Assessing Sustainability in Renewable Energy: Sources, Solutions and Metrics

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Abstract – Renewable energy sources are obtained naturally and have the capacity to surpass normal amounts of energy presently being used. These sources include solar, hydropower, wind, and biomass. The costs of generating electricity vary depending on the technology being applied; with wind energy having the lowest costs and photovoltaics being known to have the highest. Different techniques of renewable energy are faced by particular challenges, such as obstacles during the process of storing energy, and intermittent nature of energy production. Evaluating the sustainable aspect of renewable energy sources necessitates considering factors such as water usage, land usage, and social impacts. Wind energy is typically known as the most sustainable source of energy, with geothermal and hydropower energy being second. This article reviews the capabilities of renewable energy sources, and their significance in achieving sustainable development. It reviews the relevance of technological progress in rendering renewable energy sources cost effective and economically viable. The sources of energy discussed in this article include biomass, solar, wind, and hydropower; discussing their varying dimensions of competitiveness and progress made. In addition, this article contributes to the knowledge of parameters employed in assessing sustainability, including environmental and financial implications connected to different sources of energy. The contributions suggests that the most sustainable energy source is the wind power, followed by geothermal and hydropower. However, it notes that geographical variations may impact the rankings.

Keywords – Renewable Energy Sources, Sustainable Energy Development, Sustainability Metrics, Renewable Energy Solutions

I. INTRODUCTION

Renewable energy, often referred as clean energy, is extracted from natural sources or processes, which are continuously renewed. For instance, sunshine and wind persistently radiate and gust, regardless of their availability being contingent upon time and weather conditions. Although renewable energy is often seen as a recent technological advancement, the use of natural resources for lighting, transportation, heating, and other uses has been practiced for a considerable period of time. The boats are propelled across the oceans by the force of wind and enabled windmills to process grain. Heat is supplied all day by the sun and allowed the ignition of fires to last into the evening. However, throughout the last five centuries or more, people have progressively shifted towards more affordable and environmentally harmful sources of energy, such as fracked gas and coal.

Sustainable Energy Development Strategies generally include three primary technical shifts: reduction of energy consumption on the side of demand, enhancement of fossil fuels substitution and efficiency of energy production with diverse forms of renewable energy. Hence, comprehensive plans for the deployment of renewable energy on a wide scale must include techniques for seamlessly advancing renewable sources into cohesive energy systems, which are impacted by efficiency measures and conservation of energy. The primary obstacle is to enhance the amount of renewable energy. Renewable energy is widely recognized as a crucial asset in several nations globally. several scholars, including [1], [2], and [3], have authored publications on renewable energy sources and their role in promoting sustainable development.

The allocation of renewable energy research publications is used to assess the respective contributions of several nations to the study subject. This implies that the nations with the highest productivity are those in which a greater number of articles about renewable energy (implemented inside those countries) and concerns about sustainability are recognized. The issue of sustainability and renewable energy encompasses 55 nations. The nations with the highest levels of activity are shown in **Fig 1**. The most prominent ones are the UK (5%), the USA (13%), Brazil (12%), China (5%), and the EU (European Union) (5%). The examination of the nation`s contribution indicates that the top 5 most engaged nations, excluding the category of "others", make up 40% of all published outputs. These countries are the UK, USA, EU, Brazil, and China. The "others" group comprises nations with a limited number of papers, namely one or two, on the study subject.

Renewable sources, like solar and wind, make up a minuscule portion of the overall usage. Nevertheless, the potential is significant. The proportion of renewable energy has significantly increased in some areas and nations over the last several decades. This has led to the identification of two key problems in implementing renewable energy policies for sustainable development. One objective is to include a significant proportion of intermittent resources into the energy system, particularly in relation to the provision of electricity.

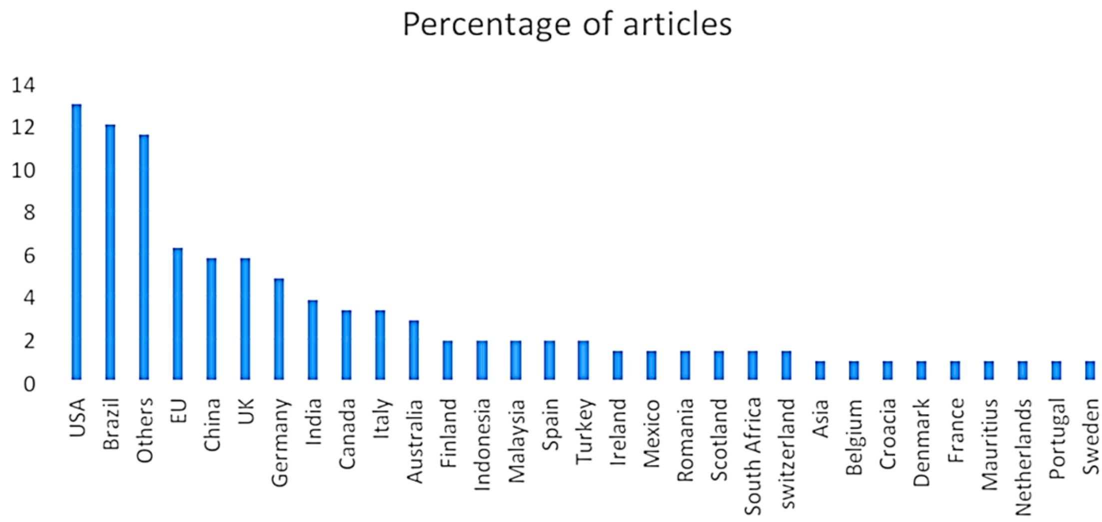

Fig 1. Most Productive Nations Producing Sustainability and Renewable Energy Articles

