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Climate Change Impact on Solar Power Generation : A Sustainable Energy Planning Perspective for Kenya

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Abstract: In the wake of the rising impacts of climate change, solar energy is poised to be crucial in the future of global energy security and sustainable development. However, in developing countries such as Kenya, there are limited studies on the consequences of climate change on solar power generation. This study was conducted with the aim of assessing how climate change affects solar power generation in Kenya, with the goal of informing strategies to bolster its resilience, adaptability, and overall energy planning. From the theoretical background of sustainable development, the research utilized a case study design using secondary data sources to unveil multifaceted aspects. Key secondary data examined included key policy documents and other documents retrieved from official websites. Through document content analysis, the evaluation focused on the vulnerability of solar power resources to climate change impacts by categorizing the findings into three main themes: the impact of climate change on solar energy generation, strategies for mitigation and adaptation, and policy implications for Kenya's overall energy planning. The results revealed a pressing need for explicit studies on how climate change affects solar power generation in Kenya. Estimating these potential impacts is crucial to ensuring the security, reliability, and sustainability of solar energy resources. Recommendations included pursuing adaptation strategies and technological innovations, such as integrating solar energy with other sources, while also expanding feed-in tariff incentives and policy interventions that promote sustainable solar energy utilization and further research. By implementing these measures, Kenya can enhance the long-term viability and resilience of solar energy in the face of a changing climate.

Keywords: Climate Change, Content Analysis, Energy Security, Solar Energy, Sustainable Development

1. Introduction

As societies grapple with the urgent need to transition towards sustainable energy sources in the wake of climate change, solar power generation is a rapidly growing and evolving industry worldwide, with various countries adopting different approaches and technologies to harness energy[1]. Many diverse solar power generation trends and practices are emerging in China, the US, Germany, India, Japan, Australia, and Spain, amongst other countries, with a focus on expanding their solar power capacity. Stakeholders in many parts of Brazil have launched various projects and initiatives to increase renewable energy generation[1]. Even though it is speculated that, among other reasons, these expansion attempts seek to achieve energy security and to decrease our overall carbon footprint, each nation's solar energy

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landscape is shaped by its unique geographical, economic, and policy factors, but the overall trend is a growing recognition of the importance of renewable energy sources for a sustainable future. Therefore, as solar energy installations proliferate, it is imperative to evaluate how the changing climatic conditions could influence the performance and output of solar technologies, ultimately affecting the viability and reliability of solar energy as a sustainable power source and part of the future energy planning process for many countries.

Similarly, Kenya has made deliberate efforts to adopt solar power as part of the country's energy mix. Kenya has an abundant solar energy potential because of its location along the equator. With the growing power needs, solar power is recognized as one of the energy sources that will enable Kenya to attain energy security and improve power accessibility towards a middle-income economy status by the year 2030. Kenya experiences 23,046 TWh/year, with 5-7 hours of peak sunshine and an average daily insolation of 4-6 kWh/m2, providing immense opportunities for solar power production[2]. A number of initiatives have emerged with the intention of harnessing the contribution of solar to the national economy. The government has formulated robust policies needed to support the solar power industry.The Kenya National Electrification Strategy and the World Bank's KOSAP have played significant roles in expanding electricity access through various means, including solar home systems[2].

However, climate change presents a significant challenge to the security, sustainability, and reliability of solar energy systems in Kenya owing to its negative environmental impacts[2]. High temperatures reduce the efficiency of photovoltaic panels, whereas extreme weather events can damage the solar infrastructure. Changes in rainfall patterns affect water availability in solar power plants. Therefore, adaptation to climate change is crucial for the continuing viability of solar power resources. Surprisingly, there are limited studies on the effects of the changing climate on solar power systems, mitigation measures, or the implications for overall energy planning in the country. It poses several challenges to sustainable energy access, security, and reliability. For instance, the limited studies on the topic have fostered inadequate understanding, preparedness, and adaptation of solar power. Simultaneously, extreme weather events can damage solar power installations without appropriate research. Moreover, opportunities for renewable energy expansion could be missed because of insufficient research, hindering the shift to a reduced carbon footprint and sustainable development. In addition, a lack of research could result in inefficient energy planning, leading to suboptimal investments and increased vulnerability to energy supply disruptions. The lack of comprehensive studies hinders policy development and public awareness, making it difficult to drive sustainable energy transitions. Thorough research is required to mitigate risks, inform decision-making, enhance resilience, and promote renewable energy adoption and planning.

