Sustainability Assessment for Non-Combustible Renewable Power Generation

Moses Jeremiah Barasa Kabeyi *

mkabeyi@yahoo.com

Industrial Engineering Department, Durban University of Technology, Durban South Africa

Oludolapo Akanni Olanrewaju

oludolapoo@dut.ac.za

Industrial Engineering Department, Durban University of Technology, Durban South Africa

*Corresponding Author, contacts: 22064693@dut4life.ac.za; mkabeyi@uonbi.ac.ke

Abstract

In this study, sustainability ranking is done for four predominant non-combustible renewable energy sources i.e., wind, solar, geothermal, and hydro. There are various indicators used to assess power generation technologies. They include price/cost of generated electricity, full lifecycle greenhouse gas emissions, availability of renewable sources, energy conversion efficiency, land use requirements, water consumption and social and economic impacts. The cost of electricity, greenhouse gas emissions and the efficiency of electricity generation have a wide range for each technology option because of wide range of available technology options and varied geographical dependence. The social impacts of energy sources are qualitatively based on the major individual impacts from literature. Renewable energy technologies were then ranked against each indicator assuming that indicators have equal importance for sustainable development. The study shows that wind power is the most sustainable, followed by hydropower, photovoltaic and then geothermal energy sources. However, wind has got higher land requirements and relatively higher cost of generation.

Key words

Lifecycle analysis; sustainability, sustainable development; sustainable energy; renewable energy; energy transitions.

1. Introduction

There is a global concern over greenhouse gas emissions in the energy sector from use of fossil fuels and the related threat of global warming and climate change. A shift to renewable energy sources has emerged as a policy for achieving poverty alleviation and sustainable development(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022; Kabeyi & Oludolapo, 2020c). To attain a green economy and green development, the three dimensions of sustainable development should be attained. These are economic sustainability and sustainable development, environmental justice, and environmental sustainability, as well as alleviation of global inequality and poverty, social sustainability, and social justice(Azam et al., 2015; M. J. Barasa Kabeyi & O. A. Olanrewaju, 2021)

Sustainable development of energy systems is globally becoming a significantly important consideration in policy and decision making(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022; Kabeyi & Olenwaraju, 2022). The leading global objectives are economic growth, energy security, climate change mitigation, reduction of greenhouse gas emissions and social acceptance of change measures(Santoyo-Castelazo & Azapagic, 2014). Energy remains a leading vector for the socioeconomic development of all nations whose consumption continues to grow. Therefore, very important is to develop energy systems that are affordable and cheap, reliable in supply, readily availability, accessible, socially acceptable while promoting the use and preservation of natural resources (Rovere et al., 2010). Sustainable power generation is at the centre position for global sustainable development for all countries globally. There is however serious global concern as a result of the upsurge in electricity demand to sustain humanity(Rizvi et al., 2022). Sustainability is a major concern for energy systems that must be considered when designing and developing energy systems(Jalili et al., 2021). The transition to renewable energy and low carbon sources is necessary to ensure a continuous and abundant and clean energy supply which is the main target for a sustainable and secure energy system. Many countries rely on fossil fuel as a dominating energy source but there is increasing endorsement of energy system transition towards renewable energy sources which are abundant but still have some negative impacts (Rana & Gróf, 2022).

To achieve sustainable energy development, five dimensions of sustainability ought to be considered i.e. environmental, institutional, economic, technical, and social(J. B. Kabeyi & O. A. Olanrewaju, 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022; Kabeyi & Olenwaraju, 2022). Most countries especially in the developing world rely on the business business-as-usual scenario, which is mostly based on fossil fuels which is not sustainable due to operations and maintenance costs high costs and high environmental impacts particularly from greenhouse gas emissions. In most sustainable energy and development scenarios, those with higher penetration of renewable sources of energy especially wind, solar, hydro, geothermal and biomass and low carbon but non-renewable nuclear power always rank highly(Moses Jeremiah Barasa Kabeyi, 2020; Santoyo-Castelazo & Azapagic, 2014). The challenge is that these energy sources have varying degrees of sustainability against limited resources and competing energy and development objectives. It is therefore necessary to rank and prioritise the renewable energy resource development for maximum impact and sustainability (Kabeyi, 2019a; Kabeyi & Oludolapo, 2020c; Santoyo-Castelazo & Azapagic, 2014). It is important to understand the environmental footprint of various energy sources so that future investment in sustainable energy is objective and focused on sustainable transformation Complete or full environmental footprint considers the entire energy chain lifecycle, from mines, manufacture or processing to direct and indirect emissions, and final waste disposal or recycling(Kabeyi & Oludolapo, 2020c). Energy sustainability assessment requires identification of key indicators for each stage in the supply chain. Key energy sustainability indicators are environmental and societal impacts, emissions, resource depletion, resource availability and the value that they add to the economy(Baños et al., 2011; Evans et al., 2009).

