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A Review on the Impacts of Climate Change on the Power Systems

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Abstract*: Significant development of the global power system is needed to mitigate climate change. However, patterns of power demand and transmission systems themselves depend upon the impacts of environmental change. These effects will variously hinder and facilitate adaptation and mitigation efforts; thus, they must be fully acknowledged and incorporated into models used to illustrate decarbonization pathways for power systems. Climate change and global warming impact the quality, generation, and transmission of power. One of the significant problems, islanding, is also exacerbated by climate change. The present state of climate change impacts on power systems will be discussed in detail in this paper. This paper primarily examines the effects of the environment on power generation and transmission systems. Also, the application of artificial intelligence to mitigate the issue of climate change and its corresponding impact on the power system has been discussed.

Keywords: Artificial Intelligence (AI), Global Warming, Power Quality, Power Generation, Power Transmission, Power System Protection.

I. INTRODUCTION

The Power system consists mainly of three steps: generation of power, transmission of power, and consumption of power. These three parts of the power system can be affected by changes in the environment's ideal condition. Variations in climate, such as increased temperatures and unpredictable weather patterns, are the primary factors contributing to power quality and harmonics issues in power systems. The primary reason for climate change is the massive amount of greenhouse gases and carbon dioxide generated by humans. The major problem associated with the Power system, which is called "Islanding", is also due to the environmental effects [1]. However, our understanding of environmental change effects on power systems has enhanced rapidly over the recent decades, but a comprehensive study of the impacts has not been done yet. Various studies have shown that the power system is not only responsible for contributing to climate change, but it is also vulnerable to environmental changes. These impacts are associated with various aspects of power systems, including the supply and demand of energy, power quality, transportation, and the cost of power. On the supply side, non-conventional energy resources, including wind, solar, bio, and hydropower, are affected by environmental change in varying degrees due to fluctuations and changes in temperature, precipitation, solar irradiation, and wind speed. Thermal energy resources, such as nuclear, fossil fuels, and biomass, have an impact on both the cooling systems and the efficiency of the turbine. With climate change, the effects on thermal energy generation systems may be intensified due to regional and national environmental regulations regarding the withdrawal, release, and consumption of cooling water into environmental water resources, which may result in power curtailments. Climate extremes and climate change might also impact the resilience of power systems and the power supply reliability via effects on supply systems or siting of infrastructure [2]. Furthermore, changes in the environment may affect the potential of the power supply, as well as the use of land. On the consumer side, the change in climate affects the demand for power by impacting the magnitude and duration of diurnal and occasional cooling and heating requirements. Lastly, environmental change might affect power systems indirectly by influencing the competition of cross-sectoral sources, including water for generating hydropower, which is necessary in thermal power plant cooling systems and utilised as a regional supply, as well as affecting ecosystems related to freshwater, manufacturing, and irrigation. The Power systems might also adapt to the impacts of climate change. Mechanisms of adaptation may include reducing power demands, decreasing water requirements for cooling functions through alternative cooling technologies, and enhancing the capacity for energy generation and power storage. Variations in the combination of electricity generation technology might also decrease the susceptibility of the power sector [3]. In recent decades, numerous studies and research have explored the potential impacts of environmental variations on the power sector. However, a deep literature analysis is lacking. Here, we review a wide range of research that happens in this field. Overall, this research paper addresses the gaps in understanding the local and global impacts of environmental change on power systems, offering a more comprehensive understanding that may inform future assessment and research frameworks. Fig. 1 illustrates a framework for assessing the effects of climate change on power systems. Power systems contain supplies for initial power from various sources, including wind power, bioenergy, hydropower, solar power, other renewable energy sources, fossil fuels, and nuclear power.

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It also encompasses the transition to secondary sources of energy, power grids, and transportation, as well as power demand in industry, transportation, and buildings. The temperature of the water mainly controls elements of box runoff and power plants of thermal types, and thus has corresponding matching colours. The air temperature of the box element has not coincided with that of another part because it is more susceptible to being impacted by power systems than other boxes. Cold degree days (CDD) and Heating degree days are also affecting power systems, particularly in terms of power quality.

