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A Comparative Analysis of the Sustainable Growth of Global Hydro, Solar, and Wind Power Systems (Renewable Energy Systems)

Jusu Momoh Ngobeh[1*], Mustapha Sannoh[2], Joseph Thullah[3]

[1]Parul Institute of Engineering and Technology, Parul University, Vadodara, India
[2]Ministry of Energy, Freetown, Sierra Leone
[3]Suzhou University of Science and Technology, Suzhou, China
Email: *ngobeh@gmail.com, mustaphasannoh1@gmail.com, josephthullah12@gmail.com

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Abstract

The unfettered reliance on fossil fuels for centuries has pushed the world to the brink of severe environmental crises. While individual studies on renewable energy generation capacity have been conducted, a comprehensive analysis is lacking. This study aims to address this gap by providing a comparative analysis of three major renewable energy sources—hydro, solar, and wind—and their current global utilization statistics. Additionally, it will examine the efficacy of fossil fuels and their detrimental impact on the environment. Global warming and its associated health consequences on the ecosystem are rapidly escalating. Without a complete decarbonization of our energy systems, environmental deterioration is poised to continue at an alarming rate. Fortunately, a plethora of traditional and renewable energy resources exist that have minimal or no environmental impact and have been available for years. However, these resources remain largely untapped. The full potential of RE resources hinges on the development of sustainable technologies to harness their energy to their fullest capacity. This study delves into the current global and regional RE utilization from 2013 to 2022, based on data from the International Renewable Energy Agency (IRENA) 2023. The focus is limited to the three primary renewable energy sources with the highest harnessing capacity in recent times. Employing appropriate mathematical analyses, the results reveal exponential growth in renewable energy, with an average annual generating capacity of 2353550.7 MW over the past decade. Hydroelectric power, solar power, and wind, among others, have played a significant role in the global penetration of renewable energy systems. The changing dynamics have propelled these RE resources into the spotlight in recent years, owing to their sustainability and environmental friendliness.

Keywords

Renewable Energy, Sustainable, Environment, Technology, Optimization

1. Introduction

Renewable energy, with its cornerstone sources of hydroelectric power, solar energy, and wind energy power, stands as the most sustainable energy paradigm known to mankind. Recent studies, including one by Khalili *et al.* (2022), have underscored the fundamental role of energy in human existence and sustainability [1] [2] [3]. Energy's significance extends beyond economic and social viability, permeating every aspect of human life and sustenance, regardless of its renewable or non-renewable nature. Consequently, it is incumbent upon every individual to consciously engage with the energy issue, recognizing its role as a building block of life. As the adage goes, "energy is the capacity to do work" [4] [5] [6] [7]. Embracing the energy transition and achieving carbon neutrality is the pathway to global sustainability. Global leaders, international financial institutions, and various stakeholders are united in their ambitious pursuit of decarbonization and carbon neutrality by 2030. By 2030, renewable energy is expected to account for 90% of global energy systems, according to IRENA. While the energy transition is a complex undertaking, it demands unwavering commitment, even if it discomforts the Organization of the Petroleum Exporting Countries (OPEC) [4]. The notion of an overabundance of petroleum products is a delusion, as the reality is far from that. Some oil-producing countries in sub-Saharan Africa have embraced the energy transition with mixed feelings [3] [4] [5]. The new energy revolution is achievable, enabling us to move beyond fossil fuels and integrate a higher proportion of renewable energy into the current energy paradigm, powering our machines and equipment with pure renewable energy.

For the safety of the environment not only today and tomorrow but forever human anthropogenic activities should not affect the environment immensely because the environment encompasses everything according to the annotated **Figure 1**. Reaching the targeted renewable energy penetration sustainably needs judicious financial allocations, especially for the weaker countries and regions that are unable to meet their domestic and regional renewable targets. Much research should be conducted on different renewable energy resources and their constituents. In energy transition, the world should move together in a single vehicle. Climate change effects and global warming are visible in our local countries. Both drinking and industrial water have become scarce due to unprecedented population growth and excessive heat waves, floods, and droughts around the world. Climate change is not only limited to the aforementioned problems but has also recently given rise to all kinds of diseases [1] [3] [6] [7]. Groundwater levels drop daily, infant mortality is high, and heavy metal pollution is a serious problem. Unfortunately, most of these problems are due to old fossil fuel