Many countries are turning to renewable energy resources to meet their electricity needs through centralized and decentralised generation(Kansongue et al., 2022). Biomass in form of firewood, charcoal, vegetable waste etc. are the largest source of renewable energy in many developing countries but the conversion processes are unclean and highly pollutant when burnt and can lower productivity beside competing with food sources as endangering food security. Main challenges facing renewable energy development are monopolistic energy markets and state controls and dominance in the energy sector. Sustainable energy transition calls for optimum selection and development as well as operation of the locally available renewable energy resources.(M. J. B. Kabeyi & O. Olanrewaju, 2021; Kansongue et al., 2022; Rizvi et al., 2022). In order to focus the future investment in energy, there is need to understand the environmental footprint of various energy growth scenarios, with sustainability in focus. Full environmental footprint considers the entire energy chain lifecycle, right from mining to processing and to direct and indirect emissions, product waste disposal as well as recycling. Key indicators must be identified to enable assessment of each stage to allow quantification of the environmental impact. The selected indicators will be based upon environmental and societal impacts, greenhouse gas emissions, energy resource depletion, the availability of the specific energy sources and the economic value of the energy resources(Evans et al., 2009).

Indicators from previous studies consider a handful of sustainability indicators and limited variation of energy generation technologies to gain a full understanding of the sustainability of all modern electricity generation technologies. This study identifies several other indicators that are significantly important for evaluation of sustainability of energy generation technologies beyond the traditional forms of the environment. Social, economic, and technical sustainability factors are fully considered in this study.

2. Sustainability Assessment Tools

Life cycle analysis (LCA) is an internationally accepted tool for evaluating the impact for a commodity or service. LCA of energy generation technologies facilitates direct comparison of impacts by breaking them down into relative consequences, like for example, wind power generation affects migratory birds, potential incidence of leukaemia clusters surrounding nuclear power plants. Other acceptable methods of assessing sustainability are input–output analysis, mass, and energy balances, emergy (embodied energy) accounting. Life cycle assessment is a combination of these tools, providing the most comprehensive method currently available(Evans et al., 2009). The lifecycle analysis is generally used an assessment of environmental sustainability of energy options and scenarios. With the functional unit often being defined as 'annual generation of electricity'. The global warming potential is one very important parameter in analysis since scenarios are driven by climate change targets and emission mitigations (Kansongue et al., 2022; Rizvi et al., 2022). Lifecycle analysis (LCA0 methodology facilitates the evaluation of environmental impact across all life cycle stages, the modelling of interactions with environment and accounting of all steps from extraction of raw materials to disposal or recycling. As per the provisions of ISO 14040 and 14044 and LCA is done by iterating four phases namely definition of goal and scope of the study, life cycle inventory, impact assessment of life cycle and interpretation of results (Asdrubali et al., 2015).

Impacts of electricity generation to the environment and economy can be quantified based on parameters like emissions, energy payback periods and costs related costs. Life cycle analysis (LCA) which is used for comparison is an internationally accepted tool used for evaluation of the impact associated with a product or service. The use of life cycle assessment of power or energy generation technologies facilitates the direct comparison of impacts by breaking them down into relative consequences for example the effect of wind power generation on migratory birds, incidence of leukaemia clusters surrounding nuclear power plants, contribution to fog, among others. Other methods used to assess sustainability are input–output analysis, mass and energy balances, energy (embodied energy) accounting. The lifecycle analysis on the other hand combines these tools, making it more comprehensive method of sustainability assessment(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022; M. J. B. K. Kabeyi & O. A. Olanrewaju, 2022).

