Indicators of Sustainable Energy and Electricity

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Abstract

The concept of sustainability has received much attention globally because of its multidisciplinary nature and future goal which is sustainable development. The concept relies on three basic pillars of the economy, environment, and society. Sustainable energy has two additional pillars of technology and institutional pillars. Sustainable energy systems refer to systems that can meet present demands by maintaining an adequate balance between the economy, environment, and society, while ensuring that the energy resources do not get depleted and remain available for future use. This study identified sustainability indicators for energy sources. The various sources of energy were assessed for sustainability based on indicators like price of power generated, lifecycle greenhouse gas emissions, resource availability, conversion efficiency, land requirements, social impacts, and water consumption. In the assessment, indicators were assumed to have equal importance to sustainable development and were equally important in ranking energy sources based on their sustainability. The study demonstrated that renewable energy resources are more sustainable technologies with wind power stations having the highest rank in sustainability followed by nuclear, hydro, and solar. Wind was ranked the most sustainable followed by hydropower, photovoltaics and then geothermal while coal was the least sustainable. Coal and nuclear are the most favorable based on price of electricity produced but based on average prices, geothermal and hydro have the lowest possible prices and hence most favorable. Among renewable sources, photovoltaics has the highest average and overall cost of generation, although it remains cheaper than gas and coal at the lowest limit. On electrical efficiency, hydropower has the highest efficiency while photovoltaics has the lowest electrical efficiency. Greenhouse gas emissions were low in all non-fossil fuels, with Wind, hydro and nuclear have lowest values of greenhouse gas emissions while coal has the highest greenhouse gas emissions.

Key words:
life cycle assessment; sustainability assessment, sustainable energy; sustainable development; renewable energy; sustainability indicators.

Introduction
Although energy is essential to economic, social development and improved quality of life, most of the energy is currently produced and used in ways that are not sustainable. To assess progress towards a sustainable energy future, energy indicators that can measure and monitor important changes will be needed. The supply of reliable, and adequate energy products and services at an affordable cost, and in a s secure and environmentally friendly manner and energy that conforms with socioeconomic development needs of the people, is essential for sustainable development. This is because energy is necessary input for eradication of poverty, improving human welfare and to raise peoples living standards(M J B Kabeyi & A O Olanrewaju, 2023; M. J. B. Kabeyi & O. A. Olanrewaju 2023b). The concept of sustainability relies on three basic pillars: i.e. economy, environment, and society. For sustainable energy systems, it is a system that can meet present demands by maintaining an adequate balance between economy, environment, and society, without depleting the energy resources for future use.

Energy system sustainability assessment requires several indicators from the five dimensions. One popular method used to evaluate energy sustainability is the multicriteria decision analysis (MCDA) method. This study presents an overview of the indicators used to assess energy system sustainability (Khan 2021). The need exists to identify and quantify sustainability indicators that may be site-specific and from several sources and sometimes are barely systematized and highly heterogonous. Concerns have been growing over the environmental, economic, and social impacts of power systems from different power plants. Whereas economic and technical indicators are well known for some power plants others are still under development. On the other hand, social indicators are still under development and their data is yet to be standardized (Kabeyi & Olanweraju 2022; Vega-Coloma & Zaror,2022). The current power generation practices should be changed to meet growing demand for electricity with minimal impact on the environment through measures like increased energy use efficiency especially for combustion technologies, and increasing the share of alternative energy generation technologies like hydropower, wind energy, geothermal, biomass combustion and gasification, solar and tidal power(Kabeyi & Olanweraju 2022). Increased use renewable energy sources enable freedom from price fluctuations, trade and transport issues associated with fossil fuels and increase energy security for energy deficient countries. There is need for careful sustainability evaluation since the traditional sources i.e., coal, oil and gas remain highly reliability and cheap. (Evans & Strezov 2010; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju 2022g).

Fossil fuels continue to dominate the global electricity generation sector making it a leading contributor to anthropogenic greenhouse gas emissions since their combustion releases large amounts of carbon dioxide and other pollutants to the atmosphere. Another sustainability challenge for fossil fuels is that their resources are ultimately limited and will be depleted soon or later. Although coal is a fossil fuel, its resource reserves are abundant, excessive use in power generation is responsible for the greatest share greenhouse gas emissions from power sector. This is because coal combustion emits huge amounts of pollutants to the environment like NOx, CO and SO_2, particulate matter, and air toxins(M. J. B. Kabeyi & O. A. Olanrewaju, 2023b). Coal and peat fuels account for close to 40% of the global electricity generation, while fossil fuels combined account for over 62% global electric power generation.(Moses Jeremiah Barasa. Kabeyi & Akanni O Olanrewaju 2020; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022f). Although the share of renewable sources is growing, their current market shares, except for hydro power remain low e.g.in 2008 solar accounted for only 0.02% global power generation even after growth by 33% between 1997 and 2005. Wind power grew by 50% between 1971 and 2004 but accounted for just 0.5% of total global generation in 2004 with 82 TWh generated globally(Evans & Strezov 2010; M. J. B. Kabeyi & O. A. Olanrewaju 2023e).

The reliance on fossil fuels for power generation and other energy applications has been polluting the environment as the resources drastically get depleted(M. J. B. Kabeyi & O. A. Olanrewaju, 2023a). As compared to fossil fuels and nuclear, renewable energy sources have no limitation in supply, and have minimal impact to the environment. It is therefore important to gradually replace the non-renewable energy sources with renewables(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022d). To tackle the challenges of depletion and environmental crises. Renewable energy sources are clean, inexhaustible, cheaper, and more abundant compared to fossil fuels. It is expected that by the year 200, renewable sources will account for about 40 percent of global energy supply (Asakereh et al. 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju 2022e).

Sustainability in power generation is aimed at increasing the potential of continuous production, hence reliability, minimize waste, keep at low level the risks to human health, minimize consumption of inputs. Therefore, sustainability in energy production is defined with the Green Energy concept whose aim is maintain lowest possible level of natural resources consumption minimize harmful gas emission and apply conversion methods with minimum wastage of resources. This will contribute to the slowing down the global warming and climate change, create jobs and more realize economic development (M. Kabeyi & O. Olanrewaju 2022; Onat & Bayar 2010).

The demand for sustainability measurement has been due to concerns over environmental and social issues arising from production and use of energy from different sources. In this study, the tools that can be used to assess the interplay between sustainability issues and stakeholders, are presented in this study as well as the approaches and the metrics adopted to develop a sustainable performance measurement system, along with sustainability reporting practices (Longo et al.2021)

Life Cycle Assessment

The application of life-cycle assessment (LCA) to power generation planning and technologies is a vibrant research pursuit as the world seeks ways to meet growing electricity demand with reduced environmental and human health impacts. LCA helps improve the understanding of the life-cycle energy, greenhouse gas emissions, air pollutant emissions, and water-use implications of generation options. LCA facilitate assessing and comparing generation technologies in an analytically thorough and environmentally holistic manner for more sustainable deployment decisions (M. J. B. Kabeyi & O. A. Olanrewaju, 2023a; Masanet et al. 2013).