In line with this background, this study seeks to assess the impacts of climate change on solar energy generation and devise strategies for enhancing the resilience and adaptability of solar energy generation for future energy planning in Kenya. This study is motivated by findings from the literature showing limited studies on the impacts of climate change in Africa, including Kenya, on solar energy compared to wind and hydropower[3]. To achieve the study aims of this research, the linkage between solar power generation will be explored using document content analysis from the perspective of sustainable development, followed by a review of Kenya's energy context with a special bias towards describing the impacts of climate change on solar power generation. The global findings will then be used as the lens for evaluating the impacts of climate change on solar power generation in Kenya and suggest lessons for future energy planning. Kenya was chosen as the study site because of its abundant solar resources, vulnerability to climate change, renewable energy commitments, existing solar projects, economic significance, and potential for solar energy knowledge transfer.

2. Literature Review

2.1 The Interplay of Solar Power and Climate Change: A Theoretical Analysis and Implications

The global utilization of solar power is increasing. This trend is attributed to rising fossil fuel costs, environmental concerns, and limited conventional energy reserves. Under these complex circumstances, decision-makers prioritize energy security, environmental protection, and resource conservation to enhance solar power use. However, the management of solar energy systems involves complex processes increasingly affected by climatic conditions. Therefore, investigating the effects of the climate system on solar energy production is necessary to enhance their resilience and adaptability in future energy planning. According to recent findings, solar photovoltaic (PV) technology made the largest contribution to the new installed capacity in 2017, with a minimum of 98 GW[4].

The theoretical linkages between solar power generation and climate change can be understood from the primary motive of sustainable development, which involves balancing society's social, economic, and environmental needs. The effects of climate on solar power can hinder the transition to a low-carbon economy, compromise energy security, impede access to clean energy in remote areas, undermine greenhouse gas emission reduction efforts, and affect economic development and job creation. To achieve sustainable development, it is essential to address these impacts by enhancing the resilience of the solar infrastructure, promoting climate-resilient technologies, and integrating climate considerations into energy planning. These efforts can mitigate risks, maximize the potential of solar power, and contribute to sustainable development.

Sustainable development provides the most appropriate theoretical foundation for this study because it emphasizes the harmonious integration of the facets of balanced growth. Sustainable development aligns with the goals of mitigating climate change and transitioning to renewable energy sources such as solar power. By investigating how climate change affects solar power generation, researchers can contribute to understanding the challenges and opportunities for achieving sustainable development in the region. This study can inform policymakers, energy planners, and stakeholders to develop effective strategies to address climate change impacts, promote renewable energy adoption, and contribute to a sustainable development agenda.

2.2 Empirical Analysis of Climate Conditions on Solar Energy Production: Implications for Sustainable Energy Planning

Empirical studies on the subject of this paper are scarce and have produced mixed results and trends. The literature suggests that increasing global temperatures have a detrimental impact on the productivity of solar power systems, resulting in decreased power output. Studies show that for each 10 °C rise in temperature, the productivity of solar power systems decreases by approximately 0.5%. Moreover, elevated temperatures can also influence the functioning of solar power electrodes and raise soil temperature. Photovoltaic (PV) module efficiency declines by approximately 0.5% for every 10 °C temperature increase[5-7]. Furthermore, elevated temperatures reduce the capability of underground conductors and raise the temperature of the soil[7]. The rise in temperature can result in increased operational expenses and reduced equipment efficiency. Changes in solar irradiation and cloud cover also impact the output of solar power[7-9]. Concentrated solar power is more susceptible to the effects of climate variations because it cannot effectively utilize diffused light. Various factors, such as changes in dirt, dust, snow, and atmospheric particles, can affect solar energy output [10]. An increase in the highlighted variables decreased the energy output. Although precipitation may wash away dust, it also reduces efficiency by reducing solar radiation. The availability of water also has an impact on concentrated solar power[10]. PV panels can be susceptible to damage from risky weather episodes such as fires and strong winds[11]. Strong winds can cause sand and dust to accumulate on the panels, decreasing power output. Additionally, hailstones can cause physical damage to the PV panels. Heat waves with elevated temperatures also reduce power output and potential material damage[11].

Italy, Japan, China, and the United States are leading countries in terms of solar PV capacity, totaling 402 GW. By contrast, concentrated solar thermal power has a smaller capacity of 4.9 GW. To limit global warming to 2°C, solar PV must increase its share from 1% in 2015 to 22% by 2050, requiring investments of around $5 trillion in solar PV and $2 trillion in concentrated solar power by 2050[12]. Forecasts of the future of global solar energy show that due to changing climate conditions, some regions will experience a decline in solar energy output while others will gain. For instance, Europe and China will experience a decrease in photovoltaic (PV) output, whereas Europe will experience an increase in concentrated solar power. China, Algeria, and Australia are projected to increase their solar power output. However, limited research exists on the impacts of climate change on solar energy in Africa compared to wind and hydropower, motivating this study's focus[13]. The most significant positive changes in regional solar energy production are predicted to occur in Europe, particularly Spain and Germany, with annual increases of up to 0.5% from 2006 to 2049[14]. The northern regions of India and northwest China are predicted to face notable declines in solar energy production, with annual decreases of up to 0.5%. The global direct normal irradiation is projected to decrease by 5%. Europe is expected to witness the most significant increase of up to 10%, while Africa may experience the largest reduction of up to 10%. Changes in wind speed and temperature are likely to lead to a decrease in solar generation in most regions, but the overall production is not expected to be significantly impacted[14]. These findings align with those of other studies in which project production declined in northern countries. At the same time, Eastern Europe and Northern Africa may experience solar power productivity decreases of up to 7%, while Western Europe and the Eastern Mediterranean region may experience increases of up to 10%[14]. Limited attention has been paid to the impact of climate change on solar power generation in the United States, with official reports overlooking this topic. Western Africa is predicted to experience a decrease in photovoltaic (PV) output, whereas Southern Africa may experience seasonal changes in irradiation. However, both concur with the central theme of this paper by acknowledging that there are high levels of uncertainty and a lack of absolute projections and studies on the topic[14].

