(Dincer & Rosen, 2021). Exergetic life cycle assessment (ExLCA) can be used to quantify the environmental impacts associated with the exergy losses and exergy destruction in an energy system, process or product. Environmental impact is reduced by increasing exergy efficiencies (Dincer & Bicer, 2020; Kabeyi & Olanweraju, 2022).

5.2. Exergy Analysis Procedure

Exergy analysis is used to assess and compare processes and systems rationally and meaningfully. The key capabilities are demonstrated in two key features of exergy analysis:

i.) efficiency to generate a real evaluation of how actual performance tends deviates or tends follows the ideal performance, and
ii.) exergy is clearer than energy analysis in establishing types, causes, and locations of thermodynamic losses.

Exergy efficiency was incorporated in the 2001 Swiss canton of Geneva a parameter to be sed to characterize energy performance in buildings. Exergy describes the work potential of energy, exergy-based while exergy-based analysis is used in system design or process optimization. Exergy is applied in design, assessment, analysis, and improvement of systems like application of exergy analysis to integrated energy systems like geothermal, biomass, and steam power plant generation system (Kabeyi & Olanrewaju, 2023b; Nwodo & Anumba, 2020). The framework of ExLCA is similar to LCA with main steps summarized in figure 4

Figure 4. The framework for ExLCA,

Figure 4 shows a flow diagram with inputs and outputs of matter, energy, and exergy at various steps in the life cycle of a product or process.

Exergy and its methodological advancements can be used in LCA studies. Exergy analysis is a multi-disciplinary and emerging field, with applications in resources use in both energetic and non-energetic resources. The exergy is applied in sustainability assessment for thermodynamic properties and parameters, that require less subjective choices as compared to fate, exposure, and effects models applied in most LCA methods. The measurement would make characterization independent of reference substances like carbon dioxide for global warming potential which enables e combination of the results of different impact categories into a cumulative value by using the same unit of exergy. Extensive application of exergy analysis to conventional LCA is done through a systematic and comprehensive determination of exergies which considers standard thermodynamic conditions, emissions, pure state of resources, and individual emission amounts (Ciacci & Passarini, 2020).

5.3.Application Of Exergetic Analysis

Exergy is used to describe the work potential of energy, while exergy-based analysis is applied in system design and process optimization. Exergy is used to assess, analyze and , and improve systems like integrated energy systems including biomass, geothermal, and steam power systems(Nwodo & Anumba, 2020). Table 2 summarizes the impotence of exergy by topic stated.

Table 2. Summary of the importance of exergy classified by subject area.

Subject of application	Application of exergetic analysis
Life cycle analysis	Exergy facilitate analysis of cumulative resource consumption
	Exergetic life cycle assessment (LCA) is more appropriate approach in quantifying environmental problems like natural resource depletion
	Exergy provides additional indicator for LCA, energy efficiency, and resource quality need
Production processes	Exergy analysis is used to account for efficiency and exergy losses needed to provide a more accurate inventory
	Exergy is used to quantify results of manufacture, consumption and disposal of goods, and services on a single scale—exergy loss
Technology assessment	Exergy enables both qualitative and quantitative evaluations of resource consumptions
Built environment	The exergy concept is applied to deepen understanding of space cooling and heating for development of low-exergy systems for future buildings
Sustainability index	Exergy-based sustainability index is used to overcome the limitations of the subjectively defined weights applied in other sustainability assessment tools
Energy systems	Exergy analysis evaluates the performance of energy systems to optimize their efficiencies
Global impacts	Used to improve efficiency of a process, exergy analysis to reduce global impacts related to the processes and systems analyzed

From table 2, it is noted that in life cycle analysis, exergy-based approach is useful in quantifying energy and material resources, and determine consumption and depletion of natural resources, as well as an indicator of resource use efficiency.

In manufacturing or production, exergy is used to keep inventory of exergy losses and efficiencies based on a single scale. In technological processes, exergy is applied to achieve sustainability to show extent of using renewable energy resources, account for technological efficiency and waste conversion useful, neutral, or harmless products in built environment, exergy is used to deepen the knowledge on how the built environment can develop low-exergy future systems and is used as a scientifically based building assessment tool. Exergy analysis is used in the optimization of efficiencies of energy systems and thus reduces global impact of energy systems. (Kabeyi & Olanrewaju, 2020; Nwodo & Anumba, 2020).