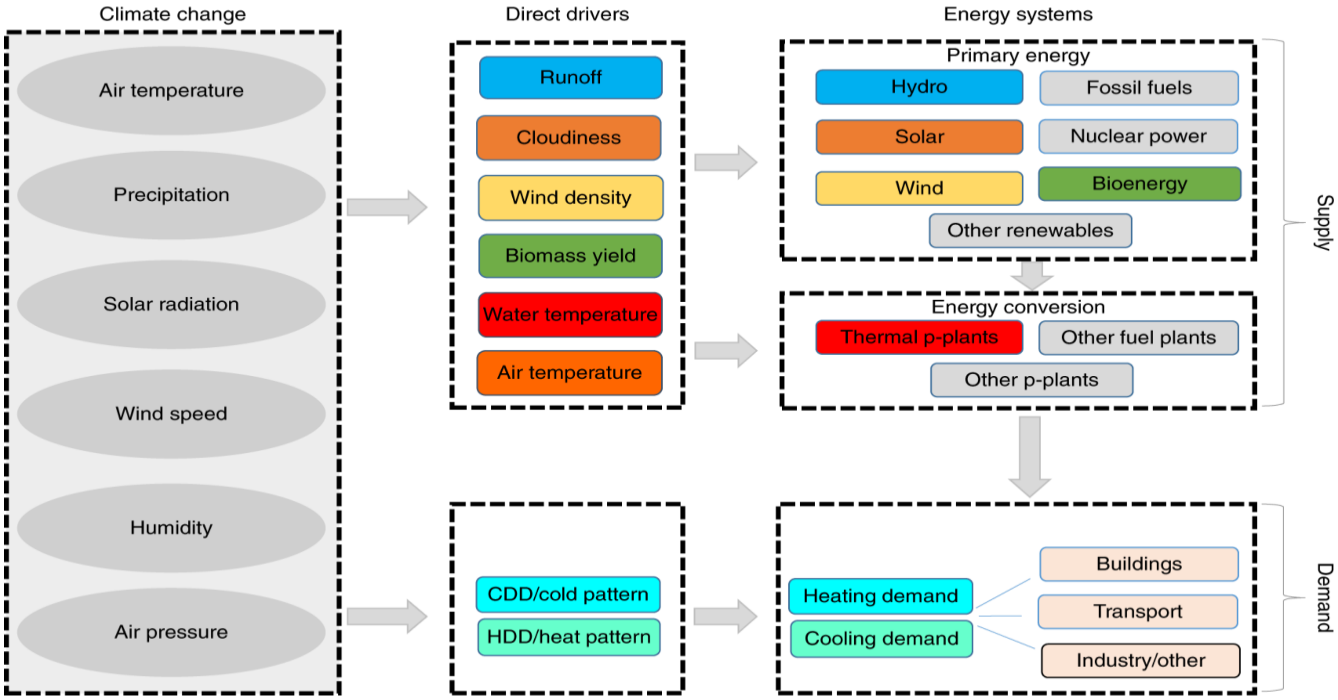

Fig. 1. The Conceptual Framework and Architecture Estimation for the Climate Change on Power Systems [4]

II. LITERATURE SURVEY

Over the last two decades, researchers have focused on the impacts of environmental change on power systems. J. Cronin *et al.* [5] present a review of gaps and trends in the impacts of environmental variations on energy systems. To provide an overview of the current state of knowledge in this area and identify research priorities, this article primarily reviews previous research topics on the effects of environmental change on the power supply system, summarising the local studies, their outcomes, and the resources for disagreement. S. N. Chandramowli *et al.* [6] discuss the impact of environmental variation on energy systems and their markets. This article highlights the areas of research where the frontiers of knowledge have progressed potentially like a significant increase in air temperature; estimation of temperature-sensitive demand; the localized effect of variations in environment on the resources of wind; vulnerabilities of supply due to reduced availability of water; effects of cooling water at plant-level for the generation of power etc. This research review provides insights into the future design of electricity markets and system models. G. M. Tina *et al.* [7] discuss a wide range of impacts of change in climate on power systems, by analyzing a proposed model of power generation and demand systems. This paper also examines the meteorological variables that affect power demand and generation. The research is primarily focused on Italian future perspectives regarding the power system's energy production and demand. This article examines the impact of environmental change on Italy's current and future power systems.