Furthermore, existing literature shows that from 2005 to 2019, even though the Asia-Oceania region attracted the largest investments in renewable energy, including solar power, these regions are also major contributors to global greenhouse gas emissions, contradicting expectations[15]. The contrasting trends in CO2 emissions between regions have motivated energy sector stakeholders to take proactive steps in implementing further environmentally conscious measures by encouraging the widespread adoption of renewable energy sources. This study will provide lessons on how to promote energy sustainability through solar energy.

In Greece, a study examining the effects of the changing climate on solar generation using different models shows an increase in solar energy output, except for specific regions like Attica and Thessaly[16]. Similarly, a study in the United Kingdom revealed positive changes in irradiation, except for small areas in the northwest[16]. In Germany, minimal seasonal variation is anticipated in the performance of photovoltaic (PV) systems[16]. In Croatia, the impact of climate change on solar energy generation is expected to be neutral due to conflicting influences. Other empirical studies have also shown that while solar panels generate a localized cooling effect, converting solar energy to heat, especially in urban areas, contributes to higher temperatures, offsetting the initial cooling effect. These processes affect global atmospheric circulation and regional precipitation patterns[16]. Overall, the literature review indicates the increasing global importance of solar energy, primarily driven by the growth of solar photovoltaic (PV) technology. However, the impacts of climate change on the reliability, efficiency, and output of solar energy have received limited research attention, particularly in most developing countries. To enhance the resilience and adaptability of energy systems for future energy planning, prioritizing solar energy security and environmental protection is required, hence the need for this study in the case of Kenya.

With a growing population of approximately 50 million, Kenya stands as one of the largest economies in Sub-Saharan Africa (SSA). The country's GDP has been consistently growing[17]. Kenya seeks to attain middle-income status by 2030, according to Vision 2030. This vision serves as the government's blueprint and outlines a comprehensive plan to achieve this goal. To realize this vision, the Kenyan government has made substantial investments in various areas of infrastructure, including transportation (roads, railways, sea ports, airports), provision of piped water, and improvement of information and communication systems. These investments are considered essential drivers for economic development in the country[17]. To secure funding for various infrastructure projects, the Kenyan government introduced infrastructure bonds in 2009. These bonds had maturity periods ranging from 12 to 25 years. They attracted both domestic and international investors, including small-scale investors, due to their tax-free status and relatively high coupon rates, often surpassing 10%. From 2008/09 to 2017/18, the Kenyan government successfully issued 13 infrastructure bonds totaling Ksh 413 billion. By mid-2018, after some bonds had been amortized, the outstanding stock of these bonds amounted to Ksh 303 billion[17]. In pursuit of their economic development objectives by 2030, the Kenyan government acknowledges the vital role of electricity. With this objective in mind, they established a goal in their 2007 plan to attain widespread electricity accessibility by 2020. Notably, between 2010 and 2016, there was a substantial surge in the percentage of households with electricity access, surging from 18% to 65%.

This progress was attributed to the establishment of new power plants and the expansion of electricity grids, as reported by the International Energy Agency (IEA) in 2017. However, despite having a total installed grid-connected capacity of 2,300 MW in 2015, Kenya still needed an additional 2,700 MW of electricity generation to achieve universal access to electricity by 2020[18]. To accomplish this objective, the government leveraged regulatory and utility reforms to facilitate the entry of private investors and enhance private-sector involvement.

To realize its objective of reaching a middle-income economy by 2030, Kenya must prioritize energy security and accessibility to effectively address the escalating energy requirements. The nation has witnessed a noteworthy surge in peak electricity demand, ascending from 899 megawatts in 2004/05 to 1,194 megawatts in 2010/11. Furthermore, there has been a substantial increase in the number of electricity consumers, more than doubling from 735,144 to 1,753,348 within this timeframe. This surge in energy consumption is also apparent in the heightened utilization of petroleum, with energy consumption reaching 3.77 million tons of oil equivalent in 2010, compared to 2.9 million tons of oil equivalent in 2004. Multiple factors contribute to the fluctuations in consumption, encompassing the expansion of gross domestic product (GDP), escalating electricity demand, population growth, urbanization, motorization, and the prevalence of air transport[18].