Life cycle analysis (LCA) is an internationally accepted tool used to evaluate the impact for a product or service, hence the LCA of power plants enable direct comparison of a range of impacts by breaking them down into relative consequences like effect of wind turbines on migratory birds, potential incidence of leukaemia clusters near nuclear power plants, methane release by hydropower plants etc. other methods of assessing sustainability, include input–output analysis, energy and mass balances, emergy (embodied energy) accounting but LCA is a combination of these tools, and gives a more comprehensive method currently available(Evans et al., 2009).

Factors Affecting the Development of Alternative Electric Energy Resources

Alternative energy resources often refer to renewable energy resources. The term currently includes hydrogen cells and nuclear power systems. Factors influencing successful development as well as limitations to alternative energy resources, can be grouped into perceptual, political, legal and financial depending on a countries level of development (Onat & Bayar 2010).

Perceptual factors

Other than nuclear systems the perceptual disadvantage of alternative energy resources is their inherent complementary role. The alternative energy technologies are generally new, with little and do not have proven success in installation, operation, and maintenance and often still under research and development. It is generally assumed that alternative energy resources that supply small scale, dispersed, instable energy generation cannot provide sustainable energy. There is perception that the alternative sources are complex systems that are difficult to operate and maintain, especially in developed countries. Nuclear power plants are perceived very pessimistically due to radioactive wastes and impact of accidents like the Chernobyl accident and The Fukushima Disaster (Onat & Bayar 2010; WISE 2017). The need to diversify electricity sources amidst continuous increase in electricity demand and concerns over greenhouse gas emissions and global warming, has generated demand for new energy resources. Although public opinion pressures sensitive to environment are effective in developed countries than the developing, use of domestic resources and coupled with high expectations that foreign investment are attracted keeps the hope for in developing countries in alternative sources of energy(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju,2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju 2022a).

3.2. Political Factors

Lack of comprehensive and harmonized policies to support the energy market faces brings obstacles to the deployment of power plants. This creates political structures that support financing of fossil energy resources at the expense of alternative sources of energy. For many countries, the main policies still do not consider social-environmental effects of fossil fuels while contributions of clean and environment friendly energy sources are ignored. The rearrangement of energy markets for many developed countries are generally focused on the principle of non-interference that allows private sector to limit the investment in renewable resources. Rapid development of energy demand for developing countries and their desire creates room for nontransparent and open-ended decisions which creates irregular and unsustainable energy infrastructure developments. Short-term policies which promote conventional sources of energy generate negative impacts on environment particularly development of many fossil fuel power plants which rely on expensive fuels across the power system(Onat & Bayar 2010).

Successful development of alternative energy sources requires several measures like climate change taxation, sensitization, application of green protection certificate and enforcing of alternative energy policies. Other measures are promotion of rural electrification and equitable distribution of energy to all regions for developing and developed countries (Onat & Bayar 2010).

3.3. Legal factors

Many developing countries and some developed countries are yet to enforce transparent and effective laws on energy. The available environmental laws are not sufficient while many. existing laws are not adequately executed (Onat & Bayar, 2010). There is a need to facilitate international credit companies and financial institutions to enhance support for environmental projects. Enforcing legal regulations and laws that encourage use of renewable energy resources and developing a legal framework to support private sector make important contributions to energy development should be priority(Onat & Bayar 2010).

3.4. Economic factors

The most important economic disadvantage of alternative energy sources except for nuclear energy is deficiency in financing structures for small energy projects as they are designed for big projects. This creates ineffective and irregular competition between the conventional energy projects and the alternative or non-conventional sources. The initial investments costs of alternative energy technologies are generally high while the external costs are often not considered. Fuel cells are seen as highly risky group in terms of financial and marketing strategies while wind and photovoltaic transformation systems, particularly in respect to research and development (R&D) activities, classify photovoltaic cells as high risk technologies group in terms of marketing and finance(Onat & Bayar 2010). These economic challenges facing alternative sources of energy can be solved by developing financial products for different renewable energy projects. (Onat & Bayar 2010).

Sustainability Factors in Power Generation

It is necessary to understand the environmental footprint of projected energy growth scenarios, focusing on sustainable energy generation practices to direct future investment. The full environmental footprint accounts for the entire energy chain lifecycle, right from the mines g and processing to direct and indirect emissions, waste disposal and/or recycling. In the assessment of each stage of the chain, key indicators must be identified to allow quantification of impact. (Evans et al. 2009; Kabeyi & Olanweraju 2022).

There is a range of other significantly important indicators that must be considered in sustainability evaluation of energy generation technologies. In addition to the traditional form of the environment, the human social economic environment is also impacted by electricity generation methods. The work presented here seeks to assess and rank the relative sustainability of non-combustion renewable energy technologies, photovoltaic, wind, hydro and geothermal, using data collected from the literature(Evans et al. 2009; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju 2022e). important sustainability indicators used in this assessment with the main justification for their selection are price of electricity generation unit, greenhouse gas emissions, availability, water usage, land requirements, efficiency of energy transformations etc.(M. J. B. Kabeyi & O. A. Olanrewaju 2023e; Kabeyi & Olanweraju 2022).

Environmental Indicators

Important environmental indicators, include ozone layer depletion potential (ODP), photochemical oxidation potential (POP), freshwater aquatic ecotoxicity potential (FAEP), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), marine aquatic ecotoxicity potential (MAETP) and terrestrial ecotoxicity potential (TEP). These indicators can be valued based on ISO 14.040-44:2006 standards for life cycle assessment using the CML 2000 v.2.05 mid-point impact models(Vega-Coloma & Zaror 2022).

Carbon Dioxide Emissions

Greenhouse gas emissions are one of the most important criteria for determining the cleanest energy sources. GHG emission is expressed as the amount of equivalent CO_2 per kWh produced and indicates its effect on global warming (Asakereh et al., 2022). Fossil fuel power plants like coal and natural gas have higher emissions of carbon dioxide compared to other sources e.g., average emissions from coal are about 1004 g carbon dioxide per kW h while natural gas emits between 500–600 g. which is like fuel cells. Emissions from geothermal are about 170 g/kW h. on average basis. Emissions from wind and solar systems mainly occur in the production of PV panel and auxiliary elements while operation level emissions are as low as 2–3% of the lifecycle emissions. The main environmental concerns foe nuclear power plants are negative the radioactive wastes, while carbon dioxide emissions are close to the wind and solar systems making nuclear energy cleaner than fossil fuels (Onat & Bayar, 2010). Table 1 shows relative emissions from various energy sources and their relative Ranking.

Table 1. average greenhouse gas emissions expressed as CO_2 equivalent for individual energy generation technologies.

		g CO2−e/kW h	
1	Photovoltaic	90	3

2	Wind	25	1
3	Hydro	41	2
4	Geothermal	170	4
5	Coal	1004	6
6	Gas	543	5

From table 1, it is noted that wind followed by hydro has the lowest greenhouse gas emissions while coal followed by natural gas have the highest greenhouse gas emissions per unit power produced.

