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Effects of Climate Change on Energy Systems in Global and Regional Settings

Abhisimta Roy [1*], Anoushka Roy [2]
[1]Department of Botany, Kalinga University, Naya Raipur 492101, Chhattisgarh, India
[2]Department of Electrical Engineering, Odisha University of Technology and Research, Bhubaneshwar 751003, Odisha, India
***Corresponding author** – Abhismita Roy
Email address: abhismita.roy@kalingauniversity.ac.in

ABSTRACT
Although we have gained a greater understanding of how climate change affects energy systems over the past few decades, there is still a lack of comprehensive knowledge about its impact across different spatial scales. In this study, we have analyzed 220 research studies that project climate change impacts on energy systems on a global and regional scale. On a global scale, we expect to see a rise in cooling demand and a decline in heating demand, while there will be slight decreases in hydropower and thermal energy capacity. However, the impacts on a regional scale are more uncertain and vary across different regions, with the most significant effects occurring in South Asia and Latin America. Our analysis highlights the uncertainty of the impact of climate change on energy systems due to the use of various methods and datasets that lack standardization. To conduct a comprehensive assessment of climate impacts on energy systems, we recommend using a consistent multi-model assessment framework to support energy planning at both regional and global levels.
***Key words** - Climate Change, Electricity Supply, Renewable Energy, power generation*

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INTRODUCTION

Studies conducted by the Intergovernmental Panel on Climate Change (IPCC) and other research have demonstrated that the energy sector is not only a contributor to climate change but is also susceptible to the effects of climate change [1-3]. These impacts are linked to different aspects of energy systems, including energy supply and demand, as well as the cost and transportation of energy. Renewable energy sources, such as bioenergy, hydro, solar, and wind power, are affected by climate change to varying degrees due to changes and variations in precipitation, temperature, wind speed, and solar irradiation [5,6]. Temperature-related impacts on cooling systems and turbine efficiency also affect thermal power plants, including fossil fuel, biomass, and nuclear plants [7,8]. The national and regional environmental regulations on cooling water withdrawal, consumption, and release into natural water bodies may exacerbate the effects of climate change on thermal power plants [9,10]. Climate change and climate extremes can also impact the resilience of energy systems and the reliability of energy supply through their impact on transmission systems or infrastructure siting [11,12]. Moreover, climate change can impact the potential supply of energy, such as bioenergy, through its impact on land use and competition with other sectors such as food production [13,14].

Regarding the demand side of energy, climate change has an impact by affecting the duration and magnitude of diurnal and seasonal heating and cooling needs [15]. Additionally, climate change can indirectly affect energy systems by influencing competition across sectors for resources such as water for hydropower production, cooling thermal power plants, and domestic use, freshwater ecosystems, irrigation, and manufacturing [16]. This could lead to a need for alternative water sources, like desalination, and potentially result in additional energy demand. Energy systems are capable of adapting to climate change impacts, which may involve decreasing energy demand, reducing water demands for cooling through alternative cooling technologies, such as recirculating versus once-through, increasing energy generation capacity, and energy storage. Furthermore, changes in the mix of electricity generation technologies can reduce the vulnerability of the energy sector to climate change impacts [18-21].

Over the last 20 years, many studies have analyzed the possible effects of projected climate change on the energy sector. However, a comprehensive systematic analysis of the literature is currently missing. As a result of the growing number of studies on this topic, it is essential to create a synthesis of the impacts of climate change on energy systems using scenario results from existing literature and examining possible assessment frameworks, especially at regional and global scales. This study provides a review of the literature on projected climate change impacts on both regional and global energy systems. The potential impacts of climate change on energy systems are synthesized, highlighting significant variations per energy source and region. As a result, this analysis highlights the need for more knowledge and research on climate change impacts on energy systems at regional and global scales and offers guidance for future research and assessment frameworks.