Renewable energies have consistently played a predominant role in the electricity mix of Kenya, accounting for over 75% of the total electricity generation supplied to the national grid[19]. Historically, hydropower projects dominated the renewable energy sector in Kenya and provided the main source of baseload electricity generation. However, in 2014, geothermal energy surpassed hydropower as the leading power production source in the country. Geothermal energy accounted for 51% of power production, while hydropower contributed 38%. This shift highlights the increasing importance and utilization of geothermal energy in Kenya's power generation mix. Due to limited prospects for new hydropower projects and the growing vulnerability of existing plants to drought conditions, the government has recognized geothermal power as the most cost-effective energy source. Geothermal power has been identified as a preferred option for providing baseload electricity[19]. Additionally, the government is reassessing proposals for constructing a coal-fired power plant in Lamu County[19]. Although there were considerations for establishing nuclear plants, the government has postponed those plans until 2036 due to its current focus on prioritizing renewable energy initiatives[19].

In the 1990s, Kenya's government underwent a restructuring and liberalization process in the energy sector following the influence of the World Bank. This process, referred to as the "neoliberal energy transition," resulted in the current hybrid market structure of Kenya's energy system. While state-owned or state-dominated companies like KenGen and KPLC continue to have a significant presence in the electricity sector, private investment, particularly from independent power producers (IPPs), has become increasingly important. Private-sector investment in renewable energy is driven by feed-in-tariffs (FITs), which offer a fixed price per kilowatt-hour (kWh) for a period of 20 years. These FITs provide assurance for investors, ensuring the purchase of the generated electricity and reducing market risks[19].

In the context of Sub-Saharan Africa (SSA), the progress in developing geothermal, wind, and solar energy sources is still in its early stages. However, Kenya is notable among the countries in the region for making significant strides in harnessing these renewable energy sources on a larger scale[19]. However, the significant initial financing demands associated with large-scale renewable energy projects in Kenya surpass the capacity of the country's public finances. Consequently, the government actively seeks participation from international and domestic donors and the private sector. To facilitate this involvement, Kenya has implemented supportive policies and frameworks, aiming to attract financial contributions from external and domestic sources. From the foregoing review, it is evident that the growing human population and the need to promote sustainable development by protecting environmental resources are amplifying Kenya's quest for clean energy sources. As such, key policy documents recognize the need to harness the utilization of renewable energy sources such as solar power.

Analysis of historical data, including temperature, precipitation, sea level changes, glacier extent, and extreme weather events, provide evidence of climate change in Kenya. The Kenya Meteorological Department's records of temperature and rainfall over the past five decades show a consistent temperature rise and increased irregularity in rainfall patterns. The National Environment Management Authority's State of the Environment Report of 2021 supports these findings. While annual rainfall has shown a mostly neutral to slightly decreasing trend, the long rainfall season has experienced a decrease, while some regions have seen increased precipitation between September and February[20].

Generally, there has been a decline in the intensity of 24-hour rainfall. Since the 1960s, numerous regions in Kenya have observed a consistent temperature rise. This is evident in meteorological data, which indicates a decrease in occurrences of extreme cold temperatures in the arid and semi-arid lands (ASALs) of the country. The consequences of rising temperatures in Kenya include the loss of Mount Kenya glaciers and rising sea levels. The rising temperatures in Kenya are expected to negatively impact biodiversity and ecosystem services. Climate change is influencing the frequency and intensity of extreme weather events, such as droughts and floods, in the country. Evidence suggests that drought cycles have shortened over time, with droughts occurring more frequently, even annually, between 2007 and 2012.

It is important to understand the relationship between energy production, usage, and climate change when developing effective policies and strategies to address climate challenges in the energy sector. A review of existing literature shows that in both urban and rural households in Kenya, biomass energy sources such as charcoal and firewood are still widely utilized. Ensuring secure access to biomass energy is crucial for enhancing resilience. Similarly, equal attention should be given to the efficient production and utilization of biomass energy. This can be accomplished by implementing sustainable plantation forests, utilizing sustainable methods for commercial charcoal production, and adopting efficient charcoal kilns and cookstoves. Nevertheless, as the impacts of climate change continue to worsen, solar energy has emerged as another renewable energy source that has garnered attention. Solar energy is highly preferred among renewable sources due to its abundance, sustainability, and lack of environmental harm. It is versatile, capable of generating electricity and providing heat. Advancements in energy storage have increased its reliability, compensating for sunlight variations. Decreasing costs, aided by technology and government support, make solar power increasingly affordable and competitive. Furthermore, the solar industry has created numerous job opportunities and economic benefits[21].