This article explores the capacity of renewable energy sources and their contribution to attaining sustainable development. It emphasizes the significance of technical progress in enabling renewable energy to rival traditional energy sources in terms of competitiveness. The essay also examines several renewable energy systems, their expenses, greenhouse gas emissions, and constraints. The text highlights the need of evaluating sustainability in a quantifiable way and provides crucial components for attaining sustainable development. The article asserts wind power as the most renewable energy source, with geothermal and hydropower following suit. However, it notes that geographical conditions might impact the hierarchy. The rest of the article has been organized as follows: Section II reviews some of the renewable energy sources and potential solutions. Section II focusses on discussing various sustainability metrics for renewable energy sources, such as price of electricity generation, greenhouse gas emissions, technological and availability limitations, energy generation efficiency, land use, water consumption, ranking, and social impacts. Section IV presents a summary of the assessment of sustainability in renewable energy: sources, solutions, and metrics.

II. RENEWABLE ENERGY SOURCES AND SOLUTIONS

The Earth's ecosystem has vast natural energy flows, which have the theoretical capacity to surpass present energy consumption by a significant margin, therefore meeting human requirements to a great extent. For instance, if solar power plants were installed on only 1% of the globe`s desert land, they would capable of providing enough energy to meet the current global demand. The presence of abundant resources and advanced technology for harnessing renewable energy raises the issue of future progress, which ultimately hinges on the economic and political viability compared to other energy sources. Technological advancement is crucial for the competitiveness of renewables, since it directly impacts the performance and prices of conversion technologies.

However, the Intergovernmental Panel on Climate Change (IPCC), Shell, the World Energy Council,and many UN organizations anticipate an increasing prominence of sustainable energy in the twenty-firstcentury, with significant benefactions from solar, wind, biomass, and hydropowersources [4]. There is a diverse range of technologies already available or being developed to offer affordable, dependable, and environmentally-friendly energy services from renewable sources (as shown in **Table 1**). However, there is a significant disparity in the level of advancement and the level of competition among these technologies. Furthermore, the performance and competitiveness of a system are influenced by the specific local circumstances, including socioeconomic and physical factors, as well as therural accessibility of fossil fuels. Electricity may be generated from all kind of renewable sources of energy. The advancement of sources such as wind, and solar into a power system poses significant issues. This poses a lesser challenge for geothermal, hydropower, and biomassenergy sources. Only a limited number of them are capable of directly generating liquid and gaseous fuels, in addition to heat.

Table 1. Categorization of Renewable Energy Conversion Technologies

Technology	Energy Product	Application
Marine energy *Production of marine biomass* *Osmotic energy/ Salinity gradient* *Wave energy* *Conversion of ocean thermal energy* *Current energy* *Tidal energy*	 Fuels Electricity Electricity Electricity, heat Electricity	 Research and advancement phase Theoretical options Demonstration, research, and advancement phase Research, demonstration, and advancement phase Advancement and research phase Applied; relatively expensive
Biomass energy *Digestion* *Burning (domestic scale)* *Extraction* *Burning (industrial scale)* *Pyrolysis of solid fuels* *Production of power / gasification* *Production/pyrolysis of liquid fuels* *Fermentation and hydrolysis* *Production of fuel/ gasification*	 Biogas Heat (space heating, cooking) Biodiesel Process electricity, steam, heat Charcoal Heat (CHP), electricity Bio-oils Ethanol H_2 , methanol, hydrocarbons	 Applied commercially Applied widely; available advanced technologies Applied; relatively expensive Applied widely; potential for advancement Applied widely; Wide range of efficiencies Phase of demonstration Pilot phase; some crucial obstacles Applied commercially for starch / sugar crops; generation from wood under improvement Phase of advancement
Hydropower	Electricity, power	Applied commercially; large- and small-scale applications
Wind energy *Offshore wind turbines* *Battery charging and water pumping* *Onshore wind turbines*	 Electricity Power, movement Electricity	 Demonstration and advancement phase Small machines of wind widely applied Widely applied commercially
Geothermal energy	Electricity, steam, heat	Applied commercially
Solar energy *Artificial photosynthesis* *Photovoltaic conversion of solar energy* *Usage of passive solar energy* *Solar energy using low-temperature* *Solar thermal electricity*	 Hydrogen or H_2 rich fuels Electricity Ventilation, cold, heat, light Cold and heat (drying, space and water heating, cooking) Electricity, steam, heat	 Applied and fundamental research Further advancement needed; Applied widely; rather expensive Applications and demonstrations; no active parts Applied and demonstrated solar drying; solar collector applied; solar cooker applied widely in some areas Further advancement required; demonstrated

Clean energy solutions strive to attain the following essential objectives to enhance sustainability: (a) enhanced efficiency, (b) optimized resource use, (c) improved cost-effectiveness, (d) enhanced environmental impact, (e) heightened security of energy, and (f) enhanced analytical and design capabilities. These are also closely associated with a 3S notion known as source-system-service. To ensure comprehensive cleanliness, we must do certain duties within the three designated categories, as seen in **Fig 2**. When beginning the development of a sustainable solution, it is crucial to choose a renewable energy source. Various factors must be considered, including ecosystem sustainability, abundance, safety, local availability, dependability, and cost-effectiveness. The most auspicious sources seem to be renewable energy. When analyzing particular systems, it is important to examine irreversibility's, as well as exergy and energy efficiency, in summation to the primary objectives previously mentioned.