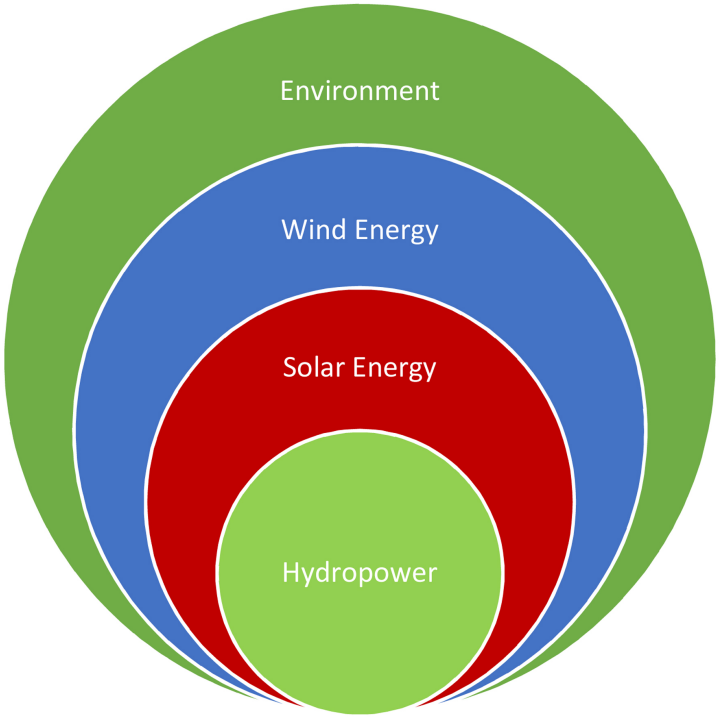

Figure 1. Integration of renewable energy sources into the environment.

energy production and other unproductive technologies that are not sustainable. The only solution for sustainability in the 21st century is ecological resilience with green technological advancement.

Hydropower, solar, and wind are the three major sources of renewable energy systems with negligible carbon source emissions. Therefore, with the widespread adoption of this type of energy, there will be minimal or no issue with the greenhouse effect on the environment, which is more closely associated with the use of fossil fuels, which are still heavily used worldwide. There are numerous health problems associated with greenhouse gas emissions and pollution derived from the use of carbon-based energy sources (fossil fuels). The socioeconomic benefits of renewable energy are undeniable. The full use of renewable energy will reduce carbon emissions and give rise to the use of a smart grid. The smart grid will further reduce greenhouse emissions by utilizing only renewable energy sources, minimizing or eliminating any carbon source impact. This energy transition will foster sustainability in socioeconomic development. Individuals will become either consumers or both consumers and producers (prosumers), leading to significant employment opportunities in the energy sector [9]. The paradigm of energy will undergo a radical transformation due to the high penetration of renewable energy, particularly hydropower, solar, and wind. The use of renewable energy will also save a large amount of money spent not only on energy tariffs but also on any government of any country. The government spends a large amount of money on military activities, especially in industrialized and developing countries around the world (the USA, China, Russia, France, the UK, In-

dia, and South Korea, as indicated by researchers). African countries also spend a significant amount of money on the use of fossil fuels. In many countries, including Sierra Leone, governments owe electricity providers millions of dollars in electricity tariffs. This debt continues to grow due to the use of fossil fuels and their associated high tariffs. With the transition to renewable energy sources, which are abundant in nature and not easily depletable, energy companies may not have difficulty meeting the financial obligations of all consumers in terms of affordable tariffs [10] [11] [12].

2. Hydropower

Hydropower has been around for a long time and is very sustainable, according to a recent study by Siri *et al*. 2020 on the sustainability of hydropower without environmental impact. A similar report looks at the existence of the Hawaii-Wailuku River project for hydropower over 50 years with less independence from oil and with a low electricity tariff. Hydropower is in combination with different types such as pumped storage, pico-power, and mini-power plants has a major impact on the energy mix around the world. The statistical results show that the recent work by Choma'c-Pierzecka *et al*. 2022, 12.7% of the share of hydropower in the renewable energy mix in the European Union is officially far behind [8] [9] [10]. Hydropower converts the available potential energy present in the reservoir into kinetic energy, which sets in motion the wheel or turbine that is coupled with the generator to produce electricity. The process is simple, sustainable, and environmentally friendly. Countries with abundant water resources, such as China, Brazil, and Ethiopia, are fully harnessing the potential energy from hydropower resources. It is believed that countries with a high proportion of renewable energy in their energy systems have lower electricity tariffs. This is supported by personal experience in China, Ethiopia, Brazil, and India.