In Kenya, several solar projects are already operational or in development, with the Garissa Solar Power Station being the most well-known. Kenya experiences high levels of sunlight, with 5-7 hours of peak sunshine and an average daily insolation of 4-6 kWh/m2. The country has a significant potential for photovoltaic installations, estimated at 23,046 TWh/year. Solar power is primarily considered a viable option for rural electrification and decentralized applications[21]. To promote the use of solar energy, the government has provided subsidies for standalone photovoltaic systems in households and public institutions for a considerable period. Furthermore, commercial and industrial sectors are increasingly recognizing the importance of solar power. For instance, farms cultivating flowers and vegetables have already taken the lead in adopting renewable energy systems to meet their own power needs. There is also a growing trend of hybrid PV-diesel island grids[21]. Over the next few years, approximately 18 MW of existing diesel-run stations will be retrofitted to incorporate solar power.

Additionally, the Rural Electrification Authority (REA) has plans to establish new hybrid island grids using renewable energy sources. In 2015, a few sizable solar projects, each approximately 40MW in capacity, were granted Power Purchase Agreements (PPAs). Although the current feed-in tariff for utility-scale solar stands at \$0.12/kWh, some projects have submitted bids for PPAs at a significantly lower price, approximately two-thirds of the standard rate. If successfully constructed, these solar projects will become some of the largest photovoltaic plants in sub-Saharan Africa. However, negotiating PPAs and securing suitable land access for these projects pose challenges that require determination and a willingness to take risks. Additionally, the growth of power demand has been slowing down, which raises concerns and casts doubts on the viability of other photovoltaic initiatives[21].

Historically, in the 1980s, off-grid solar solutions gained traction with the support of donors, mainly for lighting and water pumping in institutions like schools and hospitals. However, the high cost of solar technology limited widespread acceptance and usage. For example, a basic 40 Wp system cost around 900 to 1,200 US dollars due to the expensive solar home system kits at that time. During the early stages of off-grid solar solutions, the market potential for alternative energy became apparent as the cost of solar technology decreased. Companies such as Arco, Helios, BP Shell, and Siemens recognized this potential and emerged as key participants in the solar-powered battery sector. Despite low national electrification rates, technicians, suppliers, and entrepreneurs saw opportunities to provide energy solutions for limited power needs, like light bulbs and a small black-and-white television[21].

From the late 1990s to 2014, Kenya experienced a significant increase in adopting off-grid solar products. Factors driving this growth included the Solar Markets Transformation Program, which aimed to facilitate financing for small-scale enterprises. The widespread availability of mobile phones and the introduction of the M-Pesa mobile money payment platform further contributed to the success of the pay-as-you-go business model in the solar market[22]. The Kenya Renewable Energy Association (KEREA) was formed in 2002 by the Kenya Bureau of Standards to establish industry standards for off-grid solar systems. By 2012, Kenya had over one million off-grid solar products in use, indicating the government's acknowledgment of their significance. In 2014, an energy policy was introduced to raise the electrification rate to 65% by 2020 and achieve universal electrification by 2030[22]. The Kenya National Electrification Strategy of 2018 aimed to provide electricity access to different households through various means, including grid expansion, grid intensification, mini-grids, and solar home systems. Off-grid solar solutions were recognized as an integral part of the strategy. The World Bank supported this effort with the Kenya Off-grid Solar Access Project (KOSAP) in 2019[22]. However, there are no studies that have explored the effect of climate change on solar energy generation, hence the need for this pioneering study.

3. Research Methodology

3.1 Research Design

The Case Study Research Design was utilized in the study. It focuses on understanding the specific context, processes, and outcomes related to the impacts of climate change on solar power resources. The case study design was chosen because it allows for an in-depth examination of the specific case and provides a comprehensive understanding of the complexities and contextual factors[23].

3.2 Research Locale

Kenya is located in East Africa and is known for its abundant natural resources, diverse wildlife, and rich cultural heritage. Famous wildlife reserves, stunning landscapes, and various ethnic groups offer unique research opportunities. Its biodiversity and diverse ecosystems make it an ideal location for studies on anthropology, ecology, and conservation, particularly concerning the impact of climate change. The country's diverse landscapes, ranging from savannas to forests, provide excellent research sites. Kenya's status as an economic and political hub allows for research in fields such as technology, international relations, economics, and the political sciences.

3.3 Data Sources and Collection Process

This study used secondary qualitative data to evaluate the impact of climate change on solar power resources in Kenya using document content analysis. Secondary data examined in this study include the key policy documents reviewed and other documents retrieved from official websites. The data was analyzed qualitatively to generate the implications of this paper. The process of document content analysis involves identifying relevant documents, selecting a sample for analysis, developing coding schemes or categories to organize the data, and systematically analyzing the content of the documents to draw conclusions regarding the research question. The data collection processes, including document review, research locale, and administration, were executed between March and June 2023.