Fresh water Consumption

Water is essential for cooling thermal power plants like coal, nuclear, natural gas, and biomass while bioenergy is needed for production of feed stocks. All power plants and conversion systems require water at some point of their life cycles. Mining and fuel processing and manufacturing itself determines upstream water impacts, while conversion mechanisms of specific conversion technologies influence the operation-related water consumption and impacts(Masanet et al. 2013). Impacts of water use can be classified into three categories i.e., withdrawal, consumption, and contamination. Consumption is through evaporation, transpiration, or incorporation of water during the operations of the power plant like water evaporated in cooling towers. Consumption reduces the amount of water immediately available for other uses e.g., human consumption as potable water, industrial and agricultural needs. Availability of is a serious concern for water scarce regions as well as regions where climate change is likely to increase the water stress Technologies like hydropower significantly increase water consumption through evaporation from reservoirs (Masanet et al. 2013).

Water withdrawal is the amount of water temporarily diverted from natural sources for applications like cooling of power plants. Water withdrawal is significant for power plants and industrial processes in developed countries where about 45% of freshwater withdrawals. Withdrawal has a negative impact on aquatic ecosystems if it returns with effluents at a higher temperature compared to source temperature. Withdrawal for hydropower applications can increase the dissolved oxygen content besides changing the water flow patterns(Kabeyi & Olanweraju, 2022; Masanet et al., 2013). Lack of water withdrawal or reduced withdrawal may affect power generation efficiency and even plant safety e.g. for nuclear power plants (Masanet et al. 2013).

Fuel processing can lead to water contamination and ecosystem damage and hence increase the risk to human health and safety. Upstream fuel process activities like mining operations and fuel processing can reduce water quality like contamination of waterway from mine tailings or sludge ponds, and emissions from fossil-fuel combustion which pollute the air and eventually deposited into water bodies. Fly ash from coal power plants from holding ponds may leach into the groundwater systems, and even cause dam failures causing downstream flooding with toxic slurries. In nuclear power generation, uranium mining affect water quality with contamination occurring during fuel reprocessing. Upstream production of solar PV cells, related upstream mining and manufacturing operations also leads to release of hazardous pollutants to water from industrial facilities for production of renewable technologies plant and equipment even though operation related water consumption may be minimal (Masanet et al. 2013).

Water consumption by energy production systems is a very important indicator of sustainability. The main challenge remains how to get an accurate value which remains very difficult especially for the renewable energy resources. From literature, it is indicated that nuclear plants have highest water freshwater requirements mainly for cooling of the reactors varying between 30 kg to 100 kg per kW h based on the cooling technology and reactor design. Hydro power plants create significant water loss of 65–70 kg per kWh through evaporation., while natural gas consumes 15–30 kg fresh water per kWh. Fuel cells consume have low fresh water requirements of about 2 kg/kWh while solar and hydroelectric power plants consume less than 1 kg per kWh(Evans & Strezov, 2010). The operation of solar and wind power stations consumes negligible amounts of fresh water. For geothermal, fresh water consumptions depends on the resource type and conversion technology(Kabeyi & Oludolapo, 2020), but generally between 2kg–300 kg/kWh depending on the resource and technology, with those power plants having brine reinjection having the lowest water consumption(M. J. B. Kabeyi & A. O. Olanrewaju 2022). Figure 1 below shows a comparative graphic of power generation systems with respect to output and water consumption.

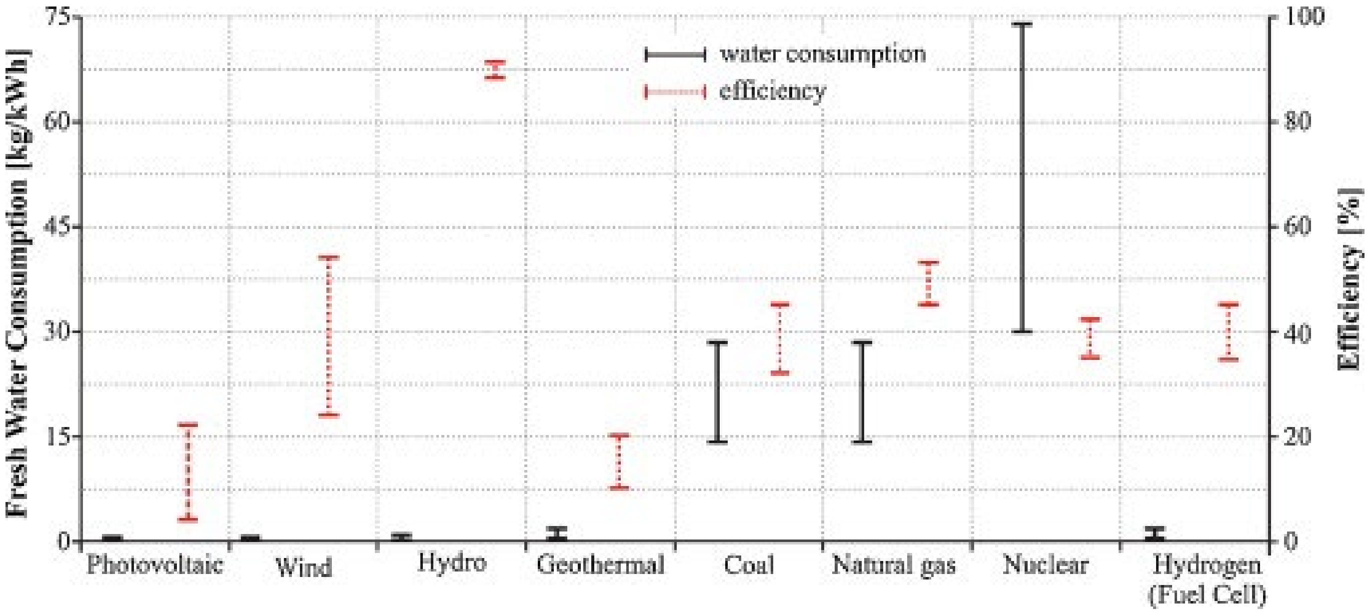

Figure1. Efficiency–freshwater consumption comparisons of power generation systems.

Figure 1shows the water consumption by various power plants with nuclear having the largest average water consumption, while geothermal and photovoltaic has the lowest average water consumption per unit power produced. Accurate data quantifying water consumption during electricity generation is difficult to obtain, particularly for renewable energy technologies. It is difficult to distinguish between water withdrawal (water that is taken, then returned to circulation) and water consumption (water removed from circulation outside the plant/unit). Water consumption seems to be a more accurate indicator of sustainability, since it is water 'lost' from circulation that will have an impact. (Evans et al. 2009).

Land use

Land use is one of the key requirements for energy production from renewable sources for specific installed capacity. Land occupancy for power generation directly affects the environment and the surrounding landscape. Land requirement is affected by the intensity of renewable energy and the efficiency of the conversion technology(Asakereh et al. 2022; Masanet et al. 2013).