Life cycle analysis can be used as a tool to assess sustainability. it is the responsibility of the analyst to ensure that all the necessary inputs and outputs are taken into consideration and weighted. Life cycle assessment has a number of weaknesses, like it is unable may not account for some functions of an energy resource like dual function of hydroelectric dams or the reliability of electricity supply. LCA has a challenge of attributing full value to more flexible generation options(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022a; Kabeyi & Oludolapo, 2020b). There are many significant indicators that should be considered when evaluating sustainability of energy generation technologies. Technology selected has an impact on the traditional environment, human social and economic environment(Kombe & Muguthu, 2018).

Commonly used approaches to measure the environmental impact associated with different energy technologies are carbon foot printing, other GHG accounting approaches and Life Cycle Assessment (LCA). Single indicator approaches like Carbon Footprint, are more attractive than LCA due because they are simple although it may lead to oversimplification. For power generation technologies, focussing only on greenhouse gas emissions may result in wrong conclusions with respect to environmental consequences. Many renewable energy technologies have an impact on water, landscape, ground, and wildlife, and hence evaluation of carbon dioxide emissions alone is not sufficient. A wide range of variables should be considered in sustainability evaluation of power generation technologies while the life cycle analysis (LCA) is desirable to avoid shifting of impact from one life cycle phase to another making Life Cycle Sustainability Assessment (LCSA) model a valid supporting tool (Asdrubali et al., 2015; J. B. Kabeyi & O. A. Olanrewaju, 2022; Kabeyi & Olenwaraju, 2022).

Renewable energy power plants are characterized by a wide range of power, technologies, plant configurations and applications. A number of environmental indicators are used to carry out life cycle analysis of power plants for the common renewable energy sources and technologies like wind, solar, biomass and geothermal. Bioenergy and biomass have many typologies like biofuels, solids and liquid biomass, biogas, as well as wide range of technologies like direct combustion, gasification and co-combustion with fossil fuels making analysis complex (Asdrubali et al., 2015; M J B Kabeyi & O A Olanrewaju, 2021b; M. J. Barasa Kabeyi & O. A. Olanrewaju, 2021; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022).

3. Sustainability Assessment Indicators

In line with the dimensions of energy sustainability namely economic, social, environmental, technical, and social, a number of indicators and parameters can be used to measure sustainability e.g., land use requirements, greenhouse gas emissions, unit cost of power generation, water consumption, load and capacity factors, and social impacts(J. B. Kabeyi & O. A. Olanrewaju, 2022; Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022; Kabeyi & Olenwaraju, 2022).

i.) Greenhouse gas emissions

Availability and limitations of each technology must be considered since some technologies or fuels may be heavily resource constrained.

ii.) Conversion efficiency of the energy transformation

Conversion efficiency is an important indicator for technology comparison. More efficient processes generally have lower process requirements, lower capital, and lower operating costs. Inefficient processes often have room for technological advancement and innovation.

iii.) Land use requirements

Land use requirements are important as renewable energy technologies are often claimed to compete with agriculturally arable land or to change biodiversity.

iv.) Water consumption requirements

This is very important especially in water scarce locations arid climates. It is not acceptable nor sustainable to have high water consumption and evaporative losses in power generation processes when water supply is problematic.

v.) Social impacts of energy systems

This can help correctly identify and quantify the human risks and consequences and hence acceptance and understanding of some technologies that are often subject to public objection.

After assessment of selected indicators, the renewable energy technologies were ranked against each other, with each indicator given equal importance.

3.1. Price of Electricity

Each energy resource and technology selected for electricity generation varies in price. On the basis of full life cycle average cost, the price ranges are as shown in table 1. The full life cycle cost of each energy generation technology considers the plant construction, plant installation, commissioning, facility operation, plant maintenance, cost of plant decommissioning, cost of recycling, and disposal cost of the plant or facility(Evans et al., 2009). Table 1 below shows the unit cost of electricity of various sources of energy.

Table 1: Unit cost of electricity by source(Evans et al., 2009)

	Technology/Resource	USD/kWh	Rank
1	Solar	0.24	6
2	Wind	0.07	4

3	Hydro	0.05	3
4	Geothermal	0.07	4
5	Coal	0.042	1
6	Gas	0.048	2

From table 1, it is noted that hydro has the lowest cost followed by geothermal and wind among the renewable sources, but coal and gas are cheaper. Solar is the most expensive among the 4 main renewable sources of energy compared. Technological improvement has however ensured that solar is cheaper than coal and gas which are fossil fuels.