P. Chen *et al.* [8] present an analysis of optimal temperature as a basis to illustrate the variation of weather and changes in climate impact on the peak load in the summertime in the Harris County area of the United States. Because it is crucial to know how to mitigate the effects of weather on long-term and mid-term planning efforts to build a perfect power system. M. T. Craig *et al.* [9] present the assessment and estimation of environment change's effects on renewable energy resources such as solar and wind resources by creating solar and wind profiles of generation for a period of reference and five changes of climate projections. Then, drive an economic and unit commitment dispatch model to send a highly non-conventional fleet of generators with these profiles. This article utilizes five models of global climate to illustrate the impact of environmental change on the energy sector. D. Burillo *et al.* [10] illustrates various ways in which climate change impacts the infrastructure of electric power, options for adaptation, and options for mitigation. Because climate change adaptation and mitigation are the primary forces driving the modernisation of electric power system infrastructure, which will lead to an increase in non-conventional energy systems, this article presents a quantitative case analysis to highlight vulnerabilities associated with heat waves in the southwestern United States desert, including the performance of infrastructure for long-term forecasting, as well as several demand-side and supply-side strategic options to ensure reliable operations.

S. Parkpoom *et al.* [11] discuss how climate change will impact Thailand's long-term, daily, and seasonal demand for electricity. Here, regression models are used to identify patterns of daily load across each month of the year. The projections of temperature from the UK Hadley Centre's climate model are then utilised to estimate hourly sensitivity to changes in the diurnal and mean temperature ranges. M. Panteli *et al.* [12] present comprehensive and essential activities of research and findings of project Resilient Electricity Networks for Great Britain, mainly focusing on possible implications of climate change related to supply and demand forecasts, ratings of components, and extreme weather impact on the reliability of the system. The primary objective is to provide more profound insights into several weather and climate-related challenges that Great Britain's electricity system may face in the future. J. N. Fidalgo *et al.* [13] illustrate the impacts of environmental change on the mix of power in Portugal in the long or medium term. This paper utilises climate scenario simulations and projections of available power plants by consumption type to analyse their impacts. The results of this research article indicate that the most favourable climate scenarios suggest that a system of non-conventional energy sources is more favourable in the medium term.

III. ARCHITECTURE OF THE POWER SYSTEMS

The power system, also known as the electrical grid, is a complex network that is designed to generate, transmit, and distribute electricity from power plants to consumers. The structure of the power system can be divided into three main components: generation, transmission, and distribution [14].

A. Generation

This process involves producing electricity from various sources, including coal, natural gas, nuclear, hydroelectric, wind, solar, and geothermal energy. Power plants are responsible for generating electricity, and they are usually located near the source of the energy they use.

B. Transmission

Once electricity is generated, it must be transmitted over long distances from power plants to distribution centres, cities, and towns. High-voltage transmission lines are used to transport electricity over long distances, and they are typically owned and operated by transmission system operators (TSOs).

C. Distribution

The final component of the power system is distribution, which involves delivering electricity to end-users, such as households, businesses, and industries. Distribution systems comprise low-voltage lines, transformers, and other equipment that step down the voltage of electricity, enabling it to be used safely by consumers. Distribution systems are typically owned and operated by local utilities.

In addition to these three main components, the power system also includes various control and monitoring systems that are used to ensure the reliability and stability of the grid. These systems include protection relays, automatic control systems, and energy management systems, among others. The power system is a complex and interconnected network, and ensuring its reliable operation requires the collaboration of various stakeholders, including power generators, TSOs, local utilities, and regulatory agencies [15]. A complete architecture of the power system is well defined in Fig. 2.