6. Results of Life-Cycle Assessments

6.1. Greenhouse Gas Emissions and Environmental Impacts

The environmental impacts of greenhouse gas emissions and global warming include.

i.) More intense precipitation events cause flooding, landslides, avalanche, and mudslide damage.
ii.) Increased summer drying over most mid-latitude continental interiors and associated risk of drought.
iii.) Increase in tropical cyclone peak wind intensities, mean and peak precipitation intensities.
iv.) More intense droughts and floods associated with El Nino events in many different regions.
v.) Rise in sea-level and an increase in the intensity cyclones which can displace millions of people in lowlands.

6.2. Understanding the studies on greenhouse gas emissions

The potential impacts of climate change have led to many studies focused on greenhouse gas emissions assessment which have produced data on emissions of “CO_2 equivalent therefore CO_2 and other greenhouse gases are captured in the assessment. Greenhouse gases have different effects on the climate with different life spans in the atmospheric. The global warming potential is used to assess the greenhouse effect of various substances and different substances have different greenhouse gas potential e.g. a gram of CH_4 has a *global warming potential* of 23, relative to a gram of CO_2 assessed over a 100-year period. (Gagnon et al., 2002).

6.3. Main findings concerning greenhouse gas emissions.

Based on greenhouse gas emissions, run-of-river hydropower presents the best performance among all systems, followed by nuclear, reservoir-based hydropower and wind power. Run-of-river hydropower with no upstream reservoir) and nuclear energy are less flexible, and wind power is intermittent. A backup system is needed for these energy systems and maybe fossil fuel, which significantly increases the final emissions factor of the overall electricity system. Coal has the highest emission factor which is about twice the emissions of natural gas combined cycle(Gagnon et al., 2002)..

For hydropower, a common source of greenhouse gas emissions is the decay of flooded biomass whose assessment is site specific based on factors like reservoir per kWh which varies with topography. The amount of flooded biomass, per unit of area, varies by a factor of 5 (500 t/ha for tropical forest versus 100 t/ha for boreal climate. For average size reservoir per kWh, in boreal or mountain regions, the emissions factor for hydropower is approximately 60 times lower than modern coal-fired generation(Gagnon et al., 2002)..

For greenhouse gas emissions from hydropower reservoirs decaying biomass in hydropower reservoirs, have persistent uncertainties. Reservoirs in boreal or mountain regions have small amount of flooded biomass, but reservoirs in tropical environments, have higher emission factors, depended on many site-specific conditions(Gagnon et al., 2002)..

6.4. Future Performance of Energy Systems Concerning Greenhouse Gas Emissions

The global expectations over issues like climate change are high since many studies target only one stage of the life cycle, yet life-cycle assessment may show different expectations since some technologies emit less greenhouse gas emissions at one stage of their life cycle, only to emit more at another stage. Alternative fuels such as ethanol coming from crops may have lower emissions at combustion compared to oil, but crop production related emissions offset these benefits. In another example, fuel cells emit almost zero emissions operation, but production of hydrogen has got higher level than natural gas turbines. For carbon sequestration, scrubbing of CO_2 emissions from flue gas is complex and expensive. For sulfur, the benefits of scrubbing technologies are justifiable by the fact that the waste generated by these technologies are manageable, but for CO_2 emissions, it is complex because carbon is responsible for about 50% CO_2 emissions of the coal, while sulfur is 1% or 2% in coal, making capturing all this carbon and pumping it in deep underground reservoirs is energy intensive, polluting, and expensive hence fewer relative benefits. Therefore, the next few decades, may not see major technologies developed to solve the climate change challenges. Therefore, energy efficiency measures and renewable energy technologies will remain the best options to reduce greenhouse gas emissions in the near(Gagnon et al., 2002).