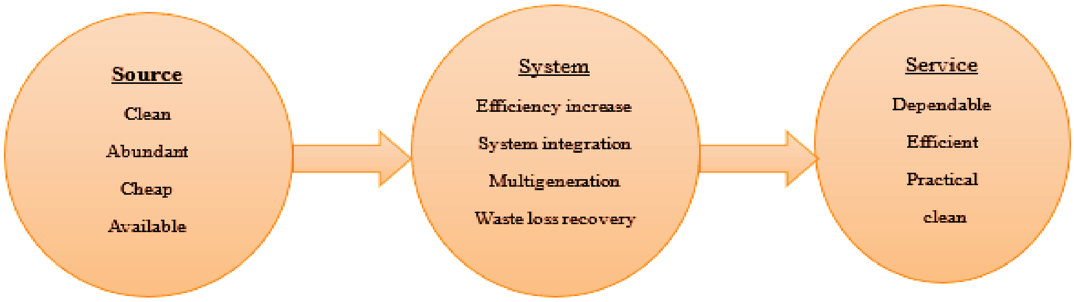

Fig 2. 3S Sustainability Route (source-system-service)

The literature extensively focuses on the study, implementation, and advancement of systems of clean energy, emphasizing the importance of technology in this field. **Fig 3** depicts several renewable energy system options alongside conventional fossil fuel-based options. Arbolino et al. [5] conducted a technical evaluation by integrating principles of industrial ecology into a collection of ecosystem sustainability measures. The research quantitatively evaluates the sustainability of several technology solutions. The sustainability indicators were developed by using the second law of thermodynamics. These implications include the resources renewability, the emitted substances toxicity, the materials utilized input, the goods recoverability at the end of their lifespan, and the technical competence. Nevertheless, there is a dearth of a singular standard or widespread agreement on measures for measuring sustainability. Significant efforts have been made by business, academia, and social groups to allocate resources.