Data on climate change and solar power resources were obtained from existing literature using desktop search engines, especially Google and official records. During the desktop search, appropriate keywords related to the topic, such as "climate change," "renewable energy," "energy security," "energy equity," and any other relevant terms, were chosen. In some cases, advanced search techniques—such as quotation marks ("”) to search for exact phrases or the minus sign (-) to exclude certain keywords—were used. Notes were taken to keep track of the reference sources. The collected information was later synthesized and used to develop insights and support the arguments presented in this study. Data on the trends in climatic variables were obtained from the official website of the Kenya Meteorological Department (KMD), which provides information on weather conditions in the country. Weather condition forecasts and reports were released daily, weekly, monthly, and quarterly by the KMD. Additional secondary data were gathered by reviewing key policy documents on climate and solar power resource issues [Table 1], which provided more context for this study.

Document content analysis is the preferred research method because it is less expensive than other research techniques, such as surveys or experiments, as the data are readily available and do not require researchers to collect new data. Unlike surveys or experiments, document analysis does not require direct contact with participants, which can be useful when studying sensitive topics or when the researcher wants to avoid influencing the participants' behavior. Document content analysis is more objective than other research approaches because it relies on the content of documents rather than the researcher's interpretation of the data.

[Table 1] Key Policy Documents

No.	Name of document	Description	Source
	Constitution of Kenya, 2010 [24]	Article 42 has established the right to a clean and healthy environment. Solar energy has the potential to help Kenya achieve this provision.	Internet
	Vision, 2030[25]	The Vision 2030 blueprint requires that the government put in place a more robust legal, institutional, and policy framework for private sector participation in energy production, including solar energy.	Internet
	Energy Act, 2019[25]	This legislation serves as the primary legal framework for the energy sector in Kenya.	Internet
	Renewable Energy Feed-in Tariffs Policy, 2012 [26]	This policy document establishes Kenya's feed-in tariff mechanism for renewable energy sources, including solar power.	Internet
	Kenya National Electrification Strategy, 2019[27]	This strategy document aims to guide the expansion of electricity access in Kenya.	Internet
	National Energy Policy, 2019 [28]	This policy document outlines the government's overarching energy objectives and strategies for sustainable energy development in Kenya.	Internet
	Draft National Solar Energy Policy[29]	Although still in the draft stage, this policy document provides valuable insights into Kenya's government's vision and strategies for solar energy development.	Internet
	Climate Change Act, 2016[30]	This legislation provides a legal framework for addressing climate change in Kenya. It establishes the legal basis for developing and implementing climate change policies, plans, and programs.	Internet

3.4 Data Analysis

The data obtained in this study was qualitatively analyzed using the three facets of sustainable development, which include social, economic, and environmental aspects. The evaluation focused on the vulnerability of solar power resources to climate change impacts. The analysis also involved identifying regions or areas more susceptible to adverse effects and understanding the social, economic, and environmental consequences of potential disruptions in solar energy generation. The analysis outputs were organized into three thematic groups, namely, the impacts of climate change on solar energy generation, mitigation and adaptation strategies, and the policy implications of the findings on overall energy planning in Kenya.

4. Results

The themes from qualitative data analysis revealed that Kenya is on track toward harnessing the opportunities for solar power adoption and development. The results show that in the quest for achieving its sustainable development aspirations through harnessing clean energy sources, Kenya is increasingly leveraging its solar resources to improve electricity access in rural areas and promote efficiency, reliability, and sustainability in commercial and industrial sectors. The adoption of off-grid solar solutions started in the 1980s but has faced investment cost limitations. However, with decreasing costs of solar energy technologies and government policy support (Table 1), many initiatives and programs aimed at promoting solar energy are emerging. Initiatives such as the Kenya National Electrification Strategy and the World Bank's KOSAP solar home systems program have played crucial roles in expanding the country's access to electricity. The government has also been at the forefront of providing subsidies for standalone photovoltaic systems in households and public institutions. Consequently, the commercial and industrial sectors are increasingly adopting solar power. Other initiatives that promote solar energy include the Solar Market Transformation Program, which facilitates the financing of small-scale enterprises. Moreover, the widespread adoption and use of mobile phones and related innovations have promoted solar energy technologies.