6.5. Acid precipitation

Acid precipitation remains a major environmental concern. The SO_2 and NO_x emissions acidify lakes rivers and forests and affect their productivity. It is, however, difficult to identify the direct link between ecosystem impacts and atmospheric emissions. Additionally, vulnerability of forests varies based on soil types involved. It is generally difficult to establish a direct link between one specific emission and the ultimate environmental damage they cause. Therefore, emission factors may be considered as indicators of "potential" impacts(Gagnon et al., 2002).

For forest productivity, impacts of pollutants include.

i.) Acid will remove essential nutrients from soils like (K, Ca, Mg).
ii.) Acid may mobilize toxic metals like aluminum which damage crops or plant roots.
iii.) Nitrogen from pollutants, although the main nutrient of plants, can create resources unbalance and make trees more vulnerable to frost and diseases and frost.
iv.) Emissions cause photochemical smog which can cause damage to leave.
v.) They contribute to climate change which can heat stress or intensity of droughts(Gagnon et al., 2002).

Sulphur dioxide leads to formation of sulfuric acid while NO_x leads to the formation of nitric acid before contributing to the formation of acid precipitation. NO_x also contributes to smog formation from related chemical reactions(Gagnon et al., 2002)..

Fuels have different Sulphur compositions with coal having sulfur content varying between 0.5% to 5% even more in exceptional cases. The average Sulphur content for oil and diesel is about 0.2% for light oil/diesel and 2% for heavy fuel but the percentages vary significantly from one region to another. Natural gas has virtually no sulfur content as it is removed in processing plants after extraction. Various technologies are available for the removal of Sulphur dioxide with some capable of scrubbing as high as 90% of SO_2 emissions. Technologies that involve high pressure and temperature combustion like diesel engines, generate high levels of NO_x emissions. For coal, which has significant amounts of nitrogen are also part of the fuel, leading to high NOx emission factors.

Emission factors for hydropower and nuclear energy are hundreds of times lower than those of fossil fuel-based technologies like coal power generation systems without scrubbing. Therefore, based on SO_2 and NO_x, emissions produced, coal, oil and diesel-based power generation systems are significant contributors to acid. Biomass has low SO_2 but a very high factor for NO_x. Hence a significant source of acid precipitation. Natural gas is also a significant contributor to acid precipitation because of the NOx emissions. Wind power can reduce the use fossil fuel-fired plants by substituting them leading to reduction in net emissions although in some cases wind power may increase the use of oil-fired plants as back up.

The main source of SO_2 is fossil fuels, particularly coal and oil-fired power plants. Through scrubbing technologies, the SO_2 emissions can be reduced by more than 90%, but the technologies are expensive and reduce the power plants efficiency. Burning low Sulphur fuels is another option but these fuels are costlier need longer transportation(Gagnon et al., 2002)..

6.6. Land requirements

Emerging renewable energy technologies like wind and solar have large land requirements. Land demand continues to grow due to use in agriculture, cities and industries, and land for other uses. The alternative sources of biofuels, like ethanol from crops, need large areas of farmland(Gagnon et al., 2002)..

For many countries including the United States, most reservoirs were built for irrigation and water supply. Several reservoirs are small or have no power generation function and would have even higher land use factors per TWh. Fossil fuels have less data available and hence some upstream activities are not considered e.g. surface mining of coal requires more land than underground mining, but no data is available to distinguish them. (Gagnon et al., 2002).

The lowest land requirements are from nuclear energy if the land required for long-term nuclear waste disposal, but inclusion disposal land requirements seriously increases the nuclear energy land requirements since less land is needed but over a very long time in many thousands of years e.g. 0.1 km/TWh is required for waste disposal, multiplied by 30 000 years, for 30 years of generation, the factor would increase from 0.5 km/TWh to 100 km/TWh) (Gagnon et al., 2002).

Renewable energy sources led by biomass plantation have the highest land requirements per unit of energy. This is followed by renewable sources i.e., hydropower, wind power and solar power with almost similar requirements with significant variations based on site-specific conditions. Coal requires much less land than any renewable source of energy in an assessment based on direct land requirements only i.e. power plants and mining activities. Land and related indirect use are not included in the data. Yet these areas are huge and can multiply the land use factors of energy sources(Gagnon et al., 2002)..