Present Vulnerabilities of the Energy Sector

The energy sector is vulnerable to climate change impacts in several ways, including the supply and demand of energy, as well as the cost and transport of energy. Renewable energy sources such as hydro, solar, and wind power are impacted by climate change in varying degrees due to changes in precipitation, temperature, wind speed [20], and solar irradiation [19]. Thermal power plants (fossil fuel, biomass, and nuclear) also face temperature-related impacts on cooling systems and turbine efficiency [22]. Climate change can affect the resilience and reliability of energy systems via impacts on transmission systems or infrastructure siting, as well as impact energy supply potentials for bioenergy [27,28]. On the demand side, climate change can influence energy demand by affecting heating and cooling requirements. Additionally, cross-sectoral competition for resources such as water for hydropower production, cooling thermal power plants, and domestic supply can indirectly impact energy systems [23-26]. However, energy systems can adapt to climate change impacts through mechanisms such as reducing energy demand, increasing energy generation capacity and storage, reducing water demands for cooling operations, and changing the mix of electricity generation technologies [27].

Several academic articles have conducted reviews of the literature that explore the impact of climate change on specific components of energy systems, which encompass all aspects related to energy production, conversion, transportation, and utilization. These reviews have focused on topics such as hydropower, solar, wind, bioenergy, thermal power, cooling and heating, costs and electricity markets, critical infrastructure, and multi-segment impacts. For this study, the analysis of climate change impacts on energy systems is based on a total of 220 papers published between 2002 and 2019. The analysis examines impacts on the supply side, including the potential of renewable energy sources such as solar, wind, and bioenergy, as well as thermal power plants. The study also looks at the demand side, including heating and cooling requirements, and integrating systems such as costs and transportation/transmission systems.

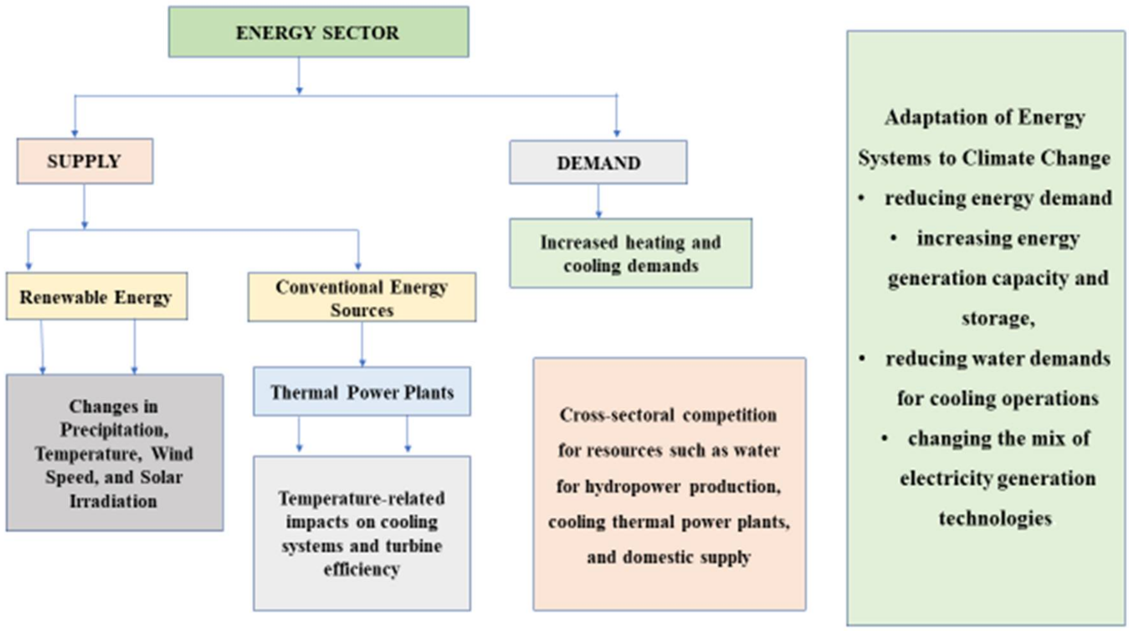

Fig. 1 Predicted Impacts of Climate Change on Power Systems and Adaptation Measures

Impacts on Energy Systems

The impacts of climate change on hydropower supply are caused by changes in precipitation, evaporation, and runoff patterns that affect streamflow variability and volume [29,30] . Most studies on the impact of climate change on hydropower focus on regional scales and find different effects of climate change across regions. The majority of studies suggest a decrease in hydropower potential, although global studies show both positive and negative impacts in different regions, leading to a small overall decrease in potential [31,32]. Climate change impacts on hydropower generation vary seasonally, and there is uncertainty regarding the magnitude of impacts at individual plants and regional and global levels [33-37].