3.2. Greenhouse Gas Emissions

For this analysis, greenhouse gas emissions in grams of CO_2 equivalent are generally estimated based on the full operational life cycle of each of the generation technology. The emissions include those involved in from the equipment and plant manufacturing to full operation and maintenance of the technologies or energy systems. The lifecycle emissions vary widely from one technology to anothe(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022a, 2022b; Kabeyi & Oludolapo, 2020b)r.

Fossil fuels which have higher emissions continue to dominate the generation. For example in 2005 coal contributed 76% of the generation, 15% came from natural gas, oil contributed 2% oil, 6% was hydro while 1% non-hydro renewables(Evans et al., 2009). Hydro has the lowest emissions, but net emissions is affected by the total land cleared for dam construction, climatic conditions, type of terrain flooded, and amount of biomass submerged in the water which generates methane and other gases. Highest emissions from hydro are realised in Tropical and Amazonian Forest reserves. Methane has a global warming potential 25 times higher than CO_2, over 100 years so any methane emissions significantly increase CO_2 equivalent emissions(Evans et al., 2009; M J B Kabeyi & O A Olanrewaju, 2021c). For Geothermal energy, emissions are significantly impacted by technology used with general composition of waste gases being over 90% CO_2 by weight. Others are hydrogen sulphide (H_2S)(Hammons, 2004; Kabeyi & Oludolapo, 2020a, 2020d). Today, most geothermal power plants capture and make use of carbon dioxide or reject it back into the well(Bronicki, 2016; M J B Kabeyi & O A Olanrewaju, 2021a). The average emissions for each technology are summarised in table 2 below.

Table 2: Greenhouse gas emissions per unit power generation(Evans et al., 2009)

	Technology/Resource	gCO2e/kWh	Rank
1	Solar	90	4
2	Wind	25	2
3	Hydro	41	1
4	Geothermal	170	3
5	Coal	1004	6
6	Gas	543	5

From table 2, it is noted that hydro has the lowest lifecycle emissions followed by wind, solar and geothermal. Geothermal has the highest emissions which however are less than emissions from coal and natural gas.

Wind has the lowest $CO_{2\text{-}e}$ emissions of about 25 g/kWh $CO_{2\text{-}e}$. followed by Hydro with 41 and photovoltaics with 90 while geothermal has the highest carbon dioxide equivalent emissions compared to solar, wind and hydro(Evans et al., 2009).

3.3. Technological Sustainability

Technological considerations include availability of the renewable energy technologies and their limitations to generate base load electricity. Although the earth intercepts over 170 000 TW h/year from the sun irradiation varies from place to place by season and time of the day. The use of photovoltaics is currently limited by storage for use at night and on cloudy days. The main challenge of wind power is intermittence. Wind turbines should not operate at very high wind speeds a of over 25 m/s to avid damage of the turbine (Baños et al., 2011; Evans et al., 2009). Wind power from intermittency problems, however Edmonds et al. [31] hence spreading capacity a wide geographical area can help minimise fluctuations. Turbines should not operate during very high wind speeds of greater than 25 m/s to prevent turbine damage. Low wind speeds may not start the turbine rotation hence no generation(Edmonds et al., 2007).

Hydropower generation operates at highest availability, high reliability, and high flexibility compared to other technologies(Egré & Milewski, 2002). It is easy to start and stop a hydropower plant as well as change the output making it ideal for use in supply of both baseload and peak load. Hydropower supplied about 20% of the world's electricity generation in 2005 at about 2600 TWh and global potential of 8,100 TWh/years(Balat, 2006). The ranking of renewable sources of energy based on technical feasibility or limitations is summarised in table 3 below.