6.7. Future Performance of Energy Systems Concerning Land Requirements

There is little likelihood that technological development will lead to significant land use reductions. No new technology may be needed to reduce areas affected by acid precipitation for coal and oil. For hydropower, the size of reservoir is important and reservoir areas are about 5 times smaller than existing ones per unit of energy. Future development of renewable could be significantly constrained by land requirements. Compatibility with existing land uses land uses differ widely and is guided by factors like population density(Gagnon et al., 2002).

Hydropower may have other water uses like irrigation, water supply or flood control. In terms with competition with food production, many t renewable energy projects have little negative impacts on agriculture e.g., land around windmills can still be used for agricultural production while solar energy can be developed on rooftops and over water masses like reservoirs as well as non-arable land. Hydropower can be developed in mountainous or rocky terrain while water from hydro reservoirs can be used for irrigation(Gagnon et al., 2002).

However, future energy option like biomass plantations for energy production through direct combustion or bio refinery and anaerobic digestion can be severely limited by availability of land and hence feedstock(Gagnon et al., 2002).

6.8. Energy Payback Ratio

Energy payback ratio is the ration of energy produced during the power plants normal life span, divided by the energy required to pay for the construction, maintenance and fuel for the power generation facility(Gagnon et al., 2002).

6.9. Environmental Issues and Payback Ration

A system with a low payback ratio requires much more energy to maintain it and which generates more environmental impacts. The environmental impacts for fossil fuels are realized during extraction, transportation, and processing of fuels while for renewable sources, the main impact is from building or facility construction. A payback ratio of close to one implies that the system consumes as much energy as it produces hence does not need to be developed(Gagnon et al., 2002).

LCAs have focused mainly on greenhouse gas emissions from energy in the recent context of climate change commitments. The emissions vary dramatically based on factors like materials used and how they are produced, e.g. aluminum from smelters using hydropower as electricity and smelters using fossil fuels like natural gas and coal to produce the same(Gagnon et al., 2002).

The main benefit of using energy payback ratios as a metric is that is less affected by upstream choices of energy supply, which minimizes the fluctuation in evaluation of greenhouse gas emissions energy payback ratio one of the most reliable indicators of environmental performance. Energy payback ratio as an indicator minimizes fluctuations in results of studies without eliminating them. Renewable energies can have very large variations in energy payback ratios. due to wide variation of site-specific conditions i.e. topography for the case hydro, quality of the wind for wind energy, and solar intensity of solar radiation for solar energy(Gagnon et al., 2002).

6.10. Payback Ratio of Energy Sources

Various analyses show hydropower clearly has the highest performance, with energy payback ratios of 205 and 267 while fossil fuels have of 5 to 7. The value for hydro with reservoir 205 and 267 for run-of-river. Best wind sites have payback ration of about 80 without back up. Biomass has about 27 for power from forestry waste and 5 for. planted trees due to higher energy inputs. The higher the distance of the power plants from biomass sources, the lower the payback ratio. Natural gas has a payback ratio of about 5 with some energy being spent on transportation over long distances. The ratio for natural gas power plants located close to the source of natural gas is higher. With high investment on transportation, the payback ratio for coal is also low at about 5 as well as investment on scrubbing of SO_2, which requires lime and other resources that need transportation and other investment in production and delivery on site and disposal(Gagnon et al., 2002). Table 3 shows the payback ratios for different generation technologies.

Table 3: Payback ratios for generation technologies

	Technology	Payback ratio
1	Hydro with reservoir	205
2	Run –of river hydro	267
3	Wind	80
4	Forestry biomass	27
5	Cultivated biomass	5
6	Natural gas	5
7	Coal	5

From table 3, it is observed that hydro with reservoir has the highest payback ration, followed by wind. Coal, natural gas, and cultivated biomass have the lowest payback ratios.