4.1 Impacts of Climate Change on Solar Energy Generation

Results from the analysis reveal that Climate Change is evident in Kenya. Climatic changes are evident through rising temperatures since the 1960s and a generally decreasing trend in annual rainfall. There is an increasing occurrence of intense climate events like droughts and floods, with shorter drought cycles observed over time. Droughts were recorded annually from 2007 to 2012. However, the content analysis reveals no studies that explicitly highlight the impacts of climate change on solar energy systems in Kenya. Nonetheless, reviewed literature shows various ways climate change affects solar energy generation. Increasing temperatures can impact the efficiency and performance of solar photovoltaic (PV) panels. Higher temperatures can lead to reduced electrical output and increased degradation of PV panels. Additionally, changing rainfall patterns and prolonged droughts affect solar power plants that rely on water for cooling and cleaning. Solar energy systems are also vulnerable to extreme weather events, such as storms and floods, which can cause physical damage and disrupt energy generation.

4.2 Adaptation Strategies and Technological Innovations

The results from the content analysis revealed there are no studies that explicitly highlight the adaptation strategies and technological innovations being pursued to mitigate the impacts of climate change on solar energy systems in Kenya. However, there is a growing trend of developing hybrid PV-diesel island grids for private companies seeking to meet their energy demands. Results also show that in the next few years, approximately 18 MW of existing diesel-run stations will be retrofitted to incorporate solar power systems. Additionally, reviewed literature shows that the Rural Electrification Authority (REA) and other stakeholders have plans to establish new hybrid island grids using renewable energy sources. But, the objective is not necessarily to address the impacts of climate change on solar energy systems. Nevertheless, diverse strategies are being pursued to improve the cooling and cleaning mechanisms of solar power plants in water-scarce regions. Moreover, researchers are pursuing integrating energy storage systems and smart grid technologies to enhance the reliability and flexibility of solar energy generation.

4.3 Policy Implications of the Impacts of Climate Change on Solar Energy

The results from the analysis show that the country has a robust legal and policy environment for the adoption and development of solar power resources. However, currently, no studies have explored the policy implications of the effects of climate change on solar systems in Kenya despite recognizing renewable energies, including solar energy, as part of the electricity mix of Kenya, accounting for over 75% of the total electricity generation supplied to the national grid. Interestingly, policies promoting sustainable solar energy resource utilization have been developed. For example, in August 2002, the government created the Kenya Renewable Energy Association (KEREA) to create industry standards for the off-grid solar sector. In addition, the private-sector investment in renewables, including solar energy, is incentivized by feed-in-tariffs (FITs) that the government guarantees for a long period. Unfortunately, government policy also appears to relegate solar energy resources as less important by primarily considering it as only a viable option for rural electrification and decentralized applications.

5. Discussion

This study sought to textually assess the implications of the impacts of climate change on solar energy generation and devise strategies for enhancing the resilience and adaptability of solar energy generation for future energy planning in Kenya. Results from Kenya show evidence of climate change, as demonstrated by the historical monitoring of rainfall and temperature data. Results show an increasing trend of the likelihood of temperatures rising in the country while rainfall continues to be depressed. Evidence of extreme weather events is also growing, as demonstrated by the Kenya Metrological Department data. While this state of the environment has the potential to affect the security, performance, reliability, and sustainability of energy systems in the country, results from this study show that the country lacks explicit studies that explore the impacts of climate change on solar energy production despite acknowledging it as a critical ingredient in the countries energy mix and key energy planning documents [Table 1]. These results are not unique to Kenya but extend to the larger African continent[1]. Moreover, the reviewed literature shows there is limited attention to the impacts of climate change on solar power generation in the United States[1]. Nonetheless, globally, in the wake of the rising impacts of climate change due to the increased use of fossil fuels, solar power is increasingly being pursued with significant investments for its immense environmental protection benefits[1]. Between 2005 and 2019, the Asia-Oceania region attracted the highest investments in renewable energy. In Kenya, renewables, including solar energy, are increasingly being pursued given their significance in attaining the specified economic development objectives by 2030, which include reaching a middle-income economy by 2030, attaining energy security and accessibility to meet the growing energy demand, and reducing carbon emissions. The Kenyan government had set a target to achieve universal access to electricity by 2020, as stated in the Kenyan government's 2007 plan[2][16]. However, results also show that many countries are blowing hot and cold at the same time on their policy agenda towards promoting solar energy utilization. For instance, in Kenya, despite recognizing the importance of solar energy in the country's energy mix, government policy only recognizes the potential for solar energy in the context of rural electrification and smaller decentralized applications [This oxymoron type of solar power agenda could be acquiring credence from similar circumstances taking place in other regions of the world. For instance, reviewed results show that even though the Asia-Oceania region has high investments targeting the development of solar power, the region is amongst the highest contributors to global greenhouse gas, and this contradicts expectations of harnessing solar technologies, thereby slowing down the widespread uptake of solar energy technologies[4].