Hydropower, solar, and wind power are making significant strides in the renewable energy landscape, becoming indispensable components of the energy transition (Governing the transition to renewable energy) [13]. Without these major power resources, the energy transition will be hindered due to the limited generating capacity of other renewable energy sources in the energy matrix, based on their exhaustible availability. A comparative analysis of these major energy sources and their potential integration into power grid systems has been conducted. According to **Figure 2**, hydropower is not leading the way in many countries, but on a global scale, solar and wind power are gaining momentum. Hydropower development is a time-consuming process, and not every region possesses sufficient water resources with the necessary head to drive turbines for power generation. Unlike solar energy, wind energy is almost ubiquitous, albeit with varying power-harnessing capabilities. Wind and other technologies are relatively inexpensive, except on a larger scale. Hydropower development requires significant time and labour, making it unsuitable for a leading role in the

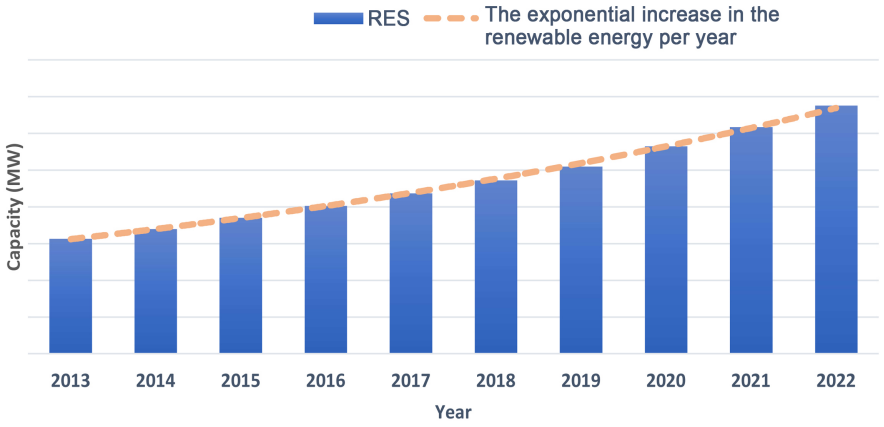

Figure 2. Global annual renewable energy generation capacity (MW).

energy matrix. Water availability is crucial, and the dam head is essential for both potential and kinetic energy, which impinges on the turbine to provide the necessary power output from hydropower. Financial considerations are another factor, although dams have been unjustly burdened with excessive emphasis on their susceptibility to failure. Safety can also be a major concern. Hydropower dam failures are rare, but their consequences can be catastrophic, as seen in a few countries worldwide. Maintenance is another issue, and the fact that technologies are constantly changing could be another factor in the slow development of hydropower around the world, as we can see in the graph in **Figure 3**.

3. Solar Power

Solar power has a significant impact on the energy transition. This renewable energy source is abundant and virtually limitless in supply, despite uneven distribution in certain geographical regions. Photovoltaic technology is abundant in nature, but its full potential is yet to be realized due to technological limitations and economic constraints. Solar power is making an impact on the diffusion of the energy mix despite some challenges to its full exploitation. Recently, in the work of these researchers; Chanchangi *et al*., 2022, solar energy economic buoyancy with environmental potency has become an alternative source of energy in attaining UN-SDs 7 [11] for developing countries and in sub-Shaharan Africa, especially Nigeria, etc. Fossil fuel with insufficient production is politically hampered and environmentally challenged with economic constraints that impede social injustice and conflicts in most countries in the world [12]. Photovoltaics and solar power were recently, studied by Xu *et al*., 2022 despite their penetration into the power grid system impacting power optimization of balancing active and reactive power in the system by the right technology [13]. According to these researchers Wahid *et al*., 2023, electricity generation is an anthropogenic process that usually hurts the environment if not taken care of. Solar energy is considered environmentally friendly and has no adverse effect on the environment [14].