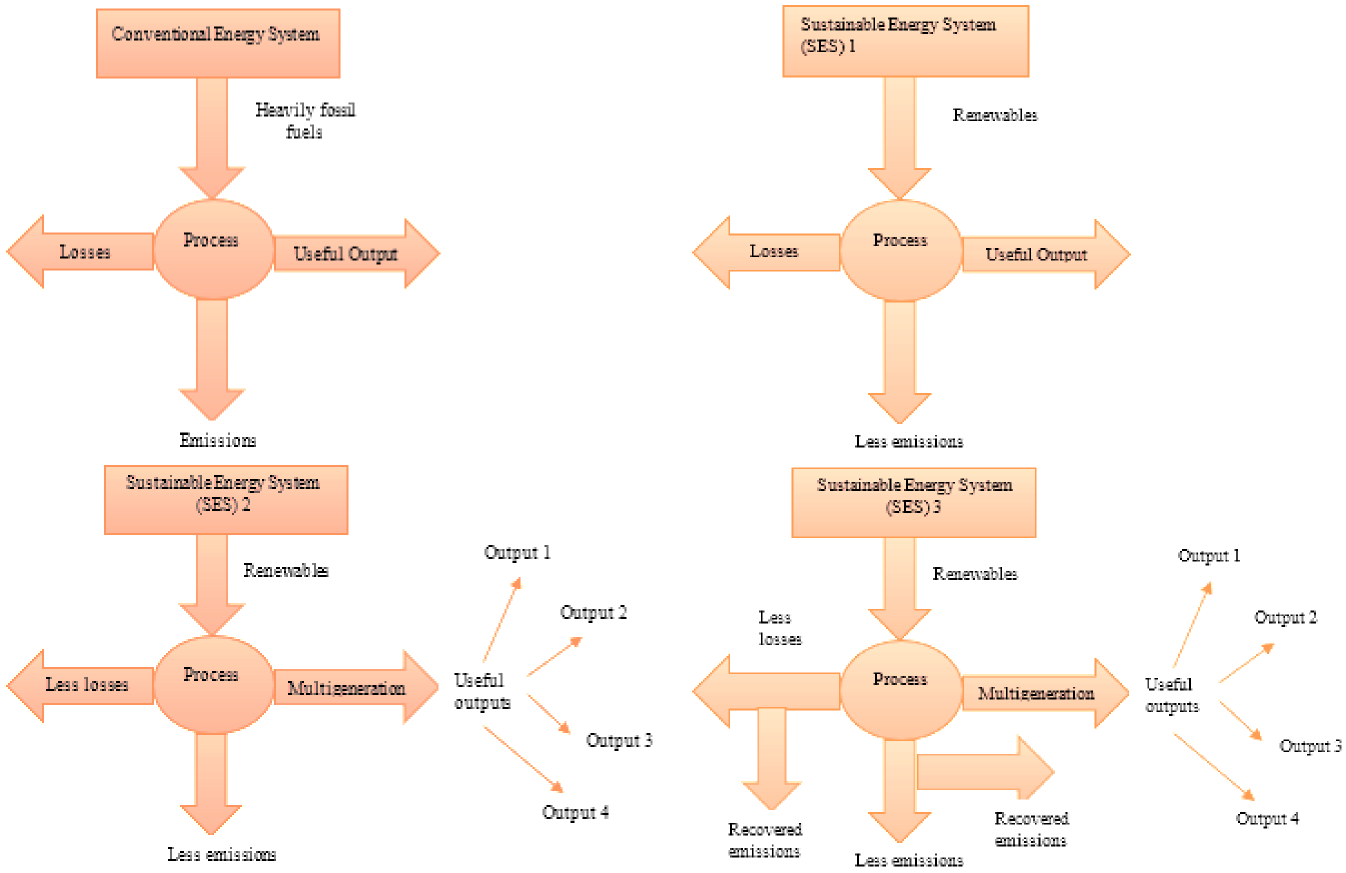

Fig 3. Possible Viable Energy System Options

Significant efforts have been made by business, academia, and social groups to develop methods and guides for assessing viability in a universally measurable and accepted manner. In 2005, the International Atomic Energy Agencyreleased a set of 30 energy metrics aimed at measuring sustainable development [6]. The environmental, social (fairness and safety), and economic dimensions of sustainability are included by these metrics. The United Nations Commission on Sustainable Development established a fundamental collection of 50 indicators for sustainable advancement in 2007 [7]. In 2012, Cinelli, Coles, andKirwan [8] conducted a comprehensive analysis of sustainability assessment methodology. They gathered information on the construction of sustainability indices, which included strategies, scaling, normalization, weighting, and aggregation procedures. A technique for assessing the energy technologies sustainability performance was described by Mainali and Silveira [9], which also looked at several methods to sustainability analysis. Kaygusuz [10] review various environmental issues such as the depletion of stratospheric ozone, and negative implications of greenhouse gases, to effectively establish a connection between sustainable development, the environment, and energy

In relation to the review, Dinçer [11] discussed the connection between sustainable development and renewable energy. The discussion identifies monitoring and evaluation tools, financing, public awareness, data dissemination, renewable energy sources, creative energy techniques, and ecosystem training tools as fundamental components for attaining sustainable development.Rosen and Dinçer [12] employ principles of energy to evaluate environmental effects of renewable energy systems. The research establishes a correlation between the greater employment of sustainability and renewable energy via the implementation of environmental, technical, social, commercialization, and economicimpact evaluations. Ahmad and Tahar [13] established sustainable development criteria and examined seven distinct green energy options according to these criteria. Their criteria include the following: green energy impact, technical impact, practical application effect, and sustainability based on green energy impact. Moussawi, Fardoun, and Louahlia-Gualous [14] determined that cogeneration and trigeneration alternatives exhibit potential as clean energy system candidates due to their superior efficiency, resulting in reduced greenhouse gas (GHG) emissions when compared to traditional single output energy systems.

III. SUSTAINABILITY METRICS FOR RENEWABLE ENERGY SOURCES

Price of electricity generation

Table 2 displays the mean costs of power production for each energy producing method. Every technology provides power generation with a vast spectrum of prices. **Fig 4** shows the range of costs related to electricity production over the full life span of every form of energy creation technology. These costs include disposal, construction, recycling, commissioning/ installation, maintenance, operations, and decommissioning. The figures are derived from a large number of literature sources. The prices for power production from both gas and coal in **Fig 4** are shown only for the purpose of comparison.

Table 2. Average prices of electricity and amount of greenhouse gases released measured in CO_2 for various energy producing systems

	G CO_{2-e} /kWh	**USD/kWh**
Gas	543	$0.048
Photovoltaic	90	$0.24
Geothermal	170	$0.07
Wind	25	$0.07
Coal	1004	$0.042
Hydro	41	$0.05

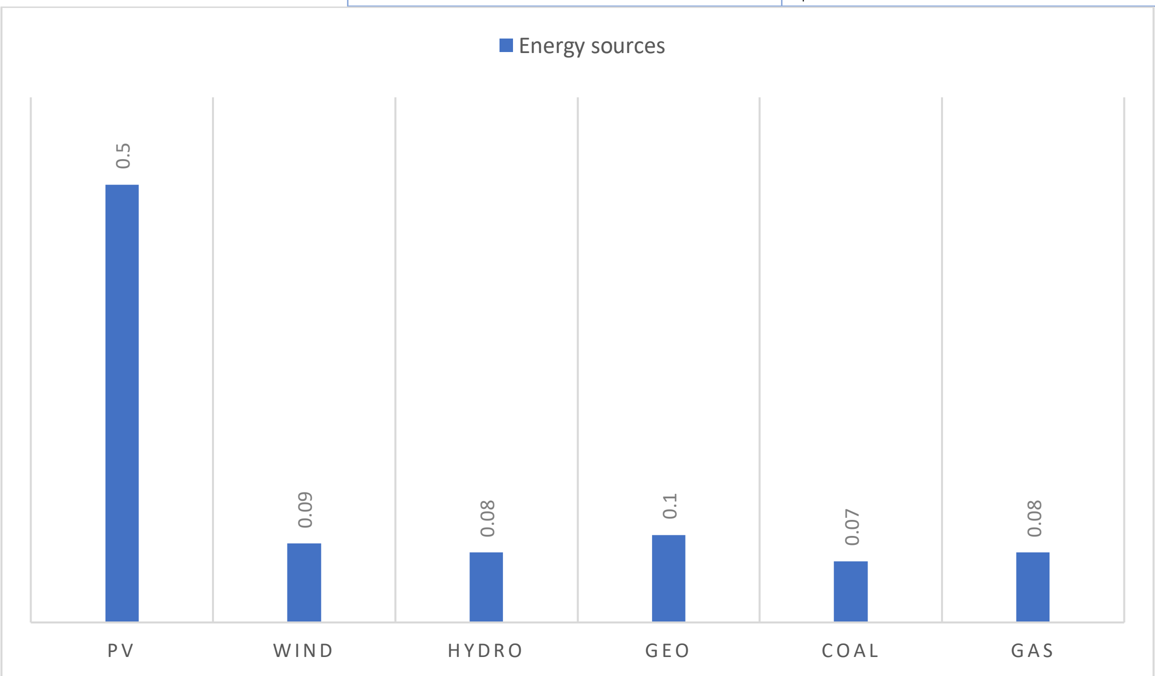

Fig 4. Generating power per kilowatt-hour (kWh)

Interests' calculations on capital are many statistics cited in the literature. However, none of these figures take into consideration the transmission cost, which may reach up to 1.50 c/kW h [15] in cases when extensive lines of exchange are required. Renewable energy sources, especially offshore wind farms, are increasingly often used for transmitting electricity over long distances compared to non-renewable sources. Backup systems for intermittent renewables, like wind and photovoltaics (PV), have not been included into the cost estimates. The maximum threshold for PV was truncated for the sake of simplicity, with the highest recorded value being $1.25/kWh, without any provided rationale for the very elevated figure.