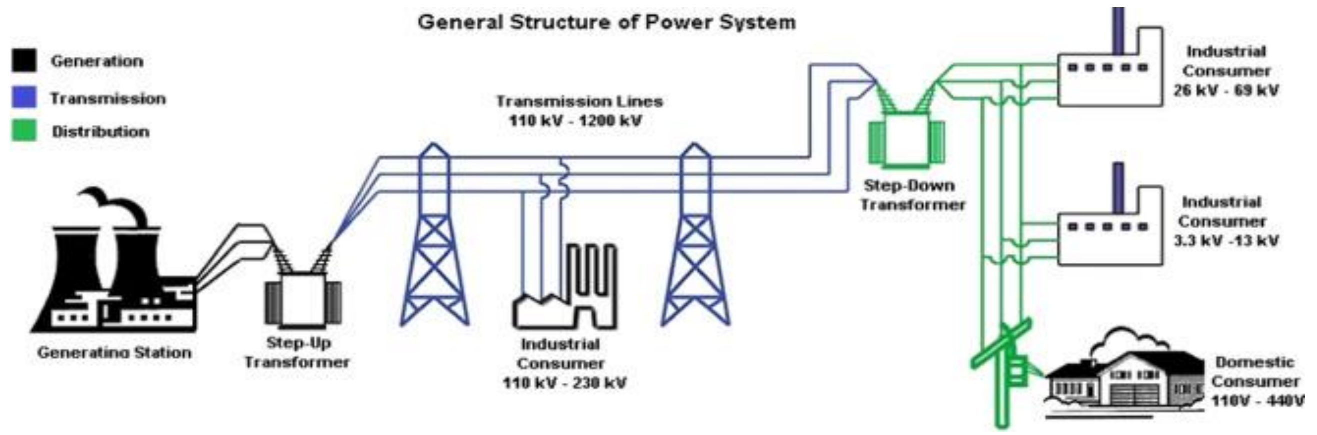

Fig. 2. An architecture of a complete power system [15]

IV. MAJOR IMPACTS ON POWER GENERATION SYSTEMS

Power systems have three main stages: the primary stage, also known as the generation stage, the secondary stage, also known as the transmission stage, and the third stage, also known as the distribution stage. There are various resources available for generating power. Fig. 3 illustrates almost every resource of electricity generation. At the generation stage, the impacts of environmental variation on the type of hydropower outcomes are influenced by fluctuations in evaporation, precipitation, and runoff patterns, which affect the volumes and variability of stream flow. Almost every research study on climate variation emphasises the impact on hydropower at local scales, focusing on the distribution of various environmental fluctuations across regions, with a consistent estimate of reduced hydropower capacity. The effects of climate change on hydropower development are complex and interactive issues.

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Environmental variation is a global issue; however, the impacts of ecological fluctuations on hydropower generation are not uniform across various spatial scales [16]. The non-uniform impacts depend on factors such as regional hydrological conditions and geographical features.

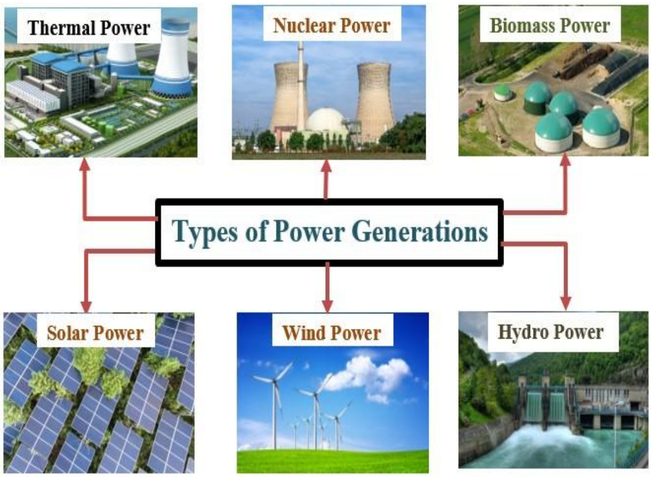

Fig. 3. Some Major Types of Power Generation

Studies generally describe unexceptional or minimal positive impacts of environmental variation on local solar power capacities as an outcome of fluctuation in temperature and irradiation, with contradicting variations across associations of simulation in a few cases [17]. The outcomes of the environmental impact on solar power potential are mixed, with varying results and studies across different regions. The direct effects of environmental change on solar energy are approximately 5%, which is a minimal yet robust impact. These impacts are minimal because variations of irradiation remain minor and harmful impacts of global warming generally happen at high latitudes, which have a very low potential for photo-voltaic than the areas of low-latitude regions [18].