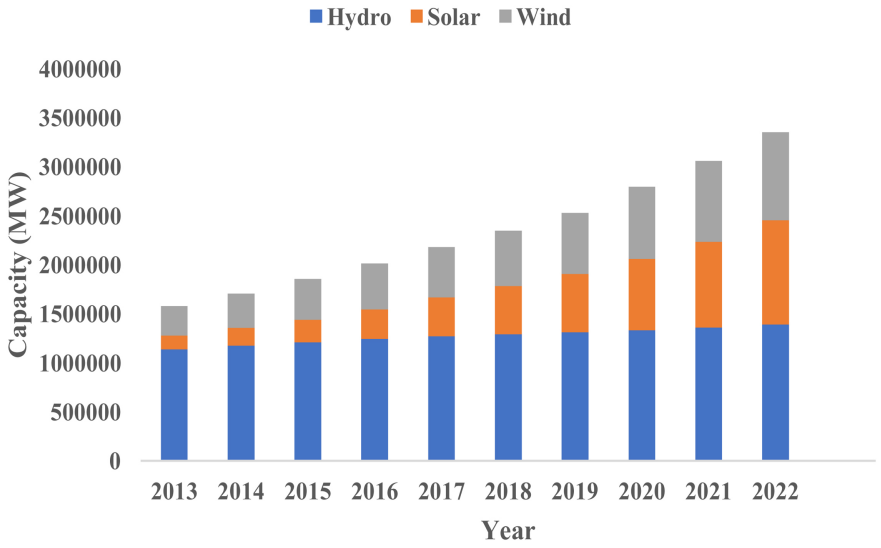

Figure 3. Global annual hydro, solar, and wind energy generation capacity (MW).

4. Wind Power

Among other renewable energy resources, the most exploited ones are hydropower, solar, and wind, and are making breakthroughs in the energy transition. Other parts of the world are making significant sacrifices to enhance their wind power generating capacity [14]. Wind energy is an environmentally friendly technology that harnesses the power of wind through wind turbines. Over time, wind technology has advanced significantly, leading to the development of more efficient and sustainable wind turbines. More research has been done to overcome this [15]. Apart from technological challenges, other factors hinder the widespread adoption of wind energy around the globe. The policies of most industrialized nations, including China, the USA, India, and Germany, fall short of adequately promoting the integration of wind energy into their energy portfolios. These policies fail to provide the necessary incentives for the expansion of wind energy [16] [17] [18]. Technological limitations further serve as a disincentive to wind energy adoption. More effective, well-founded, and sustainable policies are urgently needed, not only to address these limitations in the aforementioned countries, which are among the world's largest energy consumers but also, to actively promote wind energy as a viable renewable energy source with zero carbon emissions.

Despite the significant attention garnered by wind energy as a renewable energy source with minimal environmental impact and zero carbon emissions, wind turbines face a significant challenge: efficiency. Enhancing wind turbine efficiency necessitates further research [19] [20]. Moreover, selecting wind turbines tailored to specific terrains is crucial, as wind speeds vary and lack uniformity. Atmospheric conditions influence the turbine's nonuniform speed, which drives turbine rotation and electricity generation. When the prime mover receives insufficient kinetic energy to rotate the turbine, electricity production dwindles.

The planetary gear, which is responsible for boosting turbine speed regardless of wind velocity, requires improvement.

The erratic wind speed, which accelerates wind turbine rotation, introduces fluctuations into the grid-connected wind power system. This distorts power quality due to voltage conditions, potentially causing the power grid to lose synchronization when connected without power sources capable of compensating for power interruptions. However, research can yield effective solutions to manage these anomalies.

Enhancing the wind turbine's Betz constant is crucial. According to some literature, the Betz constant for wind turbines stands at 0.53%. Wind turbine designs, regardless of type (vertical or horizontal) and size, require improvement. Optimizing structural designs that leverage aerodynamics will significantly enhance turbine efficiency. Until these improvements are implemented, wind power generation will remain suboptimal. The wind turbine mechanism should fully convert mechanical energy into electrical energy for power optimization of either a standalone or grid-tied wind power system [21].