The subsequent highest recorded figure was reported by Kosmadakis et al. [16] at a rate of $0.57 per kilowatt-hour. However, it is important to note that this number was accompanied by a detailed explanation of the calculations and assumptions used. The vast variety of pricing for energy production in photovoltaics is mostly attributed to the diverse array of solar cell types available, as well as location-specific factors like the cells manufacturing cost and the intensity of sunshine. Each non-heating technology of renewable energy exhibits low operating costs and high capital intensity, since they do not need any fuel. The primary expense of photovoltaics is in the process of silicon purification, which consumes 60% of the energy required to produce a frameless multi-crystalline module.

The majority of the life cycle costs for photovoltaics are attributed to capital expenditures, which make up more than 95% of the total. Consequently, any fluctuations in interest rates significantly affect the whole life cycle pricing. This outcome is to be anticipated with any other technology that requires significant investment of cash. The expenses associated with wind energy may be reduced by meticulously choosing appropriately sized turbines, based on the individual wind conditions at the location. The building of hydro dams is responsible for almost all of the expenses associated with hydro power, whereas the expenditures for operating, maintaining, and refurbishing the plants are very modest. Additionally, hydro power plants have lengthy lifespan. The prolonged duration of project development, exorbitant expenses, and the inherent hazards associated with exploratory drilling significantly contribute to the escalation of geothermal pricing. According to Osman et al. [17], drilling may represent as much as 50% of the whole project expenses. There is a wide range in the price per kilowatt-hour for all technologies, but the largest variation is seen for photovoltaics. The average value for each technology was almost near to the minimum price than the maximum price. Hydroelectric power had the minimum average cost, while wind and geothermal power had the same cost. Nevertheless, geothermal power had a narrower range of price variances compared to wind power. Photovoltaics are much more costly compared to other technologies.

Emission of Greenhouse gases

The greenhouse gas discharges, illustrated in grams of CO_2 in **Fig 5**, were primarily calculated based on the whole life span of each technology of sustainable energy. This includes taking into consideration the CO2 e discharges from the production of the plant up until the technology is fully operational. Significant variations in emissions are seen across different technologies. Wind energy provides the minimum carbon dioxide equivalent discharges, with an approximate value of just 25 grams per kilowatt-hour. Both hydro and photovoltaics exhibit minimal emissions, with reported average values below 100 g/kW h CO2 e. The mean discharges from electrical energy are moderate, measuring at 170 g/kW h. Nevertheless, the variation encompasses all potential ethics for gas discharges and might potentially reach levels comparable to those of a low-discharging coal-fired power plant. With the exception of hydro technology, CO_2discharges are responsible for the majority of carbon emissions in all other technologies. The majority of emissions associated with photovoltaics and wind generation stem from energy use during the production process. For these instances, emissions are usually calculated based on the average grid mix specific to the manufacturing location.

The composition of grid mixes varies significantly depending on the locality. For instance, in Australia in 2005, the usual grid mix consisted of 1% non-hydro renewables, 76% coal, 2% oil, 15% natural gas, and 6% hydro, . For hydroelectricity, regions with colder temperatures, lower levels of dams, and biomass with greater densities of power (a measure of the dam's capacity compared to the region it floods) result in fewer emissions per kilowatt-hour. The CO2 emissions resulting from dam building are greatly influenced by the kind of terrain that is flooded. The presence of a greater amount of biomass during inundation of dam and the existence of greater draw down zones lead to higher discharges. Reservoirs in Amazonian and tropical regions exhibit the most significant discharges, as shown by Sorribas et al. [18].

The primary greenhouse gas discharges associated with dams are methane, which is produced by the anaerobic breakdown of biomass at lower depths. These discharges typically diminish over time as the original biomass reserves are depleted. According to Dean et al. [19], methane has a potential for global warming that is 25 times stronger than carbon dioxide over a timeline of 100 years. Hence, even little alterations in methane emissions will lead to significant modifications in CO2 equivalent emissions. Technology choices have the most important influence on geothermal emissions. Waste gases consist of more than 90% carbon dioxide (CO_2) by weight, thus, if they are discharged directly, the emissions will be substantial. However, in contemporary times, the majority of plants either collect carbon dioxide and generate dry ice, or reintroduce it into the well.