Data on land requirement is based on the entire life cycle of the energy system, from extraction, power generation and waste disposal, capturing both direct and indirect land use(Masanet et al. 2013). According to literature, traditional fossil-fuel power plants have lower land-use requirements do the renewable energy sources. For coal and natural gas, upstream impacts of mining or extraction and transportation dominate the land-use requirements. Surface coal mining has more direct land use compared to underground coal mining. In nuclear power plants, fuel mining and power plant site use account for two-thirds of life-cycle land use. Generally, nuclear has got more land coverage compared to coal-fired plants, mainly due to safety considerations in layout design(Masanet et al. 2013).

For renewable energy sources, the largest land use takes place during the operation stage of lifecycle except land use associated with bioenergy production from dedicated feedstock. The PV technology, especially the rooftop-mounted PV panels, have almost negligible. Additional land requirement. Hydropower has land requirement that is site-specific and depends partially on the land flooded in reservoir creation. Run-of-river hydropower has less land use than does reservoir hydropower. Renewable power generation technologies generally have static land use requirements compared to fossil-fuel-based technologies e.g., after construction, wind and photovoltaic plants have no additional land requirements. Additionally, other than bioenergy, renewable power technologies are not sensitive to land quality, and they often allow multiple land uses e.g., the PV panels and wind turbines can be deployed farmlands, deserts, or brownfields. Other land benefits of renewable technologies are they rarely change the land's geographical properties and have less threats to the soil nutrient, functional degradation, and destructive land transformation. This implies that evaluating land use alone may not completely reflect the real land impacts of power generation technologies. There is therefore need to assess the impact and compare more data like the duration and reversibility of land transformation, desirable land properties and conditions, and its use quality(Masanet et al.2013).

Land loss due to power generation can be examined using many different aspects. In case of a nuclear disaster, a nuclear power plant may affect thousands of km^2 of land area in a manner that renders the land unusable for very many years. Hydropower also can cause inevitable land destruction during dam and reservoir development. There are several negative effects on the historical and natural structure of barrage lakes. Leakages from petroleum may also cause land and water pollutions requiring high cost of cleaning (Evans et al.2009).

Sustainability assessment considering land use identifies nuclear, coal, and natural gas power stations as the most attractive and sustainable. Natural gas and nuclear power have the most advantageous land use values of 1–4 km^2/GW, which increase for coal due to operational requirements for coal like ash disposal and fuel storage facilities and space(Kabeyi & Olanweraju 2022). The value for While photovoltaic systems is generally 28–64 km^2 per GW and is the advantageous system among renewable energy resources in terms of land use. Wind power has land requirements of 50–150 km^2 / GW. Climatic conditions may change the rate of land use to significant levels like 20–40%. For hydro, land requirements and deterioration may vary based on regional geographical characteristics. The land use value for such systems varies between 75–750 km^2 per GW for hydro and 18-74 km^2/GW for geothermal. The land values represent total areas covered by the physical structure of the power system. This analysis shows that renewable energy resources, particularly the photovoltaic systems, are the most sustainable. Under such circumstances, energy produced by the Photovoltaic system will be about 40% more in average(Onat & Bayar 2010)

Wind and Photovoltaics have almost similar land use characteristics, with impacts from materials for unit manufacture and disposal/recycling and they do not require any further mining footprint. Solar can be roof-mounted, to yield negligible footprint during plant use while wind can be integrated into agricultural land which reduces the share of the footprint which is an average of .72 km^2/TWh for wind power, minus any share of this to agriculture. While photovoltaic land occupation of 28–64 km^2/TWh with no dual-purpose allocation(Evans et al., 2009; Moses Jeremiah Barasa. Kabeyi & Akanni O Olanrewaju, 2020).The footprint for Hydro power varies significantly based on local topography. But has an average land requirement of 750 km^2/TWh although in some studies, the land requirement for hydro can be as low as 73 km^2/TWh. For geothermal power plants the surface footprint is relatively small, with major since the major elements located underground(Kabeyi, 2019; Kabeyi & Olanrewaju, 2021; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022c). However, as a result of the risk of land subsidence above the earth's surface, the entire geothermal field is used in footprint determination which yields 18–74 km^2/TWh (Evans et al., 2009; M J B Kabeyi & A O Olanrewaju, 2020; Kabeyi & Olanweraju 2022)

Economic Indicators

The economic indicators of sustainability are quite sensitive to market constraints. Levelized electricity cost is one among many economic indicators of sustainable power development and generation. (Vega-Coloma & Zaror, 2022). Other indicators are total capital cost (TCC), and fuel sensitivity price (FSP)

i.) Investment cost

The investment cost is an important economic criterion for ranking renewable energy sources with wide application. Inventors seriously consider the cost and benefits of investing in investment decisions. The cost of investment influences the success and economic viability of power plant projects. Data on investment cost in electricity generation technologies can be obtained from literature (Asakereh et al. 2022).

ii.) Operations and maintenance cost.

The operations and maintenance O&M) costs consist of operating costs like salaries, energy, services costs, and cost of inputs of inputs. The maintenance aspect consists of maintenance costs, like cost of preventive maintenance and measures to improve plant reliability(Asakereh et al. 2022).

iii.) Electric cost/Price of electricity generation

This refers to the total cost per unit of power produced over the lifetime of the power plant. Preferable sources are those with lowest cost generated power since the goal is to minimize cost. The electric cost is often expressed in dollars per kWh throughout the lifetime of the power plant(Asakereh et al., 2022). The different generation technologies produce power at different costs influenced by costs related construction, installation, commissioning, operation, maintenance, decommissioning, and final recycling and/or disposal, transmission, distribution and cost of capital and insurance. For Intermittent renewables like wind and solar, extra costs include backup and storage. Photovoltaics tend to have a wide range of electricity prices because of the large range of solar cells types available, variations in specific location characteristics, and solar intensity and duration variation. The fossil fuel sources i.e. coal and gas have the smallest price variation for electricity produced(Kabeyi & Olanweraju, 2022). Table 2 demonstrates the price variations of different sources.

Table 2. Average electricity price by sources

		Price in USD ($)	Rank
1	Photovoltaic	0.24	4
2	Wind	0.007	2
3	Hydro	0.005	1
4	Geothermal	0.007	2
5	Coal	0.042	5
6	Gas	0.048	6

From table 2, it is noted that hydro supplies the cheapest source of power among the 6 sources considered followed by geothermal, wind photovoltaic. Gas and coal supply the most expensive power.

Social Indicators

There are many social indicators for social sustainability analysis like corruption index (CI), employment creation, intergenerational issues, measured as human toxicity (HT) and abiotic depletion (ADP and local community impacts measured as corruption index (CI) (Vega-Coloma & Zaror, 2022). The common social indicators are discussed.

Job creation.

Energy projects create many jobs over their life cycle for local people and thus contribute to development and increase local welfare. Direct and indirect jobs in the renewable energy sector were about 11.5 million globally in 2019. Solar ranked first with one-third of the total workforce (Asakereh et al. 2022).

Social acceptance.