6.11. Future performance of energy systems concerning the payback ratio

Fossil fuels sources of energy low energy payback ratios which will continue to decline due to reasons like depletion of reserves which tend to be replaced by wells that have higher energy requirement deep into the sea. Exploitation of fossil fuel resources like coal located far away from load centers and power stations increases transport costs by road and rail. Further investment in emission reduction technology like scrubbing of SO_2 can reduce the overall efficiency of coal generation and hence reduce payback ration while capture and sequestration of CO_2 will require huge investment in capital and energy for operation of scrubbing and disposal equipment while noting that sulfur is about 1% of coal and carbon is more than 50% of the coal. Therefore, mandatory investment in emission reduction technologies will reduce the overall efficiency and feasibility of coal and other fossil fuel power plants(Gagnon et al., 2002)..

6.12. Other atmospheric emissions

i.). Health issues

Emission factors are mainly concerned with climate change and acid precipitation, while other types of air emissions have local and direct effects on health. They include particulate matter, toxic metals like mercury and non-methane volatile organic compounds (NMVOC) which directly contribute to smog formation(Gagnon et al., 2002). Table 4 shows other atmospheric emissions from power plants.

Table 4: Other atmospheric emissions from power generation technologies (some data is not life-cycle assessment)

	Technology	NMVOC emissions (t/TWh)	**Particulate matter emissions (t/TWh)**	**Mercury emissions (kg Hg/TWh**
1	Hydropower with reservoir		5	
2	Hydropower run-of-river		1-5	
3	Diesel	1570	122–213	
4	Natural gas c.c. turbines	72–164	1–10	0.3–1
5	Bituminous coal (modern)	18–29	30–663	1–360
6	Lignite: old plant		100–618	2–42
7	Heavy oil: no scrubbing	22		2–13
8	Biomass combustion	89	190–320	0.5–2
9	Nuclear		2	
10	Wind power		5–35	
11	Solar photovoltaic	70	12–190	

From table 4, it is noted that different energy technologies have different range of values for NMVOC emissions (t/TWh), Particulate matter emissions (t/TWh and Mercury emissions (kg Hg/TWh. However, the limitation of the data is that some emissions represent direct emissions from the power plants and not life-cycle assessment values. The analysis shows hydropower, wind power, nuclear energy and natural as energy sources and technologies with lowest emissions(Gagnon et al., 2002).

ii.) Comparing mercury contamination

Some hydro reservoirs are known to release mercury in the food chain, the impact can be compared with that of coal or oil-fired mercury emissions, which contaminate the food chain of many lakes. On average, hydro reservoirs can generate 0.07 kg Hg/ TWh can be calculated while coal is about 200 times more. However, further analysis shows that about half of mercury released by hydro reservoirs is mercury was emitted by coal-fired plants and smelters (Gagnon et al., 2002).

7. Carbon Capture and Sequestration

There continuing and increasing demand to burn coal we in an environmentally acceptable manner fossil fuel power plants produce have impacts like formation of acid rains and photochemical smog formation. Emissions that need control include particulates, NO_x and SO_x and trace elements, polycyclic aromatic hydrocarbons and, importantly, CO_2. This has led to technologies that are more environmentally friendly, by reducing pollutant emissions, called clean coal technologies(Petrescu et al., 2017).

The two ways of reducing coal emissions are efficiency improvement which improves output and lower emissions lower emissions per unit of energy output and application CCS technologies to reduce C_{O2} emissions. by 80–90%. CCS is an arrangement between the further use of fossil fuels to satisfy increasing energy demand and reduction in CO2 emissions. Carbon capture is not a single technology, instead it is a suite of technologies, some of which can be applied to existing coal-fired power stations, while other technologies are still new technologies and are evolving(Petrescu et al., 2017),(Toporov, 2014) .

There are different techniques used to capture the CO_2 released by fossil fuel plants, especially coal plants and to sequester it in storage sites. Three approaches used to integrate CO_2 capture technologies with power generation systems are post-combustion, pre-combustion and oxy-fuel combustion. (Petrescu et al., 2017). In post-combustion technology, carbon dioxide is removed after combustion of fossil fuel. This technology can be implemented as a retrofit option for operating our existing power plants. Technologies that could be employed with post-combustion CCS include adsorption i.e. physical absorption, cryogenics separation, chemical absorption, and membranes technology (Petrescu et al., 2017).