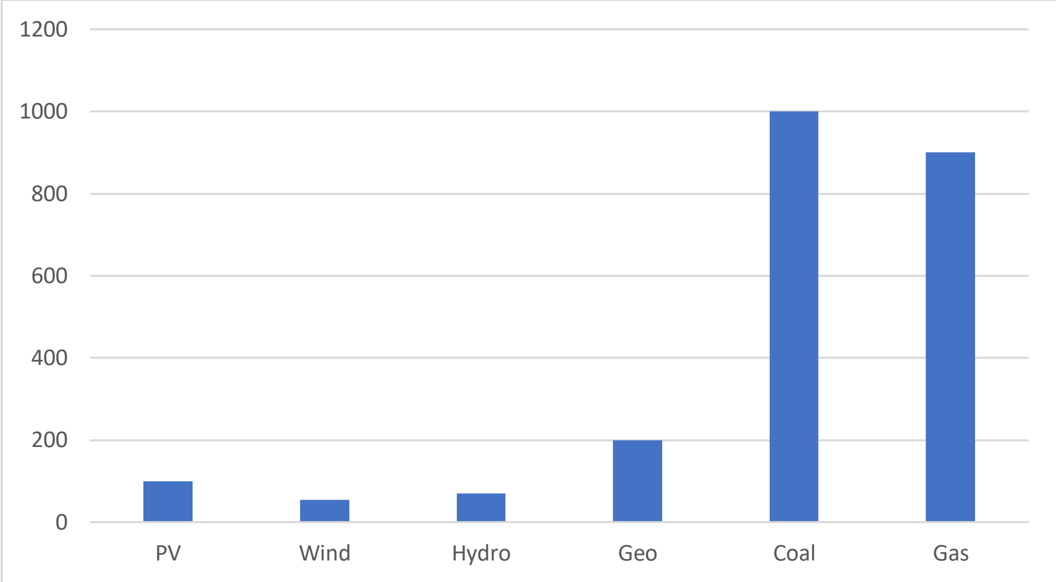

Fig 5. Emissions of Carbon Dioxide Equivalent throughout the Process of Generating Power

Technological and availability limitations

The assessment of technologies of sustainableenergy and their limits in generating base capacity is an additional element that has to be considered. The Earth receives an annual solar energy of about 170,000 Terawatt-hours (TWh), with the amount of sunlight varies significantly depending on the location and season. Nevertheless, photovoltaics has constraints in terms of storage challenges during periods of darkness and overcast weather, when the cells cannot be powered by the sun. Wind power is likewise affected by the issue of intermittency. However, Drake and Hubacek [20] propose that the problem may be mitigated by implementing dispersed capacity throughout a large geographic region. Turbines should not be in operation with wind velocities above 25 m/s to avoid potential turbine damage. Similarly, turbines will not function when wind velocities are below 3 m/s. The International Energy Agency (IEA) estimates that the worldwide wind potential is 40,000 terawatt-hours per year.

Hydropower has superior flexibility, availability, and dependabilitycompared to other technologies. Hydroelectric power facilities have the ability to be started, halted, or adjust their production levels in a matter of minutes. In situations where there is an abundance of water (H_2O) resources, hydropower may serve as a sustainable source of both peak load and base load electricity. In 2005, hydropower account for approximately 21% of the globe's consumption of energy, amounting to 2600 TWh [21]. It is estimated that the commercially viable potential for hydropower globally exceeds 8100 TWh/annum. Electrical power is constrained by its geographical requirements, since it can only be harnessed in locations where the resource is available. However, there are several suitable sites globally, spanning over 24 nations, with a total operational capacity of 57 terawatt-hours per year. Geothermal energy is appealing due to its capacity to consistently generate electricity at all times, providing a continuous power supply. The extraction rates for power generation will consistently surpass the refresh rates. However, reinjection aids in restoring equilibrium and substantially extends the lifespan of geothermal plants. The choice of the reinjection location must be meticulously made in order to prevent any occurrence of short-circuiting. Reinjection of fluids also amplifies the occurrence rate, albeit not the intensity, of seismic activity.

Table 3. Efficiency of Electricity Generation

Energy Source	**Quantification**
Gas	45-53
Photovoltaic	4-22%
Geothermal	10-20%
Wind	24-54%
Coal	32-45%
Hydro	>90%

Energy generation efficiency

The efficiency of energy generating technologies are included in **Table 3**. Currently, hydropower boasts the best efficiency among all existing energy generation systems. Wind power exhibits the second greatest level of efficiency, often on par with that of coal or gas. Photovoltaics and geothermal electricity have much lower efficiency compared to other technologies. The efficiency of photovoltaic systems may vary significantly owing to the wide variety of types of cell present. The optimal competence of a cell is 30%. Crystalline silicon cells, which include both poly-crystalline andmulticrystalline types, have the greatest competences, whereas amorphous silicon cells have the minimum efficiencies. The efficiency of wind power varies significantly owing to the diverse quality of wind resources found in various areas. Awell-chosen site for a wind resource may provide an efficiency higher than 40%. The geothermal properties are diminished as a result of the steam's low temperatures.

Land use

Wind power and PV have comparable land use properties, since they both involve the usage of materials for manufacturing and disposal/recycling. Both do not need any additional mining impact. Both are similarly characterized by the presence of places that may be used for two different purposes. Solar panels may be installed on rooftops, resulting in little space use during operation. Similarly, wind turbines can be integrated into agricultural grounds, so lowering their overall impact on the environment. Jacobson and Delucchi [22] provide a comprehensive footmark of 72 km2 /TWh for wind power, with no portion of it attributed to agriculture. In a similar vein, Majumdar and Pasqualetti [23] discovered that the acreage required for photovoltaic energy production ranges from 28 to 64 square kilometers per terawatt-hour, without any allotment for dual use. The hydrological footprints exhibit substantial variations, contingent upon the specific characteristics of the local topography. Onat and Bayar [24] provide a general land demand of 750 km^2/TWhper annum, but Mwanza and Ülgen [25] provide land needs as least as 73 km^2/TWh.Electrical power stations provide compact surface footprints, whereas significant components are situated under the earth. The geothermal sector is included in the computation of the footprint due to the potential danger of ground subsidence. The usual land area required for a geothermal project is between 18 and 74 square kilometers per terawatt-hour (TWh) of energy produced.