Table 3: Technological limitations(Evans et al., 2009)

	Technology/Resource	**Characteristics**	**Rank**
1	Solar	Solar suffers from intermittence and variability. Storage is a, so a limiting factor.	3
2	Wind	Wind like solar suffers from intermittence. The turbine may not start at low speeds and high speeds hence limiting use of wind power.	2
3	Hydro	Hydropower generation has the highest availability, highest reliability, and compared to solar, wind and geothermal.	1
4	Geothermal	Resource availability is limited to few feasible sites in about 24 countries. Geothermal operates at high load factor.	4

From table 3, it is noted that hydro is the most technologically advanced energy technology followed by wind power generation and solar respectively. Geothermal has the highest technological limitations ahead of solar power generation. These implies that hydro power is the most technically feasible non-combustible renewable followed by wind, solar and geothermal respectively.

3.4. Generation Efficiency

The range of energy conversion to electricity varies by resource with hydropower having the highest efficiency of all renewable electricity generating technologies currently available. Hydro is followed by wind then followed photovoltaics while geothermal power has the lowest efficiency among the technologies under consideration(M J B Kabeyi & O A Olanrewaju, 2021a, 2021b). Solar conversion efficiency varies greatly because of a large range of cell types available in the market but the ideal efficiency is 30%. The highest solar efficiency is in crystalline silicon cells (including multi- and poly-crystalline) while the amorphous silicon has the lowest conversion efficiency. The efficiency of wind conversion also varies widely because of wide variation in quality of wind resources from one place to another. However, with proper site selection and good wind energy more than 40% efficiency can be achieved. The efficiency of geothermal energy conversion is the lowest due to low geothermal resource temperatures(Barbier, 2002; J. B. Kabeyi & O. A. Olanrewaju, 2022). The electric efficiency of the various technology and energy resources are shown in table 4 below.

Table 4: electricity generation efficiency by source(Evans et al., 2009)

	Technology/Resource	Electric efficiency (%)	Rank
1	Photovoltaic	4-22	5
2	Wind	24-54	4
3	Hydro	≥90	1
4	Geothermal	10-20	6
5	Coal	32-45	3
6	Gas	45-53	2

From table 4, it is observed that hydro has the highest electricity efficiency ahead of gas and coal technologies which come second and third but the two are non-renewable. Therefore, the second most renewable technology is wind, followed by photovoltaic and geothermal respectively. Therefore, hydro is the most efficient non-combustible renewable energy resource.

3.5. Plant Capacity factors

Capacity factor can be used as a measure of the technical sustainability(Moses Jeremiah Barasa Kabeyi & Oludolapo Akanni Olanrewaju, 2022c). The performance of various power plants based on global average capacity factors are shown below in table 5

Table 5: Global average capacity factors(Hammons, 2004)

	Technology/Resource	Capacity factor	Rank
1	Solar	0.15-0.30	3
2	Wind	0.19	4
3	Hydro	0.42	2
4	Geothermal	0.71	1

From table 5, it is noted that geothermal operates with the highest capacity factor followed by hydro. Solar has the lowest capacity factor after wind.

3.5. Land Use Requirements

Solar and wind power systems have similar land use requirements and characteristics. Wind and solar are by the opportunity for dual use sites. Solar panels can be roof-mounted, which provides a negligible footprint during use while wind can be incorporated into agricultural hence reducing its share of the footprint. According to ref. (Gagnon et al., 2002) the total footprint for wind is 72 km^2 /TWh without allocating any share of this to agriculture while Similarly, (Lackner & Sachs, 2005)noted that photovoltaic land requirement is 28–64 km2 /TWh without dual-purpose allocation of land use. Land requirement for hydro is a function of local topography but general land requirement for hydro is 750 km^2 /TWh per year (Barasa, 2020; Erdil & Erbıyık, 2015).

According to (Gagnon & van de Vate, 1997) the land requirements for hydro is as low 73 km^2 /TWh. Of the renewable sources under consideration, geothermal power plants have the small surface footprints, and has major power plant elements placed underground(Ferrara et al., 2019). The entire geothermal field is used for calculation of footprint due to the risk of land subsidence while typical land requirements for geothermal power is 18–74 km2 /TWh(Ferrara et al., 2019; Kabeyi & Olenwaraju, 2021). Table 6 shows the typical land requirements for solar, wind, hydro, and geothermal energy resources.

Table 6: Land requirement per energy source(Evans et al., 2009)

	Technology/Resource	km^2/TWh
1	Solar	28-64

2	Wind	72
3	Hydro	73-750
4	Geothermal	18-74

From table 6, it is noted that geothermal energy has the lowest land requirements per TWh while hydro has the largest land requirements.

