DECARBONIZING ELECTRICITY GENERATION MIX CONSIDERING CLIMATE CHANGE: THE CASE OF INDIA

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Overview

India is currently the third-largest carbon dioxide (CO2) emitter and the world's most populous country. In a context of global warming and increasingly frequent extreme weather events, India has set a target of achieving Net-Zero emissions in 2070. Indian electricity generation accounts for 53% of total energy-related CO2 emissions and consumption is projected to nearly triple by 2040 compared to 2019 [3]. Ensuring access to affordable and reliable electricity is critical for India's future social and economic development. This research explores the optimal electricity generation mix for India to meet its environmental goals amidst rising electricity demand and the challenges of climate change. For this purpose, we develop an optimization model for the Indian power sector. It incorporates techno-economic constraints using a linear programming approach with dynamic investment. The model investigates the optimal production dispatch and investment schedule for the five regional grids, accounting for inter-regional transmission. We use scenarios to simulate uncertainties in future economic growth, climate variation and environmental constraints. They encompass various growth rates in electricity demand, technological breakthroughs and adverse effects of climate change. Scenarios are assessed based on installed capacity and generation mix, investment path and total cost. This analysis contributes to the literature on decarbonizing future energy systems in developing countries through long-term modeling and linear optimization frameworks ([1], [2], [4], [5]). It provides insights into the identification of total cost variations associated with the electricity mix decarbonization in a context of economic development submitted to climate change.

Methods

India's current power generation mix is modeled using GAMS (General Algebraic Modeling System) software with CPLEX as the solver. The model is a dynamic, bottom-up, linear optimization framework that performs annual optimization of electricity dispatch and investment decisions from 2022 to 2070. It considers India as five nodes and minimizes annualized power system costs for each region, with the option of interregional transmission. The model accounts for fixed and variable operating costs, as well as investment and fuel costs. The modeled installed capacities include coal power plants, oil and gas power plants, nuclear reactors, solar power, onshore wind, hydroelectricity, and biomass. The key decision variables are the optimal electricity generation mix by technology (in MWh), calculated by time-slice, and the investment decisions, represented by additional capacity (in MW) each year.

We present two main scenarios to address uncertainties in the evolution of India's power system: a Business-as-Usual (BaU) scenario and a Net-Zero Emission (NZE) scenario. The BaU scenario serves as the reference case, outlining the optimal trajectory without shock and with no CO2 emission constraints. In contrast, the Net-Zero Emission scenario examines India's pathway to achieving carbon neutrality by 2070. Additionally, we model six alternative scenarios to explore deviations from these baseline cases (BaU and NZE). These include scenarios accounting for increased electricity demand, driven by heatwaves, and breakthroughs in energy technologies, reflected as cost reductions in renewable energy technologies and storage devices.

Results

For each scenario, we evaluate the total cost, the optimal electricity mix, and the optimal investment path. The results at the 2070 horizon are expected to vary depending on the scenario considered. In the Business-as-Usual scenario, considering a "typical" increase in electricity demand alongside breakthrough in renewable energy technologies and storage solutions, the total cost of electricity generation is expected to be the lowest. However, the same scenario without technological breakthroughs is projected to result in the highest CO2 emissions. Conversely, the Net-Zero scenario without breakthroughs in technology costs and with extreme peak demand is expected to achieve carbon neutrality by 2070 but may incur the highest total costs. Renewable energy sources are anticipated to represent a larger percentage in the installed capacity mix in Net-Zero scenarios, particularly when technological breakthroughs are considered. In contrast, coal is likely to remain the dominant technology in BaU scenarios due to its cost-effectiveness and economic significance for India. Finally, higher electricity demand for cooling during heat waves is likely to contribute to an additional increase in the total cost of the electricity mix.

Conclusions

The aim of this study is to evaluate the feasibility and affordability of achieving a carbon neutral power system in India, considering various demand trajectories, particularly under the impact of extreme weather events. Additionally, we analyze the results across a range of potential prices for renewable technologies and storage solutions to provide a more comprehensive view of possible future outcomes. This research contributes to the literature by offering a long-term optimization analysis of India's power system, accounting for the five regional grids and incorporating different demand levels to reflect adverse situations linked to climate change.

References

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