Chemical absorption for CO_2 capture can be applied to post-combustion systems. due to low CO_2 partial pressure in the flue gas in coal power plants. The amine technology is generally dedicated for retrofitting of existing power plants. The major challenge remains minimizing the operation and investment costs related to the technologies(Petrescu et al., 2017). The alternative chemical absorption in aqueous ammonia solutions can be used to selectively capture the CO_2 from the flue gases by use of an ammonia-based solution at reduced temperature in an absorption column. The ammonia solution is regenerated in a desorption column, and the cycle is repeated. The advantage of ammonia-based technology include low reboiler regeneration energy, high CO_2 carrying capacity, it is cheaper, low power consumption in compression of carbon dioxide (Petrescu et al., 2017).

The Ca-looping (CaL) technology is post-combustion CO_2 capture technology suitable for integration in power plants and other large CO_2 emission industrial plants, e.g., cement industry, steel plants. CAL is based on the multi-cyclic carbonation/calcination of CaO at high temperatures range of 800–950 °C. Where CO_2 in flue gases reacts with the solid sorbent (CaO) at about 500–650 °C forming calcium carbonate formation. The carbonate product is then decomposed to produce CaO which is recycled back in the carbonator to absorb more $CO_,$ and a CO_2 stream which is dried and compressed for storage. and the cycle process is repeated(Cormos, 2014).

In the study by (Odeh & Cockerill, 2008) focusing on supercritical pulverized coal, a natural gas combined cycle (NGCC) and an integrated gasification combined cycle (IGCC), with and without CCS, it was observed that for a 90% CO_2 capture efficiency, life cycle GHG emissions are reduced by 75–84% based on technology applied, the global warming potential reduced when MEA-based CO_2 capture is employed, other air pollutants such as NO_x and NH_3 increase leads to higher eutrophication and acidification potentials.

In another study, LCA study of three pulverized coal power plants with/without post-combustion CCS was undertaken. Two reference chains considered were subcritical and ultra-supercritical pulverized coal fired electricity generation. In this study, it was observed that the global warming potential reduced by over 70% when CCS were applied but notable environmental trade-offs encountered are increase in ozone layer depletion, human toxicity, and fresh water ecotoxicity potential. The state-of-the-art power plant having no CCS perform better in eutrophication, acidification and photochemical oxidation potential although we have deeper reduction in emissions in form of SO_x and NO_x in the CCS power plant (Petrescu et al., 2017),(Koornneef et al., 2008).

In the study by (Corsten et al., 2013), comparison between fuel technologies i.e. IGCC, NGCC, oxy-fuel and Pulverized Coal – PC coupled with CCS was performed. It was observed that CCS results in a net reduction of the GWP by 65-84% by power plants in their life cycle i.e., for (PC-CCS) the GWP is reduced by 68–87%, (IGCC-CCS) is reduced by 47–80% (NGCC-CCS), and in (Oxyfuel) the GWP is reduced by 76–97%. However, the deployment of CCS technology in PC, IGCC and NGCC leads to relative increases in eutrophication and acidification compared to power plants without CCS. The assessments of power plants with CCS should consider upstream emissions coal mining, coal transport, and MEA production and downstream emissions incurred in CO2 transport, and CO_2 storage for accurate assessment of environmental performance of power plants with CCS(Petrescu et al., 2017).

In the study by (Manuilova et al., 2014), Post-combustion CO_2 capture combined with CO_2-enhanced oil recovery was investigated using lignite coal as the fuel and post-combustion CCS based on monoethanolamine (MEA). The results showed a significant reduction in global warming and air impact categories. Although some categories associated with soil and water increased, the broad distribution associated with atmospheric release was significantly reduced (Restrepo et al., 2015), (Tang et al., 2014).

Life cycle greenhouse gas emissions evaluation of power plants with carbon capture and storage (CCS) is a critical factor in energy and policy analysis. Studies show that 90% carbon dioxide (CO_2) capture efficiency can be achieved with overall reduction in life cycle greenhouse gas emissions by 75–84% based on technology applied. IGCC technology is the most favorable compared to NGCC with CCS and can achieve GHG emissions of less than 170 g/kWh, IGCC technology is found to be favorable too. Through sensitivity analysis, it is established that coal power plants, have varying the CO2 capture efficiency while the coal transport distance has a pronounced effect on life cycle GHG emissions compared to changing the length of carbon dioxide (CO2) transport pipeline. Whereas the global warming potential is reduced when MEA-based CO_2 capture applied, other pollutants like increase in NOx and NH3 leads to higher impact in firm of eutrophication and acidification potentials(Odeh & Cockerill, 2008).