3.6. Water consumption

Power systems can withdraw as well as consume water based on the technology adopted. It may be difficult to distinguish between water withdrawal where water is taken then returned to circulation and water consumption where water is removed from circulation outside the plant/unit. Water consumption is an accurate indicator of sustainability as water lost from circulation has some impact. For hydro, a storage dam is needed for large hydroelectricity plants. These dams lose a lot of water through evaporation, with quantities varying depending on dam size, volume per square meter and ambient temperatures(Inhaber, 2004). Geothermal power production has the largest water consumption. Water is used for cooling and other operations but through reinjection, the used brine water is recycled. Geothermal plants generate the highest amount of up to 300 kg/kWh(Inhaber, 2004; Mock et al., 1997). Solar and wind have very little life cycle consumption of water. It is used in operation and maintenance, and the production of photovoltaic modules and wind turbines. Wind power generation has the lowest water consumption among various technologies as shown in table 7 below.

Table 7: Water consumption per kWh for different energy sources(Evans et al., 2009)

1	Technology/Resource	Water requirements (kg/kWh
2	Solar	10
3	Wind	1
4	Hydro	36
5	Geothermal	12-300
6	coal	78
7	Gas	78

From table 7, it is noted that wind has the lowest water consumption followed by solar. Geothermal has the highest water consumption ahead of coal and gas power generation.

3.7. Social Impact

All sources of energy are associated with both negative and positive impacts. Most renewable sources of energy ae locally available making renewables to offer the opportunity for electricity generation and supply. Most countries of the world are not endowed with fossil fuel sources of energy and have to be imported from other countries. (Baños et al., 2011; Evans et al., 2009). Impacts and their relative magnitudes for the technologies under consideration are summarised in Table 8

Table 8: Social impact of different energy sources(Evans et al., 2009)

	Energy resource	Impact	Magnitude	Rank
1	Solar	Toxins and visual effect	Minor-Major minor	2
2	Wind	Bird strike Noise Visual effect	Minor Minor minor	1
3	Hydro	Displacement Agricultural River damage	Minor-major Minor-major Minor-major	3
4	Geothermal	Seismic activity Odour Pollution	Minor Minor Minor-major	4

		Noise	Minor	

From table 8, it is shown that wind has the highest positive social impact, followed by solar power generation. Geothermal energy has the least social impact ahead of hydro power generation.

4. Ranking of Renewable Energy Sources

The overall ranking of the renewable sources is done by considering price, carbon dioxide emissions, energy availability and limitation, conversion efficiency, land use, water consumption, social impact, and capacity factor as summarised in table 9 below.

Table 9: Sustainability ranking for renewable energy sources

		Solar	Wind	Hydro	Geothermal
1	Price of electricity	4	3	1	2
2	$CO_{2\text{-}e}$ emissions	3	1	2	4
3	Availability and limitation	4	2	1	3
4	Efficiency	4	2	1	3
5	Land use	1	3	4	2
6	Water consumption	2	1	3	4
7	Social impact	2	1	4	3
8	Capacity factor	4	3	2	1
8	Total	24	16	18	22
9	Remarks	Third most sustainable	Most sustainable	Second most sustainable	Least sustainable

From table 9 above, the combined ranking of 8 sustainability factors shows that wind energy is the most sustainable renewable energy resource followed by hydro, solar and geothermal respectively.

5. Results and Discussion

In the ranking, where available values exist as a range, average values are applied in the comparison and ranking exercise. For quantifiable values, average and range values were considered simultaneously, in the analysis. Qualitative assessment was applied where quantitative values are not available like availability, limitations, and social impacts of the energy sources. On resource limitation, hydro was the least limited, with superior qualities needed to supply base load power, facilitate flexibility of operations and existence of a large number of feasible locations globally. Hydro is followed by wind as the second best for availability, limitations, and social impacts. Geothermal resources are more limited globally although global potential remains huge, but with less suitable locations for resource development(J. B. Kabeyi & O. A. Olanrewaju, 2022; Kabeyi, 2019b; M J B Kabeyi, 2020). In this analysis, solar classified as the most limited mainly because storage capacity is still limiting and cannot store enough for nights and on cloudy times.