5. Green Technologies

The most modern technologies for using renewable energy resources are environmentally friendly and, unlike fossil fuels, do not produce significant waste that could endanger the environment. At present, technological progress in the production of these renewable resources is very efficient, as seen from the data given on global energy production capacity or energy content [22] [23] [24]. As the global population steadily increases, the energy demand also grows exponentially. To meet this demand sustainably, industries face immense pressure to produce more goods and services while minimizing their environmental impact. Therefore, technological advancements in manufacturing processes must also be sustainable. We should refrain from developing technologies that offer no environmental benefits in terms of reliability and sustainability. Consequently, green technology stands out as a crucial solution, offering not only reduced carbon emissions and energy consumption but also enhanced productivity for socioeconomic development. The excessive use of fossil fuels is widely acknowledged as a major contributor to the current environmental crisis.

Among the many emerging technologies, there is a significant amount that has a detrimental effect on the environment. This extends beyond energy-generation technologies. Twenty-first-century technology should not harm the environment. Technologies that release harmful byproducts into the environment, directly or indirectly, should not be considered green technologies. We should adopt environmentally friendly technologies, with no adverse effects on human health, social well-being, or the ecosystem. Most androgenetic activities are not green technologies. Any technology that does not contribute to greenhouse gas emissions, even if not treated at the point of generation, is considered nongreen technology [25].

6. Results and Discussion

From the data analysis of both Figure 2 and Figure 3, it is very certain that (RE) will account for 90% of the total energy in 2030, which is the ambitious target of IRENE. The path the world is taking together in its quest for the diffusion of renewable energy is simply too amazing. However, some countries are moving slightly more slowly regionally because they lack adequate funding and technological know-how to fast-track the process. The average annual generation capacity of 2353550.7 MW of renewable energy in the last 10 years has been amazing and efforts will be intensified in the coming years to meet the 90% renewable energy in 2030 based on the given projections. Figure 3 also shows that three (3) of the main RE sources (hydro, solar, and wind) are on the rise. The 90% (RE) penetration into the traditional grid is realistic and achievable if more efforts are directed toward it and with deep commitment. Therefore, if that happens it will reduce the carbon and greenhouse effects that the world is currently facing.

The environment plays a crucial role in human activities. Maintaining environmental sanity should be our topmost priority. The environment encompasses everything, including carbon emissions from anthropogenic activities and other pollution sources that remain untreated. It bears the brunt of energy harvesting and related activities. The environment accumulates both biotic and abiotic components, leading to the formation of global warming agents such as greenhouse gases, heavy metals, and other pollutants that have detrimental effects on both humans and plants, directly or indirectly [26]. As shown in Figure 1. The environment's integral position is crucial in the construction of everything. If the environment is affected by power generation, the entire eco-environmental system is compromised.

Figure 2 illustrates the current trend for all renewable energy resources worldwide in terms of renewable energy consumption according to (IRENA). This graph will inform the world of the trajectory in which the world is moving toward the renewable energy transition. The annual incremental trend for the past decade indicates that 90% of the full penetration of renewable energy in the current power systems could be achievable by 2030.

Apart from the global analysis of renewable energy growth shown in Figure 2. some studies were also conducted to demonstrate how regional or continental levels influence renewable energy growth. Figure 4 further explains how the steady growth of renewable energy is making a significant contribution to the global energy mix. However, not all regions are equally committed to the renewable energy drive. Some countries within the same region face challenges due to technological and financial constraints associated with the rapid growth of renewable energy deployment. These constraints will undoubtedly impact their overall performance in promoting renewable energy.

Unlike the other countries listed here, China is recognized as having the highest hydropower ranking in the world. Figure 5 illustrates the nation's deliberate