Reviewed literature shows that climate change significantly impacts on solar energy systems[3-10]. Increasing temperatures can affect the efficiency and performance of solar photovoltaic (PV) panels, leading to reduced electrical output and increased panel degradation[10]. Changing rainfall patterns and prolonged droughts pose challenges for solar power plants that rely on water for cooling and cleaning. Water scarcity can hinder the operation and maintenance of solar energy systems, particularly in regions with limited water resources. Extreme weather events, such as storms and floods, can cause physical damage to solar infrastructure and disrupt energy generation. Studies on global variations in irradiation and their impact on solar energy generation reveal mixed results. Europe is expected to see both increases and decreases in production, while certain African regions may experience declines in PV output. Countries like Greece, the UK, Germany, and Croatia show varied impacts on solar generation, with some areas seeing increases and others experiencing neutral or negative trends. Limited research exists on solar generation in the United States, but recent studies suggest changes in irradiation[12]. African countries anticipate seasonal changes in solar output with uncertain estimates. Further research is needed to understand the effects of changing climatic conditions on solar energy systems and develop strategies for future energy planning[10].

Estimating the potential impacts of climate change on solar energy systems involves considering factors such as changing weather patterns, extreme events, rising sea levels, and temperature effects on panel performance. Sophisticated modeling techniques are required to assess regional climate projections and inform adaptation strategies for the long-term resilience of solar energy. From Kenya's study results, future climatic conditions will likely be more variable than current or recent ones. This increased variability and the potential longer-term implications of climate change are not adequately considered in designing many solar power systems. Yet the effects of exposure and vulnerability to climate change are already being felt. These likely climatic impacts on solar energy resources for Kenya highlight the need for devising adaptation strategies and technological innovations to enhance the resilience of solar energy systems in the face of climate change. Efforts to improve the cooling and cleaning mechanisms of solar power plants in water-scarce regions and the integration of energy storage systems and smart grid technologies are crucial for ensuring reliable and sustainable solar energy generation. Kenya faces an urgent need to incorporate climatic projections into solar power investment. This requires accelerated action, partnerships between governments, energy providers, and hydrological/meteorological agencies, and integration of solar energy with other renewables like hydropower and wind to reduce climate risks. These steps align with Kenya's pursuit of Paris Agreement targets and other international commitments.

To enhance the resilience and adaptability of solar energy in Kenya, strategies could include promoting diverse solar installations, incorporating climate change projections in site selection, integrating energy storage, adopting adaptive maintenance protocols, reviewing policies to include incentives for climate-resilient technologies, integrating solar planning into broader energy planning, increasing public awareness, and promoting energy efficiency practices. These approaches aim to optimize solar resources, minimize vulnerabilities to extreme weather events, and ensure the sustainability of solar energy systems in the face of climate change.

Future research on solar energy should prioritize quantifying the impacts of climate change, evaluating vulnerability, developing innovative technologies, studying grid integration and stability, and conducting cost-benefit analyses. It involves assessing changes in insolation rates, extreme weather events, and long-term climate patterns, identifying at-risk regions and systems, developing climate-resistant materials, and investigating the implications of climate change on grid integration. Economic implications and financial risks and benefits should also be studied to inform adaptation measures. These strategies and studies are essential for effective energy planning in the context of climate change.

Fortunately, there exist opportunities in Kenya for addressing these solar energy development and research needs through public-private arrangements. The government could foster the establishment of a partnership framework between REA, flower farms, and companies such as Arco, Helios, BP Shell, Siemens, Safaricom, and KEREA, amongst others, which could then mobilize resources for financing the development of innovative technologies and practices for mitigating the impacts of climate change on solar power resources in the country.

6. Conclusion and Recommendations

This study sought to qualitatively assess the implications of the impacts of climate change on solar energy generation and devise strategies for enhancing the resilience and adaptability of solar energy generation for future energy planning in Kenya. The has established that Kenya has complex energy sustainability challenges that could be made worse by the impacts of climate change. With the growing energy needs, Kenya is experiencing the impacts of climate change marked by temperature fluctuations. Fortunately, the country has a robust legal and policy environment for adopting and developing solar power resources. However, with growing energy needs, there is a pressing need for explicit studies on how climate change affects solar power generation in Kenya. Estimating these potential impacts is crucial to ensuring the security, reliability, and sustainability of solar energy resources. There is the need to pursue adaptation strategies and technological innovations, such as integrating solar energy with other sources, while also expanding feed-in tariff incentives and policy interventions that promote sustainable solar energy utilization and further research. By fostering a multi-stakeholder approach, Kenya can effectively implement these strategies to promote sustainable solar energy utilization, technological innovation, and research. This holistic approach will help drive the transition to a cleaner and more sustainable energy future. Further research efforts should quantify climate change impacts, assess vulnerability, and develop innovative technologies. While this study has limitations as it primarily relies on existing documents and literature, future research endeavors can address these constraints by incorporating primary data collection, engaging stakeholders, monitoring recent advancements, and leveraging diverse data sources to enhance the comprehensiveness and robustness of their findings.

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