Most studies find that climate change has small or insignificant positive impacts on regional solar power potentials due to changes in irradiation and temperature, but some simulations show conflicting changes across different ensembles [37]. Climate impacts on wind power potentials are more mixed, with varying results across regions and studies. For example, both increases and decreases in wind power potential are reported for Europe, with decreases projected in southern Europe and slight increases in central and northern Europe [40,41]. In contrast, some studies suggest favorable future wind power conditions for parts of the United States and Brazil, while others report low probability of wind power changes for South Africa. A recent global study found that wind energy potential is likely to increase in the Southern hemisphere in general [42].

The impacts of climate change on bioenergy potential are typically mixed, with CO2 fertilization potentially leading to an increase in potential, while temperature and precipitation impacts may lead to a decrease, and competition with other land uses may also be a factor [44]. However, uncertainties associated with regional variation, and future land and water availability make it difficult to quantify these impacts [45].

Climate change is expected to reduce cooling-based thermal power capacity due to reduced streamflow and warming temperatures, and global assessments suggest that over 80% of plants worldwide will be affected [46-51]. Studies show increasingly negative effects of climate change on thermoelectric power plants in Europe and the United States. However, the impact on the power system in terms of emissions, cost, and reliability may become less important as renewable energy capacity expands and depends on future expansion and market scenarios.

There are limited studies that examine the impacts of climate change on thermal power plants with carbon capture and storage, as they are expected to have increased cooling water requirements [53,55]. On the other hand, there is extensive research on the effects of climate change on energy demands for heating and cooling, particularly in the residential sector. Most studies find that climate change will lead to decreased heating demand in cold regions and increased cooling demand in warm regions, with a higher demand for electricity during the warm season [58-61]. The net impact on global energy use is initially reported to be small, but recent studies indicate that the impact could be larger when non-residential sectors, such as industry and commercial, as well as air conditioning penetration, are considered [59]. Climate extremes are expected to further escalate energy demands, and energy demand projections are subject to uncertainties related to user behavior and large-scale retrofitting projects in the built environment [62].

Climate change could potentially create a more uniform pattern of energy demand, such as increased demand for cooling when there is a peak in photovoltaic supply [39]. Studies have looked at the overall impact of climate change on energy systems in terms of total costs [63]. Some reports indicate that hydropower plants in Latin America, Europe, and the Middle East will require additional investments to cope with the effects of climate change. In contrast, countries like Bhutan, Canada, and Norway may require less investment in the power sector due to increased runoff for hydropower generation [66-69]. However, some studies suggest that climate change's impact on hydro, solar, and wind power capacity factors may result in about a 5% increase in cost for optimal system design in Europe [41,42]. The effects of climate change on energy systems' reliability are significant, as increasing supply and demand extremes can lead to consequences for system reliability [70-73]. Climate change can also affect energy-related expenditure, such as those for adaptation, storage, and generation of energy [74]. These expenditures can vary regionally, with a decrease in net expenditure in regions with high heating demands and an increase in areas with a greater need for space cooling [75]. The frequency and intensity of climate extremes, as well as changes in variability, can affect energy costs, investment, and associated critical infrastructures [76-80].

The potential impacts of climate change on the energy sector, in conjunction with industry and transportation, are significant [81]. Thermal electricity generation is expected to be most vulnerable to heatwaves and droughts, while cold waves, wildfires, flooding, heavy snow, ice storms, and windstorms pose greater risks to transmission and renewable technologies [42,46, 83] . The coinciding of peak energy demands in summer with reduced transmission and distribution capacity at higher temperatures is also expected to pose challenges to the operation of electricity grids [84]. In addition, during extreme events such as flooding and tropical cyclones, cascading effects may result in power grid and transmission line disruptions, which can lead to cross-border effects [85]. A recent example of this is the case of cyclone Idai, which caused damages to Mozambique's power grid and resulted in blackouts in South Africa. (https://www.cfr.org/blog/south-africas-blackouts-demonstrate-need-distributed-energy-resources)