Social acceptance measures of resistance and acceptance of the energy project by the local community. Social acceptance influences project starts and duration of the project hence the overall cost. Also, creating an energy supply project can lead to social progress in the local community and the region. Social acceptance is a qualitative variable, that is not directly measurable (Asakereh et al. 2022). There is a wide range of positive and negative social impacts of power generation. Renewables offer the opportunity for electricity supply in some areas that otherwise may not exist. Renewable technologies provide independence from nonrenewable sources like fossil fuels which must be imported by the non-oil producing countries The various social impacts and relative magnitudes for different conversion technologies are(Evans et al. 2009)

Today, one of the most sustainability indicators of energy resources is the social effects. Electric energy production technologies create important effects on the social life of societies. Their direct and indirect risks on human health, air pollution, global warming and external costs that occur because of losses because of sudden accidents affect the point of view of societies on energy production technologies. It is very difficult to determine the monetary value of external costs. The environmental performance indicators determined by OECD in 1998 and sustainability development indicators established by the Nuclear Energy Agency in 2002 for the nuclear systems summarize the environment and human aspects of social costs.

Technical criteria

Electricity generation potential

Generation potential is a measure of capacity of energy resources to generate electricity. The alternative with more potential for electricity generation is better. Generation capacity is affected by climate conditions, time, and seasons. For example, potential of solar and wind energy to generate electricity depend on sunshine, and wind speed, respectively (Asakereh et al. 2022).

Availability and technological limitations

Availability of a technology is the percentage of time spent in operations out of the total required time. As long as there is water, hydropower is the technology with highest availability of all technologies. Hydropower has high flexibility which enables it to change output quickly within seconds which makes it ideal for supply of both base load and peak load. Thermal power plants namely Coal, biomass, geothermal, and nuclear are widely used for baseload power supply since they have high reliably, slow response and steady operation. Natural gas power plants can supply base and peak power. The intermittence of wind photovoltaics makes them complicated in terms of specific application (Evans & Strezov, 2010; Evans et al.2009). However, advances in smart grid technology make them ideal for both base and peak load based on availability.

The Earth intercepts over 170 000 T W h/year of solar radiation from the sun. They vary from place to place greatly based on geographical location and season. The limiting factors for photovoltaics are storage at nights and cloudy days when it is difficult for the sun to power the cells. Wind too suffers from intermittency problems variability, but distribution over large geographical area can be used to alleviate fluctuations. Wind turbines won't operate at very high wind and low wind speed. This is because turbines may not technically operate at above 25 m/s as they can get damaged while at low speeds below 3 m/s, they may not start rotating. (Evans et al. 2009).

Geothermal power is geographically limited but is attractive for provision of base load power. The lifetime of a geothermal power plant is prolonged through reinjection to refresh and restore the balance in geothermal fields for continuous generation. Another benefit of reinjection is reduction in risks of seismicity and surface (Evans et al. 2009).

i.) Efficiency

Energy efficiency is a measure of the amount of useful energy obtained from an energy source using a given technology. Energy efficiency reduces energy demand and related. More efficient resources are preferred. (Asakereh et al. 2022).

Hydroelectric electric power plants are the most efficient conversion systems. The system's loss is mainly due to evaporation with no fuel consumption. The output of a synchronized hydro electric generator is more than 90%(Onat & Bayar, 2010). The efficiency of wind power plants varies based on geographical conditions but generally ranges between 24–54%. Good wind energy resource, in a well selected location can yield efficiency greater than 40%(Evans et al., 2009). Among the thermal power plants, geothermal power plants have lowest efficiency mainly on account of low geothermal resource temperature which reduces thermal efficiency significantly (Evans et al., 2009; M. J. B. Kabeyi & A. O. Olanrewaju, 2022; Kabeyi & Oludolapo 2020). The fuel cells, nuclear and coal power stations have an efficiency range of 30–45%. The efficiency of natural gas power stations is 45–55%. The structure of the solar cells influences the efficiency of photovoltaic systems, with the market being dominated by silicon cells.

he highest output of solar cells is 30–35% but use of Nano technology can increase it to 66% theoretically. Therefore, in the near future, solar cells with efficiency range of 40–50% will be a reality (Onat & Bayar, 2010). According to (Evans et al. 2009), the photovoltaic efficiency largely varies with the cell types used but ideal cell efficiency is about 30%. The crystalline silicon cells which include multi- and poly-crystalline are the most efficient while the amorphous silicon cells have the lowest. Table 3 shows the efficiency of various power plants.

Table 3. Efficiency of power plants (Evans et al. 2009)

	Technology	Efficiency Range (%)	Average (%)	Rank
1	Wind	24-54	39	3
2	Fuel cells	30-45	37.5	4
3	Coal	30-45	37.5	4
4	Nuclear	30-45	37.5	4

5	Natural gas	45-55	50	2
6	Geothermal	10-20	15	9
7	Photovoltaics	4-30	17	8
8	Coal	32-45	35.5	7
9	Hydro	≥90	90	1

From table 3, it is noted that hydropower has the highest efficiency among all the generation technologies. Hydro is followed by natural gas and fuel cells as power plants with leading efficiency. Geothermal has the lowest efficiency followed by solar power plants.

Technological maturity level.

This represents the level of reliability, and the extent existing conversion technology has spread locally, regionally, nationally, and internationally and its commercial access. Mature technology is one that is tested and has been in use for a long time, with identifies identified, problems and solution (Asakereh et al. 2022).

ii.) Possibility of decentralization

Decentralization of generation is an important technical consideration as it reduces power transmission and distribution challenges and costs. Localized generation reduces the vulnerability of energy security. Diversification of energy sources and proper distribution of energy resources is one of the main strategies to avoid dependence on one or two types of energy or centralized generation(Asakereh et al., 2022).

Results And Discussion

Energy sustainability refers to a state of equilibrium between social, environmental, economic, and technical dimensions(Moses Jeremiah Barasa. Kabeyi & Akanni O Olanrewaju, 2020; Vega-Coloma & Zaror, 2022). Delivery of uninterrupted electric energy to consumers is a very important socio-economic objective of sustainable energy and electricity. The world is witnessing rapid growth in electricity demand partly due to growth in population and technological developments particularly in industry. Increasing demand for sustainable development, requires that consumable resources are used in the most productive manner, use minimum level and quantities, and mitigate the negative effects on the environment and human health (Kabeyi, 2020; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022f). in definite areas, while some remain in the background. Energy investments vary based on various variables like the purchasing power, education level, income distribution, health standards, nutrition, literacy rates, biological variety, average lifespan, employment rates, work power and employment rates of that work power, accessibility opportunities for basic raw materials, credit note, etc. The effects the sub-parameters on energy investments and their significance order vary from one country to another(Niu et al. 2008; Onat & Bayar 2010) Various sustainability parameters can be used in the assessment as summarized in figure 2 below.