Environmental variation plays a crucial role in the fluctuation of wind variability and intensity near the surface, either through regional impacts or by influencing the mesoscale flow. The pattern of variations is both vigorous and uninterrupted, extending beyond the possibility of outline: an almost identical sequence of variations is found at the end of the 21st century, just as in the earlier periods. The impact of environmental variation on wind resources of Europe has been estimated using the latest local model of the climate of the single model ensemble from the Centre of Rossby (RCA4) [19].

Recently, thermal power generation is at risk due to climate variations, as its performance and efficiency depend on air density, hydrometeorological parameters, and ambient temperature. Also, these thermal energy generation systems are vulnerable to critical damages due to abnormal violent incidents caused by variations in climate, such as hurricanes and floods [20]. Climate change is predicted to reduce the capacity of cooling-dependent thermal power through reduced warming, decreased streamflow, and lower streamflow temperatures. Global evaluations of the thermal power plants project vulnerability indicate that more than 80 per cent of trees around the globe will yield few deductions in usable potential. Although the impact of minimising available thermal power potential on the energy system, in terms of reliability, cost, and emissions, may be considered as very minor as we move towards more non-conventional sources, it is therefore dependent on future potential enlargement and market scenarios.

The impacts of climate change on the potential of biomass power generation systems are generally mixed. An essential key element highlights the fertilisation effect of CO_2 (Carbon Dioxide) on precipitation and temperature, and compares it with the utilisation of other land as a result of climate fluctuations. Therefore, the impacts of climate quantification on biomass power remain complex because of uncertainties correlated with local fluctuation, and future water and land availability [21]. The generation of power from biomass is renewable, and the environmental impacts of utilising biomass as an energy resource are beneficial, as it leads to reduced greenhouse gas emissions, decreased water and air pollution, and land reclamation.

In recent years, due to increased awareness of climate variations, nuclear energy has gained more attention. Places that possess nuclear resources play a significant role in mitigating the emergence of climate change. Fluctuations in the climate can impact atomic reactors in various ways, including increased temperatures, high-speed winds, and land erosion, among others. As nuclear elements are radioactive and highly sensitive, their operation requires a stable environment to achieve optimal outputs.

V. MAJOR IMPACTS ON POWER TRANSMISSION SYSTEMS

Climate change can have a significant impact on power system transmission lines. One of the main impacts is the increased frequency and intensity of extreme weather events, such as hurricanes, tornadoes, and heavy snowfall, which can damage transmission lines and disrupt the electricity supply. Rising temperatures can also increase electricity demand as people turn to air conditioning to stay cool. This can put a strain on the power grid and increase the likelihood of power outages. In addition, climate change can affect the availability and quality of water resources, which are used in the production of hydroelectric power [22]. Droughts and heat waves can reduce water flow, leading to a decrease in hydroelectric power production. Finally, as renewable energy sources such as wind and solar power become more widespread, the power system will become more decentralized and distributed, with power generation occurring closer to where it is consumed. This can reduce the need for long-distance transmission lines but also requires more complex planning and management of the power grid. Overall, the impact of climate change on power system transmission lines is a complex issue that requires careful planning and management to ensure the reliability and resiliency of the power grid.

VI. ARTIFICIAL INTELLIGENCE FOR THE POWER SYSTEM

AI has the potential to play a significant role in combating the impacts of climate change

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on power systems [23]. Here are some examples of how AI can be applied:

A. Forecasting demand and generation

AI algorithms can be utilised to forecast future electricity demand based on historical data, weather patterns, and other relevant factors. This can help utilities and grid operators plan and adjust their generation and transmission capacity, accordingly, reducing the risk of power outages and improving efficiency.