Water consumption

Obtaining precise statistics on water use during the production of power, especially for renewable energy systems, is challenging. In accordance with the analysis conducted by Pan et al. [26], differentiating between water withdrawal (the process of taking water and then returning it to circulation) and consumption of water (the removal of water from circulation outside of the unit or plant) is a challenge. Consumption of water is a more precise measure of renewability since it refers to the water that is no longer in circulation and thus has a significant influence[27]. The storage dam is important for large-scale hydroelectric power facilities. These dams retain vast quantities of water, preventing it from flowing into the surrounding regions. Dams also result in significant water losses via surface evaporation, with the extent of these losses varying considerably based on factors such as ambient temperatures, dam size, and capacity per square meter.

Nevertheless, this water might have undergone natural evaporation from lakes and rivers. Geothermal power needs significant quantities of water for cooling purpose. Consumption of water may be regulated by the complete reinjection of closed-loop recirculating, contaminated and malodorous wastewater, overall pressure control, and non-evaporative coolingsystems. Both Bayer et al. [28] reached the same conclusion that geothermal facilities generate a greater amount of wastewater compared to thermal power plants, with amaximum of 299 kg/kWh. H_2O is also used in the manufacturing of wind turbines and solar modules, nevertheless small amounts are required during their maintenance and operation, resulting in very reduced water usage over their lifespan. Among the technologies examined, wind power had the most minimal water use, with photovoltaics coming in a close second.

Social impacts

The creation of energy has a diverse array of societal repercussions, including both favorable and unfavorable outcomes. Renewable energy sources provide the possibility of generating power in some areas where it would otherwise be unavailable. Australia has greater stocks of thermal fuels compared to many other nations. Renewable technologies provide autonomy from the dependance on imported fossil fuels and the uncertainties of price swings. The effects and their respective indicators for the evaluated technologies are summarized in **Table 4**. Photovoltaic cells provide an appealing origin of energy that is not reliant on fuel, eliminates the need for traditional power plants, and reduces the demand for mining. The production of solar cells entails the use of many hazardous substances that are poisonous, combustible, and prone to explosion. As cell fabrication progresses and cells get thinner, the mass needs decrease, resulting in lower dangers. However, it is crucial to treat all chemicals with care to minimize human and environmental exposure. Strategic site selection for solar farms is crucial to minimize conflicts with agricultural activities, as well as to mitigate soil erosion and compaction.

Wind power faces public backlash owing to concerns about its negative impact on aesthetics, noise pollution, and the risk of bird collisions. Swofford and Slattery [29] discovered that the building of wind farms at a local level resulted in an increase in popular approval. The probability of bird strikes may be significantly reduced by doing comprehensive investigation of the intended location before installing. The noise is usually greatly obscured by the wind's own roar. The implementation of hydropower is a subject of controversy. The rates of progress in the building of big hydroelectric projects have seen a considerable decline due to a lack of public approval. The flooding caused by dam inundation often leads to the forced relocation of both human and animal populations from their respective residences or habitats. The scale of the impact may be extensive, affecting a significant number of individuals.

Agricultural fields may be impacted by either direct flooding or the depletion of river and fertilizing sediment that flows downstream. Nevertheless, hydroelectric dams may also provide advantages to communities by enhancing flood management, providing consistent availability to agricultural water, and facilitating recreational water activities. The improper management of geothermal process fluids may have negative effects on communities because to disagreeable odors caused by H_2S and contamination with baron, radon, and arsenic. Hydroelectric fluids may undergo processing inside a fully enclosed system and then be reinjected, so alleviating these issues.

Table 4. Assessment of the social effect using qualitative methods

Technology	**Impact**	**Magnitude**
Geothermal	Noise Oduor Seismic activity Pollution	Minor Minor Minor Minor-major
Wind	Visual Bird strike Noise	Minor `` ``
Photovoltaic	Visual Toxins	Minor Minor-major
Hydro	River Damage Repositioning Farming	Minor-major `` ``

Ranking

Based on the chosen indicators of sustainability, each technology was assigned a ranking from 1 to 4 basing on the related signal, as shown in **Fig 6**. A ranking of 1 indicates that the technology performed the best for that particular criterion. When values could be measured, the arange and verage were analyzed simultaneously, since there was often substantial overlie between the figures. The qualitative assessment focused on effect categories that could not be measured, including availability and restrictions, as well as societal implications. Hydro was selected as the minimum constrained option owing to its capacity to offer base load energy, operational flexibility, and the abundance of appropriate locations worldwide. The wind was regarded as the second most favorable due to comparable factors.

Geothermal energy is rather constrained on a global scale, since there are fewer appropriate areas available. Solar energy is regarded as the most constrained due to the inability to sufficiently store extra electricity generated during daylight hours for use during nights and overcast days [30]. Wind energy was shown to have the least adverse societal repercussions when considering its benign character. Solar energy ranked second due to its effective manufacturing management and meticulous site selection, which help minimize any possible adverse effects. Geothermal ranked third as a result of heightened seismic activity and the possibility for contamination. The hydroelectric power industry had the most significant influence, mainly because of the extensive displacement of both human and animal populations caused by dam flooding.