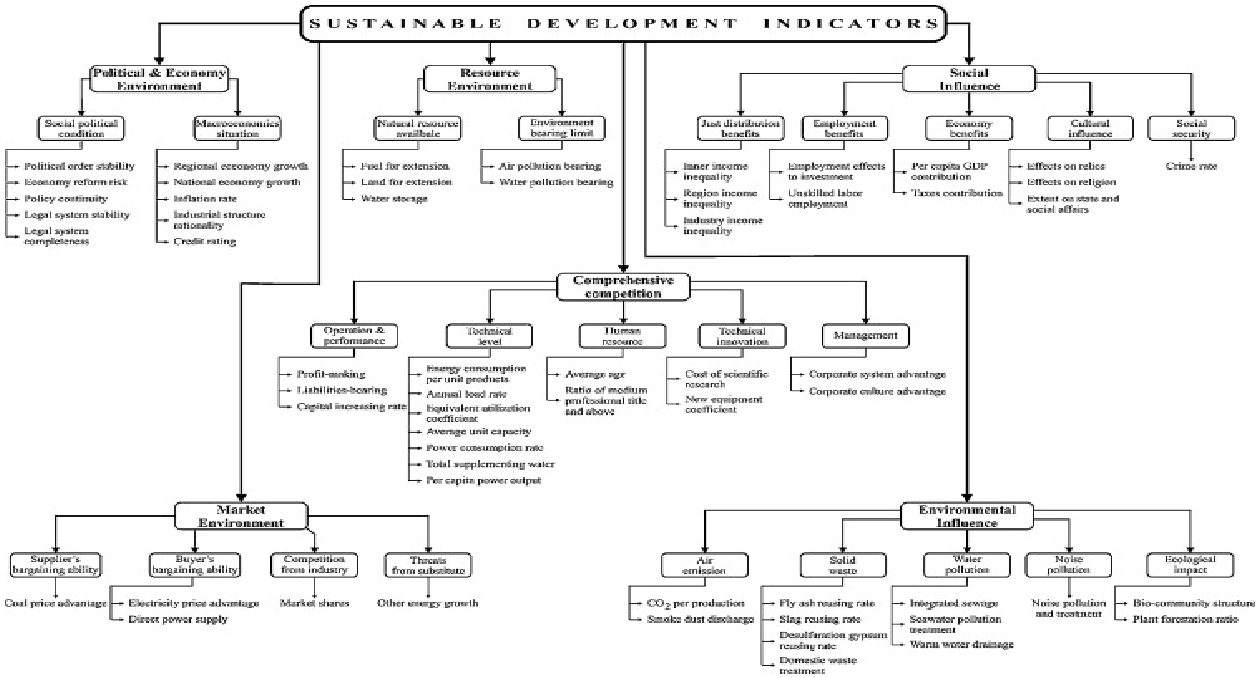

Figure 2. Sustainable development parameters(Onat & Bayar, 2010)

From figure 2, it is noted that the parameters or indicators of sustainable development are identified with the three broad dimensions of sustainable development which are social, resource environment and the political and economic environment(Moses Jeremiah Barasa. Kabeyi & Akanni O Olanrewaju, 2020; Moses Jeremiah Barasa Kabeyi & A O Olanrewaju, 2023; M. J. B. Kabeyi & O. A. Olanrewaju, 2023b, 2023c, 2023d).

5.2. Sustainability Indicators for power plants

The sustainability indicators for power plants can be classified into economic like the local energy production, consumption, fraction of installed capacity versus proven reserves, energy efficiency, energy consumption, social like job creation and participation of the people, institutional like certification of plant management, and net dependence on imports and environmental like water consumption, soil contamination, air pollution etc. W (Claudia Roldán et al., 2014). Figure 3 shows the various indicators of power plants sustainability.

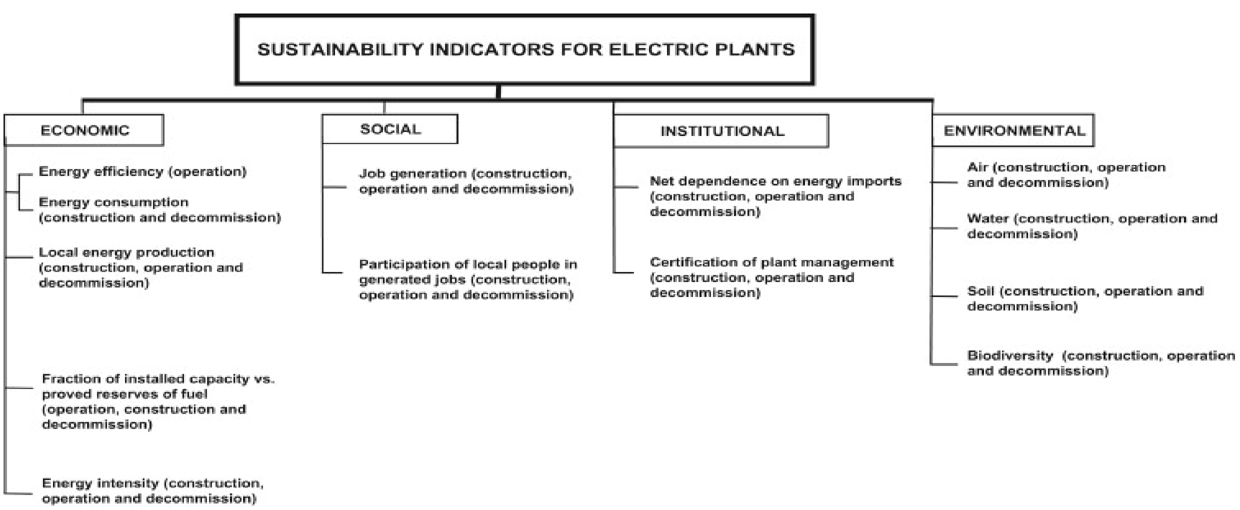

Figure 3. sustainability indicators for power plants (Claudia Roldán et al. 2014)

From figure 3, it is noted that indicators of power plant sustainability include economic, institutional, environmental and techno-economic indicators.

5.3. **Sustainability Based on Cost and Emissions.**
Important sustainability indicators used in the assessment of energy sources include carbon dioxide (CO_2) emission, power output, land use, freshwater consumption, environmental effects, social effects, and economic benefits. Based on these indicators wind and nuclear energy power scored the highest ranking in many sustainability indicators. Fuel cells applying hydrogen from non-renewable sources like coal and natural gas performed poorly in the sustainability assuagement(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022b, 2022f; Onat & Bayar, 2010). This highlights the need for renewable hydrogen for use in the energy transition. Figure 4 shows the unit cost and carbon emissions of various sources of energy for power generation.