B. Optimizing energy use

AI can be utilised to optimise energy usage in buildings and other facilities, thereby reducing energy waste and carbon emissions. Intelligent building systems that utilise AI to analyse data on occupancy, temperature, and other factors can adjust energy use in real-time to minimise waste and enhance energy efficiency.

C. Improving grid efficiency

AI algorithms can be utilised to optimise the operation of the power grid, thereby reducing energy losses and enhancing the overall system efficiency. This includes tasks such as managing power flow, balancing supply and demand, and minimising transmission losses.

D. Predicting and Mitigating Weather-Related Risks

AI can be used to predict weather patterns and identify potential risks to the power system, such as storms or extreme temperatures. This can help utilities and grid operators take proactive measures to mitigate the risks, such as reinforcing infrastructure or adjusting power generation and transmission capacity.

E. Managing Renewable Energy Sources

AI can be utilised to manage and optimise the utilisation of renewable energy sources, such as wind and solar power. This can include tasks such as forecasting output, managing energy storage systems, and optimizing the use of distributed generation. Overall, AI has the potential to play a significant role in combating the impacts of climate change on power systems, improving efficiency, reducing waste, and increasing the resiliency of the grid.

VII. RESULT AND DISCUSSION

This article reviews the impacts of climate change on power systems and highlights the significant challenges faced by the power sector in adapting to the changing climate. The review has identified the following key results and discussion points:

1) ***Increased electricity demand***: As temperatures rise, the demand for air conditioning and refrigeration increases, resulting in a surge in electricity consumption. This puts pressure on the power system to generate and distribute more electricity, which can strain the system, leading to power outages.
2) ***Reduced power generation***: Climate change can also impact the availability of traditional power generation sources, such as hydroelectric power plants and thermal power plants. Reduced water availability can reduce hydroelectricity generation, while increased temperatures can reduce the efficiency of thermal power plants.
3) ***Damage to infrastructure:*** Severe weather events such as hurricanes, typhoons, and floods can cause significant damage to power infrastructure, including transmission and distribution lines, power stations, and transformers. This can result in prolonged power outages, affecting the reliability of the power system.
4) ***Changes in water availability:*** Climate change can also cause changes in water availability, which can impact the operation of power systems that rely on water for power generation. For example, reduced water availability can limit the operation of hydroelectric power plants, while increased water levels can cause flooding and damage to power infrastructure.
5) ***Need for adaptation and investment:*** To address the impacts of climate change on power systems, there is a growing need for planning and investment to ensure the power system's resilience. This includes strategies such as enhancing the efficiency of the power system, increasing the utilisation of renewable energy sources, and developing AI-powered solutions to optimise energy use and mitigate risks.

This review emphasises the need for the power sector to adapt to a changing climate to maintain a reliable electricity supply. The challenges faced by power systems due to climate change require a comprehensive and collaborative approach involving various stakeholders to ensure the resilience and sustainability of the power system.

VIII. CONCLUSION

Climate change has significant impacts on power systems, affecting the generation, transmission, and distribution of electricity. The increased demand for electricity due to rising temperatures, reduced power generation from traditional sources, and the damage to infrastructure caused by severe weather events are some of the main challenges faced by power systems. Moreover, changes in water availability and demand patterns further complicate the situation. To combat these impacts, there is a growing need for planning and investment to ensure that power systems can adapt to a changing climate and maintain a reliable electricity supply. This includes implementing strategies such as enhancing the efficiency of the power system, increasing the utilisation of renewable energy sources, and developing AI-powered solutions to optimise energy use and mitigate risks. In summary, addressing the impacts of climate change on power systems requires a comprehensive and collaborative approach involving various stakeholders, including power generators, TSOs, local utilities, and regulatory agencies. With careful planning and investment, it is possible to build more resilient and sustainable power systems that can adapt to the changing climate and provide reliable electricity to consumers. This paper offers a comprehensive review of the impacts of climate change on power systems and their various components.

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Ethical Approval and Consent to Participate	No, the article does not require ethical approval or consent to participate, as it presents evidence that is not subject to interpretation.
Availability of Data and Material/ Data Access Statement	Not relevant.
Authors Contributions	All authors have equal participation in this article.

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