8. Results and Discussion

Life cycle assessments have identified hydropower, particularly the run-of-river and with reservoir, nuclear energy, and wind power as most sustainable energy options for power generation. Although hydropower with storage or reservoir has high land requirements, the sustainability is enhanced by high capacity factors and efficiency as well as multiple secondary applications like irrigation, domestic water supply, flood control and energy security and high reliability as well as operational flexibility(Gagnon et al., 2002).

Analyses show very attractive performance for nuclear energy in many sustainability parameters. However nuclear energy faces resistance in many parts of the world due to radioactive waste and concerns about catastrophic accidents. However, it remains difficult for LCAs to adequately address such concerns(Gagnon et al., 2002). Natural gas is the cleanest fossil fuel for power generation compared to coal and oil-fired generation. However, natural gas has high emissions, compared to renewable sources of energy. Long distance delivery and exploitation of natural gas is however characterized by high upfront emissions which may be hard to account through LCA(Gagnon et al., 2002; Moses Kabeyi & Oludolapo Olanrewaju, 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022b, 2022e, 2022g).

Coal clearly emerges as the worst option in most criteria i.e., emissions of greenhouse gases, emissions of SO_2, emissions of NO_x, volatile organic compounds, particulates emissions, toxicity, and land requirements. However, coal has a better energy payback ratio only if there is no scrubbing and the process has minimal transportation(Gagnon et al., 2002). The study shows that LCA has numerous analysis tools and data challenges, hence the need to consider the development of spatial and temporal methods. Substantial gaps remain in LCA analysis that considers spatial and temporal factors. It is important for stakeholders, decision-makers, policy makers, and practitioners to have greater understanding of how broadly applicable LCA results are or whether they are just specific to a particular region or a snapshot in time. Life cycle assessments (LCAs) should be a strong basis for decision-making in power generation, Specifications that consider spatial and temporal dimensions would be valuable in making sustainable decisions and create an environmentally sound supply chain and with minimum risks(Gagnon et al., 2002; Jordaan et al., 2021).

Life cycle cost (LCC) is not a financial accounting method, but instead a cost management tool meant to estimate and analyze all the costs associated with a product's existence. The life cycle cost (LCC) methodology has been in use since the 1960s for assessment of economic issues related to products and systems. Today, interest has grown in combining economic and environmental elements in sustainability analysis through integrating LCC and Life Cycle Assessment (LCA) meant to estimate the environmental impacts of the life cycle of a product or service.(Corona et al., 2016; Gagnon et al., 2002). The coupling of LCA and LCC can be achieved by means of E*nvironmental LCC* (eLCC), which is an expansion of conventional LCC considering all direct costs incurred during the life cycle of the product to incorporate externalities having well-defined market price and are likely to be internalized soon. These externalities include greenhouse gas emissions. The study is known as Full Environmental Life Cycle Cost if other environmental externalities are also monetized and incorporated into the analysis (Corona et al., 2016).

Although hydropower with reservoir has high land requirements, considering that it has secondary benefits and applications like provision of water for irrigation, industrial and domestic use, flood control and above water solar power, it is possible to conclude hydro with reservoir has got the highest performance.

Evaluation of life cycle greenhouse gas emissions for power plants with carbon capture and storage (CCS) is important for energy and policy analysis. Analysis shows that if 90% CO_2 is captured, the life cycle greenhouse gas emissions (GHG) can be reduced by 75-84% depending on the type of technology applied. Life cycle greenhouse gas emissions for coal power plants can also be significantly changed by reducing the coal transport distance as well as the length of CO_2 transport pipeline. The global warming potential is also reduced when CO_2 capture is employed although this may increase other air pollutants such as NO_x and NH_3 leading to higher eutrophication and acidification potentials(Odeh & Cockerill, 2008). Investment in CO_2 removal is partially offset by an increase in greenhouse gas emissions in the up- and downstream processes caused by the CCS infrastructure. The most notable environmental trade-offs caused by CCS are the increase in human toxicity, ozone layer depletion and fresh water ecotoxicity potential. Power plants without CCS are better in eutrophication, acidification and photochemical oxidation potential although they are outperformed in SO_x and NO_x by CCS power plants although the reductions can be offset by increased emissions in the life cycle leading to energy penalty and a factor five increase in NH_3 emissions(Koornneef et al., 2008).