Regional Impact

Our analysis of reviewed papers reveals substantial regional differences in the impacts of climate change on various energy technologies. While some of these differences are due to real geographic variations in climate change, in other cases, they may be due to methodological differences between studies. Studies on hydropower show mixed potential across different regions, with a significant reduction in potential in Latin America and South Asia and a smaller reduction in Western Europe, the Middle East, and North Africa [93]. However, studies on other renewable sources such as bioenergy, solar, and wind power have gaps in regional coverage and lack information [44,45]. The global thermoelectric potential and capacity are expected to decrease mainly due to rising water temperatures, but this may change with the introduction of newer, more efficient plants [43,44,87]. Additionally, the demand for heating and cooling is expected to increase in Latin America, South Asia, and Pacific Organisation for Economic Co-operation and Development regions [47,49,88]. Studies on climate impacts on costs show mixed results at the global level, but increased costs at the regional level. However, individual studies show significant differences in results, leading to opposing signals that cancel each other out when aggregated, highlighting the need for more comprehensive regional studies to inform global-scale assessments. Finally, there is high uncertainty regarding the long-term modelling outcomes of climate change impacts on energy, which has not been well investigated.

Gaps in Knowledge, Conclusion and the Way Forward

This analysis demonstrates that despite over 200 papers examining the impacts of climate change on energy systems, there have been relatively few comprehensive studies that have assessed these impacts on energy systems as a whole. This is in contrast to other sectors, such as agriculture and water, where there has been a greater focus on the impacts of climate change. Moreover, the use of diverse methodologies in energy sector studies makes it challenging to compare climate change effects across different studies. In addition, few inter-method or inter-model comparisons have been performed to understand the underlying uncertainties. Studies are often conducted using a single energy model and climate change scenario, which can lead to different models and scenarios being used for individual technologies and regions, making it difficult to provide a comparable assessment. The role of spatial scale and resolution in assessing the impacts of climate change on energy systems has also not been fully investigated. These shortcomings in the literature suggest the need for more comprehensive and standardized approaches to studying the impacts of climate change on energy systems.

In order to properly assess the climate impacts on energy systems, it is essential to have a coordinated effort that uses consistent inputs and methods at all scales while considering uncertainties. The energy sector can learn from the systematic inter-comparison of models and multi-model assessments that have been conducted for the agriculture and water sectors. Such inter-comparisons can facilitate the exchange of knowledge across sectors, improve the quality and consistency of input and output datasets, and critically examine the sources of epistemic uncertainties resulting from different model configurations [85]. Although there is a long-standing tradition of model comparison for energy scenarios, it is absent in the analysis of climate change impacts [86]. Model inter-comparison studies of climate impacts are particularly important given the expected increase in the use of renewable energy, which is highly sensitive to climate change [87,93].

The interdependence of energy systems with food and water production, known as the water-energy-food nexus, is susceptible to the impacts of climate change. Biodiversity, coastal infrastructure, and oil and gas resource availability are also affected by climate change, emphasizing the need for an inter-sectoral approach to studying the energy sector [88,89]. A consistent, harmonized assessment of energy system models using global integrated scenario frameworks such as RCP/SSP matrix can facilitate comparability across studies and provide a framework for quantifying uncertainty [87]. The proposed "ISIpedia-energy protocol" approach uses harmonized input data for energy modeling in line with ISIMIP specifications. The framework distinguishes between the impacts of climate change on renewable energy sources and their effects on energy systems as a whole [91-93]. The results of the proposed analysis framework could provide valuable inputs for the IPCC AR6 and the Paris Agreement processes, as well as studies relating to the implementation of the Sustainable Development Goals. While the proposed protocol will not replace local-scale studies, a consistent multi-model analysis of energy sector vulnerability is crucial to developing effective strategies to reduce the sector's vulnerability to climate change at the regional and global levels.

CONFLICT OF INTEREST

No conflicts of interest are disclosed by the authors.

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