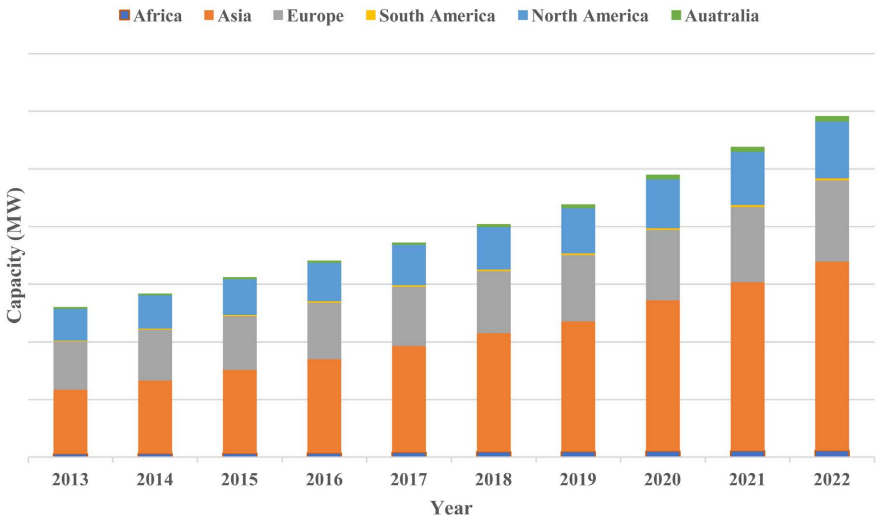

Figure 4. Continental/regional RE generation.

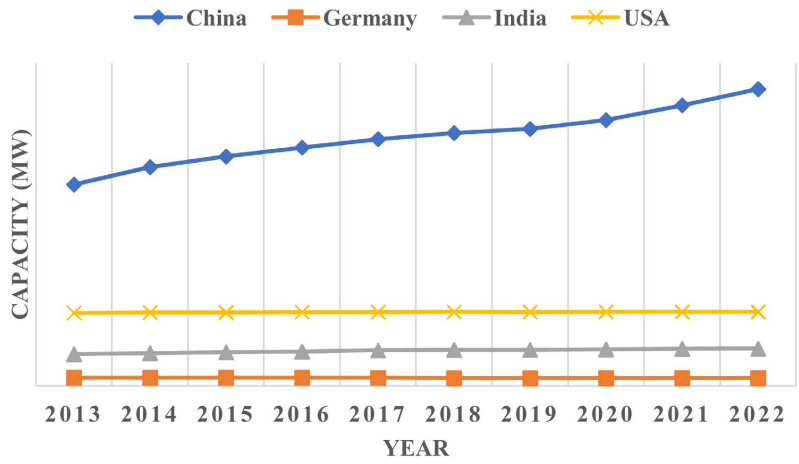

Figure 5. Hydropower generating capacity (MW) in China, Germany, India and the USA.

efforts to develop hydropower. China leads the world in terms of available power per capita, surpassing its substantial industrial power requirements. Recognizing the importance of energy, particularly the clean energy paradigm. China is making ambitious strides to transition from carbon-based fossil fuels to less carbon-intensive fuels for sustainable development and environmental protection.

As evident in Figure 6, the past decade (2013-2022) has witnessed a remarkable surge in wind power generation in China, driven by a confluence of factors, including technological advancements, supportive policies, and other underlying drivers. This exponential growth has propelled China to the forefront of wind power promotion, leaving Germany, India, and the USA trailing behind. While the USA has emerged as a strong contender in wind power development, China maintains a significant lead. India, on the other hand, occupies the lower end of the graph, potentially due to policy constraints and other factors impeding its

wind power expansion. Inadequate funding, coupled with a lack of strong leadership, could also be contributing factors.

Figure 7 illustrates the exponential growth of China's solar generating capacity in connection to other countries. This remarkable progress positions China as a global leader in solar energy production, far surpassing other major players such as Germany, India, and the USA. The graph demonstrates China's dominant role in this sector. Driven by a growing population and soaring energy demands, China has made significant investments in large-scale solar energy projects. While other countries strive to match China's impressive output, the gap remains substantial. Despite its rapid industrial development, China remains committed to utilizing renewable energy sources for its socioeconomic progress. The country's dedication to promoting renewable energy has been instrumental in its remarkable economic growth.