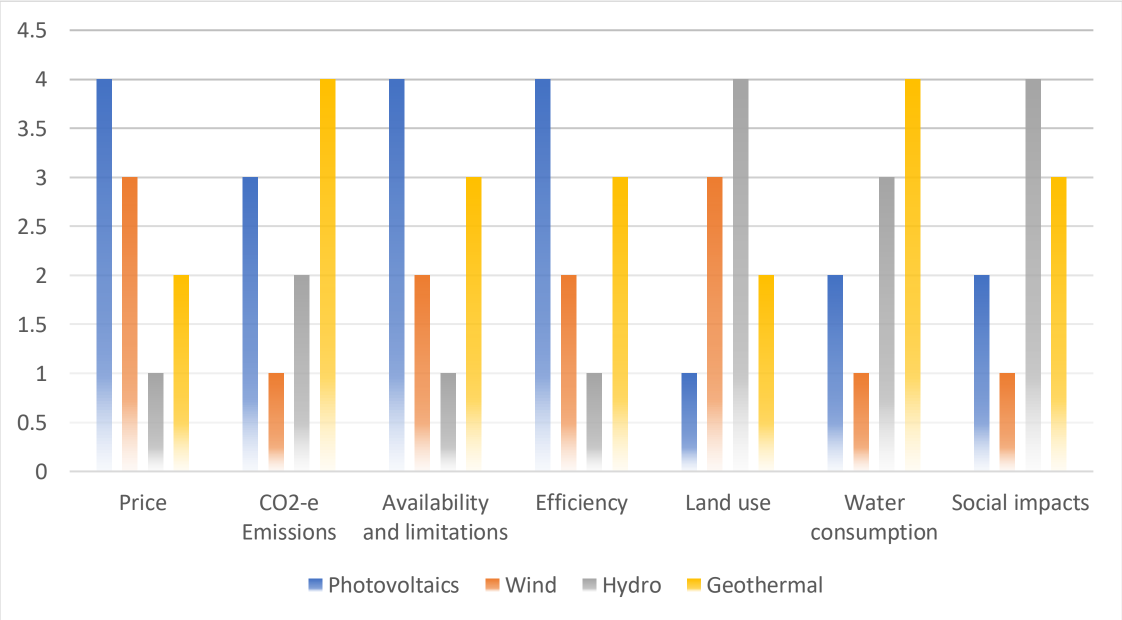

Fig 6. Sustainability Rankings

According to the rating shown in **Fig 6**, wind power is the major energy source that is sustainable, with hydropower being the second most sustainable. Geothermal was determined to have the minimum ranking among the four non-combustion technologies of renewable energy. It is fundamental to remember that the ranking was based on worldwide international circumstances, yet each technology may be greatly influenced by regional factors. Depending on the specific geographical region, some sustainability indicators may have more significance compared to others.

IV. CONCLUSIONS

The Earth's ecosystem has the potential to provide significant amounts of renewable energy that might surpass current levels of energy use. The availability of abundant resources and advanced technology for harnessing renewable energy raises the issue of future progress, depending on the economic and political viability in contrast to other sources of energy. The competitiveness of sources of renewable energy is strongly dependent on technical innovation, since it directly affects their performance and affordability. Various organizations forecast an increasing predominance of sustainable energy in the 21stcentury, with important assistances from wind, solar, biomass, and hydropowersources. There is now a diverse range of technologies available or in progress that provide affordable, dependable, and environmentally friendly energy options. However, there is a significant disparity in the level of advancement and competition among these technologies.

The objective of clean energy solutions is to enhance sustainability by maximizing efficiency, optimizing resource use, boosting cost-effectiveness, lowering environmental harm, strengthening energy security, and improving design and analytical capabilities. When formulating sustainable solutions, it is crucial to consider factors like ecosystem sustainability, abundance, safety, local availability, dependability, and cost-effectiveness. Efforts have been made to develop methods and guidelines for assessing sustainability in a universally recognized and measurable manner. Various measures have been created to evaluate sustainable development in the energy sector. The cost of electricity generation varies significantly across different energy production systems. Renewable energy sources, namely offshore wind farms, are being used for transmitting electricity over long distances, as opposed to non-renewable sources. Over the years, the price of photovoltaics has decreased, making wind energy the most cost-effective option with the lowest carbon dioxide equivalent emissions.

Greenhouse gas emissions are associated with many technologies, with photovoltaics and wind turbines mostly contributing to emissions via energy consumption throughout the production process. The composition of grid mixes varies according on geographical location, so regions with colder temperatures and smaller biomass amounts exhibit fewer emissions per kilowatt-hour. Renewable energy sources have limitations in generating continuous power, mostly owing to challenges in storage and the intermittent nature of its supply. Hydropower has remarkable availability, dependability, and flexibility, making it a dependable energy source for both peak load and base load requirements. Geothermal power is constrained by geographical requirements, despite providing a continuous power supply. The energy production efficiency of photovoltaics and geothermal electricity varies, whereas the efficiency of wind power relies on the quality of wind resources. Photovoltaics and wind production have comparable land use characteristics;however, their hydrological footprints vary. The measurement of water use is a crucial factor in determining sustainability, since large-scale hydroelectric power facilities need significant amounts of water for cooling purposes.

The creation of energy has both advantageous and deleterious consequences on civilization. Renewable energy sources have the capacity to provide power in areas where it would otherwise be unattainable. However, the production of solar cells requires the use of hazardous substances. Public resistance to wind power has arisen due to aesthetic concerns and the possibility of bird collisions. The use of hydropower is a subject of contention, and insufficient management of geothermal process fluids may have detrimental effects on the surrounding populace. Wind power is the most sustainable kind of energy, with hydropower and geothermal energy being the next most sustainable options. However, the rating may be subject to regional factors in view of global events.

Data Availability

No data was used to support this study.

Conflicts of Interests

The author(s) declare(s) that they have no conflicts of interest.

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Competing Interests

There are no competing interests.

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