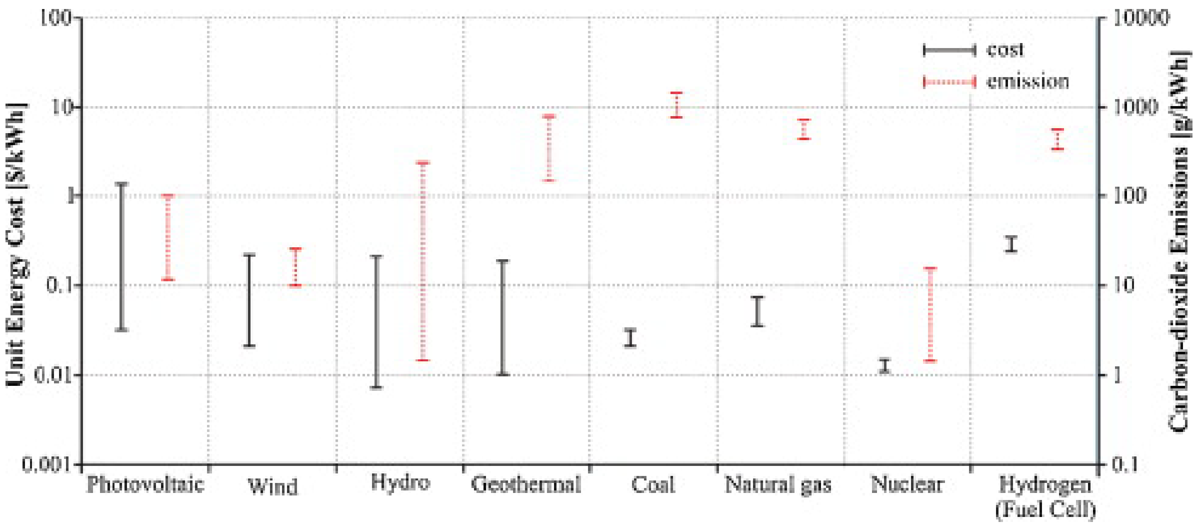

Figure 4. Unit energy costs and CO_2 emissions of power generation systems.

From figure 4, it is observed that both hydro, geothermal, photovoltaic have the highest range of values for emissions and unit cost of power. This is because of the wide range of feasible cites or locations and as well as applicable conversion technologies. Nuclear energy, coal and fuel cells have the lowest cost diversity for electricity produced.

5.3. Selection Criterion

The main criterion that drives the selection process of the energy indicators is their ability address the most important energy related issues of interest to the specific countries being considered. The indicators should be selected, defined, and classified to assist countries in developing and accessing effective energy policies for sustainable energy development to be attained. The indicators selected should assist and guide the implementation of various policies and actions in line with energy sustainability requirements i.e.:

- i.) Integrate energy issues into socio-economic development programs.
- ii.) Mix more renewable energy, low carbon sources, energy efficiency measures and advanced energy conversion technologies to deliver optimum energy products and services.
- iii.) Increase the share of renewable energy sources in the energy mix.
- iv.) Minimize energy wasteful practices like flaring and venting of gas.
- v.) Develop local programs on energy efficiency.
- vi.) Improve operation and transparency of energy information in energy market.

Reduce market distortions; and • Assist developing countries in their domestic efforts to provide energy services to all sectors of their populations. The selection criteria also included considerations about data availability (in developing countries), and the feasibility of collecting additional data deemed essential to the establishment of important indicators.

6. Conclusion

Sustainable energy is a very important element of sustainable development through provision of uninterrupted clean electricity to consumers. The demand for electricity is continuously increasing due to growth in world population industrialization, electrification, and technological developments. It is necessary to meet the increasing electricity demand for sustainable development, by using the consumable resources of the world in the most productive manner and minimum level to minimize the negative impacts on human health and environment.

The concept of sustainability has received significant attention globally because of its multidisciplinary nature and interest in sustainable development. Sustainable development and sustainability mainly rely on the three basic pillars, namely economy, environment, and society. Sustainable energy systems should meet present demands by maintaining an adequate balance between economy, environment, and society, while remaining non depletable and thus ensuring future use. Indicators are needed in the assessment of energy sustainability from the 5 dimensions of sustainable energy. Multicriteria decision analysis (MCDA) is a popular way for evaluating the sustainability of energy systems.

This study has demonstrated that renewable energy resources are more sustainable technologies compared with fossil fuel energy sources. Wind generation, nuclear, hydro, and solar power generation rank the highest in sustainability. Wind was ranked the most sustainable followed by hydropower, photovoltaics and then geothermal while coal produced power was the least sustainable. Coal and nuclear are the most favorable based on price of electricity produced but based on average prices, geothermal and hydro have the lowest possible prices and hence most favorable. Among renewable sources, photovoltaics has the highest average and overall highest cost of generation, although it remains cheaper than gas and coal at the lowest limit. On electrical efficiency, hydropower has the highest efficiency while photovoltaics has the lowest electrical efficiency. Greenhouse gas emissions were low in all non-fossil fuels, with Wind, hydro and nuclear have lowest values of greenhouse gas emissions while coal has the highest greenhouse gas emissions.

References

Asakereh, A., Soleymani, M., & Safieddin Ardebili, S. M., Multi-criteria evaluation of renewable energy technologies for electricity generation: A case study in Khuzestan province, Iran. *Sustainable Energy Technologies and Assessments*, *52*, 102220,2022. https://doi.org/https://doi.org/10.1016/j.seta.2022.102220

Claudia Roldán, M., Martínez, M., & Peña, R. , Scenarios for a hierarchical assessment of the global sustainability of electric power plants in México. *Renewable and Sustainable Energy Reviews*, *33*, 154-160, 2014. https://doi.org/https://doi.org/10.1016/j.rser.2014.02.007

Evans, A., & Strezov, V., *A sustainability assessment of electricity generation* 2010 International Conference on Biosciences,2010.

Evans, A., Strezov, V., & Evans, T. J. , Assessment of sustainability indicators for renewable energy technologies. *Renewable and Sustainable Energy Reviews*, *13*(5), 1082-1088, 2009. https://doi.org/https://doi.org/10.1016/j.rser.2008.03.008

Kabeyi, M., & Olanrewaju, O., *Preliminary design of a cogeneration Plant for a 120 MW diesel engine power plant* 12th Annual Istanbul International Conference on Industrial Engineering and Operations Management, Istanbul, Turkey, 2022. https://ieomsociety.org/proceedings/2022istanbul/411.pdf

Kabeyi, M. J. B., Geothermal electricity generation, challenges, opportunities and recommendations. *International Journal of Advances in Scientific Research and Engineering (ijasre)*, *5*(8), 53-95, 2019. https://doi.org/10.31695/IJASRE.2019.33408

Kabeyi, M. J. B. , Project and Program Evaluation Consultancy With Terms of Reference, Challenges, Opportunities, and Recommendations. *International Journal of Project Management and Productivity Assessment (IJPMPA)*, *8*(2), 47-68, 2020. https://doi.org/10.4018/IJPMPA.2020070103

Kabeyi, M. J. B., & Olanrewaju, A. O., Feasibility of Wellhead Technology Power Plants for Electricity Generation. *International Journal of Computer Engineering in Research Trends*, *7*(2), 1-16, 2020. https://doi.org/https://doi.org/10.22362/ijcert/2020/v7/i02/v7i0201

Kabeyi, M. J. B., & Olanrewaju, A. O. (2020, 14-17 Dec. 2020). Managing Sustainability in Electricity Generation. 2020 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM),

Kabeyi, M. J. B., & Olanrewaju, A. O. , Application of Geothermal Wellhead Generators in Sustainable Power Generation. *Geothermal Resources Council Transactions*, *46*(2022), 1692-1718, Article 1034703,2022. https://doi.org/https://www.geothermal-library.org/index.php?mode=pubs&action=view&record=1034703

Kabeyi, M. J. B., & Olanrewaju, A. O., *Environmental Impact of Energy Resources* International Conference on Industrial Engineering and Operations Management, Manila, Phillipines,2023. https://ieomsociety.org/proceedings/2023manila/612.pdf

Kabeyi, M. J. B., & Olanrewaju, A. O. (2023, April 28-30,). Environmental Impacts of Power Plants and Energy Conversion Systems 7th International Conference on Energy Economics and Energy Policy (ICEEEP 2023), Barcelona Spain.