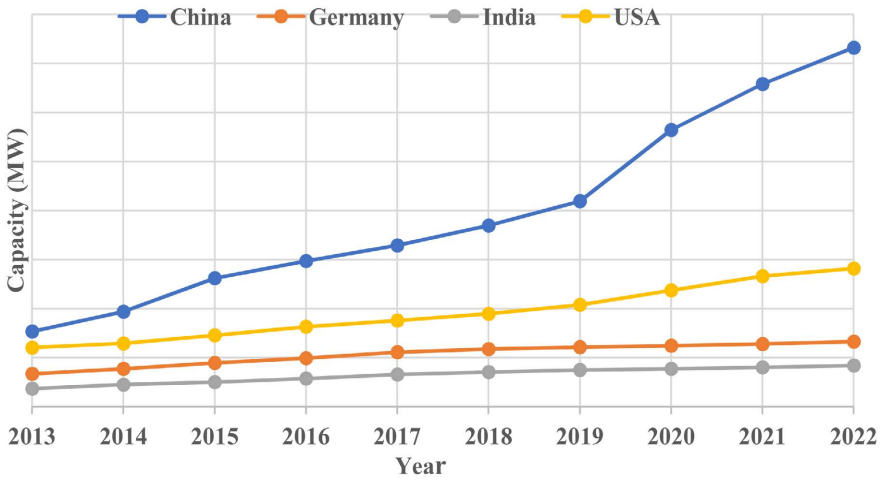

Figure 6. Wind power generating capacity (MW), China, Germany, India and the USA.

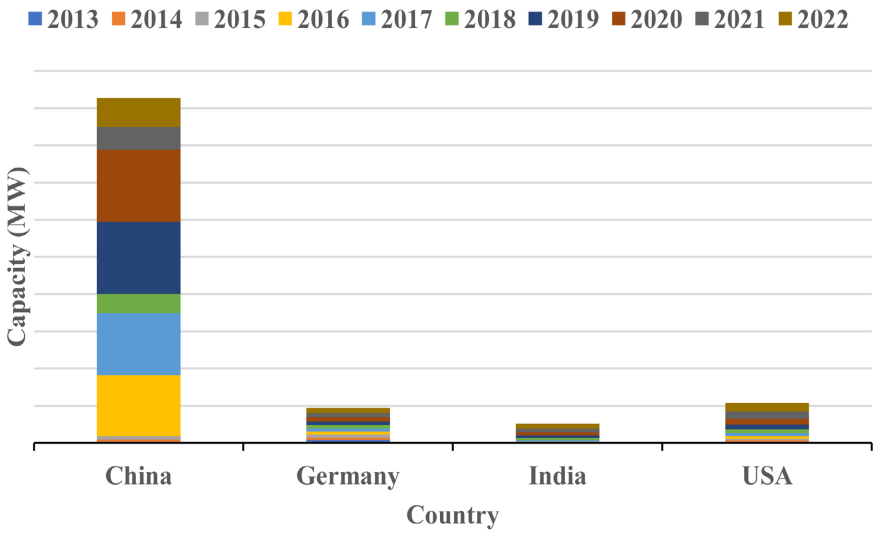

Figure 7. Solar power generating capacity (MW), in China, Germany, India, and the USA.

7. Conclusions

This research provides a comprehensive overview and comparative analysis of the sustainability aspects of three well-known renewable energy sources: hydropower, solar energy, and wind energy. The growing global demand for sustainable energy solutions has increased interest in these technologies. Furthermore, this work aims to provide a holistic assessment of the sustainability of hydropower, solar, and wind energy systems, enabling the reader to make informed decisions regarding energy production and consumption. It is a valuable resource for policymakers, energy professionals, researchers, and anyone interested in the energy transition for the socioeconomic energy landscape. This study examines their environmental, economic, and social impacts, considering factors such as resource availability, energy production efficiency, carbon emissions, and socioeconomic benefits. By assessing and comparing the sustainability of these energy sources, policymakers, and stakeholders can make informed decisions to drive the transition to a greener and more sustainable energy future.

Absolute dependence on fossil fuels and their overuse for centuries has presented the world with serious global environmental problems Much attention has been drawn to renewable energy production, but not on a large scale especially for certain developing countries due to economic and technological problems. In this work, comparative studies and an analysis of the three main renewable energy sources, as well as the current statistics on the global renewable energy generation capacity and the effectiveness of the prevailing use of fossil fuels and their dangerous impact on the environment are carried out. With the help of appropriate mathematical analyses, the result shows that there has been a strong improvement in renewable energy with an annual average generating capacity of 2353550.7 MW over the last ten years. “If people can eat and send their children to school, have access to affordable healthcare, have a roof over their heads, have some savings, and live in a clean environment with affordable electricity and clean drinking water, then we call that sustainability”.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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