For power plants without CCS, the contribution to the global warming potential (GWP), acidification and eutrophication comes from direct emissions while for power plants with CCS, the main contributor to GWP, acidification and human toxicity potential comes from indirect emissions. It is therefore important to consider emissions from upstream operations like coal mining, coal transport, and MEA production, and downstream operations like transport of captured CO_2 and CO_2 storage for accurate assessment the environmental performance of power plants (Corsten et al., 2013).

The Life-cycle assessment (LCA) is designed to meet different functions and objectives. The various applications include (Gagnon et al., 2002):

i.) Analysis of the performance of modern commercial technologies even when the performance of older technologies is totally different.

ii.) LCA can be used to present short-term performance, not necessarily the long-term or expected future performance.

iii.) LCAs can effectively use typical conditions of region or technology(Gagnon et al., 2002).

9. Conclusion

The use of life cycle analysis (LCA) for power generation technologies has a promising future as the world seeks for solutions for meeting the global growing electricity demand for electricity while meeting emissions and climate targets and sustainable development. Although they have some limitations, the LCAs of power generation technologies can shed light on the life-cycle energy, the greenhouse gas emissions, air pollutant emissions, and water consumption and other environmental and sustainability concerns. This study showed that exergy-based method is an improvement on the conventional life cycle assessment (LCA) method, and both LCA and exergy can be used in the assessment of. resource consumption and related environmental impacts. Exergy based lifecycle assessment (LCA) is more detailed in terms of assessing the quality of resource consumption and related environmental impacts. Exergetic LCA includes assessment of efficiency, recovery factor, and/or emission rate of energy resources. The characterization factors developed using the exergy based LCA method are more accurate and robust compared to the conventional LCA method. Thia is because whereas the former approach is based on standard thermodynamic properties like temperature, and pressure, the latter relies on subjective factors like s fate, exposure, and effects.

By application of LCAs it is shown renewable power technology options compare favorably with conventional and fossil-fuel based generation technologies. Most renewable generation technologies outperform conventional technologies with respect to both life-cycle primary energy use and air pollutant emissions. The conventional or traditional environmental analyses are often limited to operational impacts alone like power plant stack emissions, effluent discharge to the environment but the LCA perspective considers both upstream and downstream issues in addition to operation and maintenance level impacts. Therefore, the LCA approach naturally increases the understanding of the potential environmental trade-offs between technologies. And identify their competitive advantage. Carbon sequestration, scrubbing of CO_2 emissions from flue gas is complex and expensive. For sulfur, the benefits of scrubbing technologies are justifiable by the fact that the waste generated by these technologies are manageable, but for CO_2 emissions, it is complex because carbon is responsible for about 50% CO_2 emissions of the coal, while sulfur is 1% or 2% in coal, making capturing all this carbon and pumping it in deep underground reservoirs is energy intensive, polluting, and expensive hence fewer relative benefits. Therefore, the next few decades, may not see major technologies developed to solve the climate change challenges. Therefore, energy efficiency measures and renewable energy technologies will remain the best options to reduce greenhouse gas emissions in the power generation.

The global warming potential reduced by over 70% when CCS were applied but notable environmental trade-offs encountered are increase in ozone layer depletion, human toxicity, and fresh water ecotoxicity potential. The state-of-the-art power plant having no CCS performs better in eutrophication, acidification, and photochemical oxidation potential although we have deeper reduction in emissions in form of SO_x and NO_x in the CCS power plant. It is therefore important to consider emissions from upstream operations like coal mining, coal transport, and MEA production, and downstream operations like transport of captured CO_2 and CO_2 storage for accurate assessment the environmental performance of power plants.

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