Wind is allocated the list social impacts when social impacts were considered, because of its benign nature. Solar has the least social impacts after wind owing to the technological progress careful management during manufacture and proper site selection mitigate its potential negative impacts. Geothermal energy comes after wind with the main social impact being incidences of seismicity and pollution potential from various gaseous emissions and brine effluent. These analysis places hydro the fourth after geothermal indicating higher negative social impact from hydro primarily because of a large number of people and animals displaced during dam and reservoir development.

This study suggests that wind energy is the most sustainable renewable energy resource and technology as shown in table 9 followed by followed by hydropower then solar energy. Geothermal energy is the list sustainable renewable energy resource among the four main non-combustible renewable sources of energy. was found to rank the lowest from the four non-combustion renewable energy sources and technologies. These ranking is based on the global parameters and may not be necessarily the same for specific countries or regions of the world. The significance of specific sustainability may change ranks based on site or location under consideration.

5.0. Conclusions

This study assessed sustainability of various sources of renewable electricity based on sustainability indicators. The sustainability indicators used were price of generated electricity, full lifecycle greenhouse gas emissions, availability of renewable sources, energy conversion efficiency, land needs, water use, and social economic impacts. The study assumed that each indicator has equal importance to sustainable development and used to rank the renewable energy technologies against their impacts. This study showed that wind is the most sustainable renewable energy resource, followed by hydropower, photovoltaics and then geothermal. The values used for ranking used for relative ranking was provided using data collected from published literature.

6.0. Recommendations

Electricity policies in all countries should seek to achieve a higher and diversified contribution from renewable and low-carbon energy technologies. Among the leading renewable energy options, geothermal and hydro power technologies are the most established energy. Geothermal however suffers challenges of high upfront risks and high capital requirements leading to slow development and hence need for more investment in research and development of more efficient and cheaper technologies. Although hydro is one of the most sustainable renewable resources, most feasible resources are currently developed and hence need to change focus to small and mini hydro resources that can fit in decentralised generation systems. Wind and solar are among the top three most sustainable renewable resources but face the challenge of intermittence and variability in supply hence risky to grid stability and security. There is need to develop a resilient and intelligent grid to maximise absorption of the variable renewables. Therefore, advances of the smart grid promise to revolutionise the exploitation of wind and solar through decentralised generation. Therefore, decentralisation of generation, development of efficient conversion and storage technologies and the smart grid will greatly enhance the exploitation of the non-combustible renewable energy sources for them to play a leading role in the energy transition.

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Authors Biographies

Moses Jeremiah Barasa Kabeyi is currently a doctoral researcher in the Department of Industrial Engineering at Durban University of Technology. He earned his B.Eng. degree in Production Engineering and MSC in Mechanical and Production Engineering (Energy) from Moi University, in Kenya, MA in Project planning and Management from University of Nairobi, in Kenya and Diplomas in Project management, Business management and NGO management respectively from The Kenya Institute of Management. He has worked in various factories including sugar manufacturing at Nzoia Sugar Company Ltd, pulp and paper at Pan African Paper Mills EA Ltd, and power generation at the Kenya Electricity Generating Company (KenGen) in Kenya, in an industrial career of 16 years before moving into teaching. He has taught in various universities in Kenya including University of Nairobi, Technical University of Mombasa, and Egerton University and currently on study leave. His research interests are power generation, fuels and combustion, internal combustion engines and project management and sustainability. He is registered with the Engineers Board of Kenya (EBK) and Institution of Engineers of Kenya (IEK) and has published several journal papers.

Oludolapo Akanni Olanrewaju is currently a Senior Lecturer and Head of Department of Industrial Engineering, Durban University of Technology, South Africa. He earned his BSc in Electrical Electronics Engineering and MSc in Industrial Engineering from the University of Ibadan, Nigeria and his Doctorate in Industrial Engineering from the Tshwane University of Technology, South Africa. He has published journal and conference papers. His research interests are not limited to energy/greenhouse gas analysis/management, life cycle assessment, application of artificial intelligence techniques and 3D Modelling. He is an associate member of the Southern African Institute of Industrial Engineering (SAIIE) and NRF rated researcher in South Africa.