Kabeyi, M. J. B., & Olanrewaju, O. A. , Central versus wellhead power plants in geothermal grid electricity generation. *Energy, Sustainability and Society*, *11*(1), 7, 2021. https://doi.org/https://doi.org/10.1186/s13705-021-00283-8

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022, June 12-14, 2022). *Conversion from diesel to dual fuel power generationand implications on the transition* [Conference paper]. 7th North American International Conference on Industrial Engineering and Operations Management Orlando, Florida, USA https://ieomsociety.org/proceedings/2022orlando/356.pdf

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022a, April 5-7, 2022). *Conversion of diesel and petrol engines to biogas engines as an energy transition strategy* 4th African International Conference on Industrial Engineering and Operations Management, Nsukka, Nigeria. https://ieomsociety.org/proceedings/2022nigeria/448.pdf

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022b, July 26-28, 2022). *Energy and environment: oportunities and challenges for the energy transition* Fifth European Conference on Industrial Engineering and Operations Management, Rome, Italy. https://ieomsociety.org/proceedings/2022rome/427.pdf

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022c). Geothermal wellhead technology power plants in grid electricity generation: A review. *Energy Strategy Reviews*, *39*(January 2022), 100735. https://doi.org/https://doi.org/10.1016/j.esr.2021.100735

Kabeyi, M. J. B., & Olanrewaju, O. A. , Performance analysis and electricity potential for Nzoia sugar factory. *Energy Reports*, *8*, 755-764, 2022. https://doi.org/https://doi.org/10.1016/j.egyr.2022.10.432

Kabeyi, M. J. B., & Olanrewaju, O. A. (2022e, March 7-10, 2022). *Sugarcane molasses to energy conversion for sustainable production and energy transition* 12th Annual Istanbul International Conference on Industrial Engineering and Operations Management, Istanbul, Turkey. https://ieomsociety.org/proceedings/2022istanbul/405.pdf

Kabeyi, M. J. B., & Olanrewaju, O. A., Sustainable Energy Transition for Renewable and Low Carbon Grid Electricity Generation and Supply [Review]. *Frontiers in Energy Research*, *9*(743114), 1-45, 2022. https://doi.org/https://doi.org.10.3389/fenrg.2021.743114

Kabeyi, M. J. B., & Olanrewaju, O. A. , Technologies for biogas to electricity conversion. *Energy Reports*, *8*(Supplement 16), 774-786, 2022. https://doi.org/https://doi.org/10.1016/j.egyr.2022.11.007

Kabeyi, M. J. B., & Olanrewaju, O. A. (2023a). Bagasse Electricity Potential of Conventional Sugarcane Factories. *Journal of Energy*, *2023*, 1-25. https://doi.org/https://doi.org/10.1155/2023/5749122

Kabeyi, M. J. B., & Olanrewaju, O. A., The levelized cost of energy and modifications for use in electricity generation planning. *Energy Reports*, *9*, 495-534,2023. https://doi.org/https://doi.org/10.1016/j.egyr.2023.06.036

Kabeyi, M. J. B., & Olanrewaju, O. A. (2023c). Life cycle assessment of energy sources and applications. *AIP Conference Proceedings*, *3018*(1), 020015,2023. https://doi.org/10.1063/5.0171603

Kabeyi, M. J. B., & Olanrewaju, O. A., Life cycle carbon emissions of energy sources. *AIP Conference Proceedings*, *3018*(1), 020017,2023. https://doi.org/10.1063/5.0171605

Kabeyi, M. J. B., & Olanrewaju, O. A. (2023e). Smart grid technologies and application in the sustainable energy transition: a review. *International Journal of Sustainable Energy*, *42*(1), 685-758,2023. https://doi.org/https://doi.org/10.1080/14786451.2023.2222298

Kabeyi, M. J. B., & Olanweraju, O. A., *Sustainability Assessment for Non-Combustible Renewable Power Generation* 12th Annual Istanbul International Conference on Industrial Engineering and Operations Management, Istanbul, Turkey. 2022. https://ieomsociety.org/proceedings/2022istanbul/429.pdf

Kabeyi, M. J. B., & Oludolapo, A. O., *Viability of Wellhead Power Plants as substitutes of Permanent Power plants* 2nd African International Conference on Industrial Engineering and Operations Management, Harare, Zimbabwe,2020. http://www.ieomsociety.org/harare2020/papers/77.pdf

Khan, I. , Chapter 4 - Sustainability assessment of energy systems: Indicators, methods, and applications. In J. Ren (Ed.), *Methods in Sustainability Science* (pp. 47-70). Elsevie,2021r. https://doi.org/https://doi.org/10.1016/B978-0-12-823987-2.00016-7

Longo, M., Mura, M., Vagnini, C., & Zanni, S. (2021). Chapter 5 - Sustainability measurement Evolution and methods. In J. Ren (Ed.), *Methods in Sustainability Science* (pp. 71-86). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-823987-2.00010-6

Masanet, E., Chang, Y., Gopal, A. R., Larsen, P., Morrow, W. R., Sathre, R., Shehabi, A., & Zhai, P. (2013). Life-Cycle Assessment of Electric Power Systems. *Annual Review of Environment and Resources*, *38*(1), 107-136, 2013. https://doi.org/10.1146/annurev-environ-010710-100408

Niu, D., Wang, W., & Liu, Q. , Comprehensive evaluation of sustainable development capability for thermal power plant under market competition. 2008 4th International Conference on Wireless Communications, Networking and Mobile Computing, 2008,

Onat, N., & Bayar, H. , The sustainability indicators of power production systems. *Renewable and Sustainable Energy Reviews*, *14*(9), 3108-3115,2010. https://doi.org/https://doi.org/10.1016/j.rser.2010.07.022

Vega-Coloma, M., & Zaror, C. (2022). The Life Cycle Sustainability Indicators for Electricity Generation in Chile: Challenges in the Use of Primary Information. In Z. S. Klos, J. Kalkowska, & J. Kasprzak (Eds.), *Towards a Sustainable Future - Life Cycle Management: Challenges and Prospects* (pp. 229-239). Springer International Publishing. https://doi.org/10.1007/978-3-030-77127-0_21

WISE. (2017). *The Fukushima Disaster*. World Information Sevice on Energy. Retrieved 15 December 2022 from https://wiseinternational.org/campaign/fukushima-disaster

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