DATA 606 CAPSTONE PROJECT RESEARCH PROPOSAL

TEAM-8

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Title: Intelligent Grid: Machine Learning-Driven Optimization for Renewable Energy Stability

Abstract:
Solar and wind energy, among other renewable sources, are amazingly accelerating and changing the face of the power grid stage, but with them comes demand for more dimensions of operating procedures to encompass and maintain contemporary grid stability. These sources are very dynamic and are characterised by significant variations and intermittence that most often do not give the energy systems a chance to operate in a smooth transition. This has led mines to relief on the primary or dispatchable power sources, where in most cases this includes nonfossil fuel plants, allowing other resources to remain stationary. Imbalances in power services triggered by such power regulation are evidenced by the prescribed generation and are evidence of misutilization of renewable resources. Mechanisms addressing these issues call for an assort of actual measures based on data-driven estimation targeted at achieving grid stability and resilience while minimizing associated costs.

The current research advances a review of the present approach and an approach based on machine learning techniques to predict grid disturbance, foretell curtailment actions, and enhance complementarity among renewable and non-renewable sources. The approach utilizes a combination of historical statistical data on energy generation, curtailments, and grid load in California, acquired from the the California Independent System Operator (CAISO), and weather data, received from Visual Crossing, to assess the factors and conditions that contribute to power imbalance and curtailments. The main purpose of the framework is therefore to estimate the behaviour of interconnected renewable as well as conventional sources within the system in terms of grid stability. This is hoped to offer anticipatory implications for minimizing high levels of curtailment that are within the environmentally friendly power source utilization frameworks.

In order to provide a better understanding and practicality to the model, which is constantly facing a step of grid instability removal and some constraint violations, it is planned to turn to methods of explainable AI (XAI), offering to study the reasons for such instability as well as the curtailment events. This knowledge will be of particular use to system dispatchers and related policy-making circles who can use it to design plans for making the power system in the area more resistive and enabling the use and preservation of the different resources. Moreover, this imparts not only the management of the system stability in real time but also in the creation of strategies with how to work with the increased penetration of renewable energy in the grid.

This study will also assist in the development of mechanisms that will expedite the integration of renewable energy and avoid problems associated with limitations of available transmission capacities. Hence concentrating on an optimum energy perspective employing renewable & non-renewable sources under one umbrella in a region or region, this model aims to be the support for the establishment of a more secure and sustainable energy system while supporting clean energy and adaptation to climate change, with both being overarching aims.

Introduction:
Expansion of the application of renewable energy technologies such as solar and wind to the electric power sector is making a fundamental shift in the structure of power grids; however, such change does not come without problems. Renewable installations differ fundamentally from thermal plants, as they tend to generate and shut down based factors of the environment and tend to transition quite fast, leading to grid imbalances. Other power generation methods, such as thermal or nuclear, on the other hand, do not have the flexibility to change up a lot, so that there are loads of energy and renewable curtailment, grid relaxation, etc. In fact, renewable energy curtailments refer to reductions in the output of renewable energy from the grid associated with grid management inefficiency. This is the motivation behind the development of the current project, which is to create a machine learning-based strategy that can account for the weather conditions in connection with the power and the load factors in order to solve this challenge. There is a tendency in the proposed system to forecast grid instability, low appearances of renewable energy, and possibilities of renewable curtailments. Such an attempt focuses on improving energy management over purely the injection of more energy from renewable sources by managing the power from renewable and nonrenewable sources' interaction via historical energy production, curtailment data, and the weather condition.
It is also designed for introducing even further clarity as regards accentuated attention on including explainable AI (XAI) methods in the proposed framework. The high potential of these insights is quite promising, especially when they enable smart grid operators and relevant authorities to address operational issues, reduce the risk of curtailment, and even achieve load currents even in unbalanced network conditions. The suggested solution helps not only to achieve grids' stability but also enhances the penetration of renewable energy into the electricity grid to promote the sustainability and efficiency of the utility systems.

Background:
The changes to an alternative power pose a significant threat to energy security, but efforts to reconcile supply and demand are difficult. Shocks are present in the power system because of the temporal variability of solar and wind resources, which are often recorded on a minute-by-minute basis and run almost counter to the base load setting; hence, such resources are culled. Limited grid capacity, low levels of power consumption, and old power stations form part of these challenges, as pointed out by the CAISO.

The primary objective of this research is to use machine learning techniques for analysis of energy generation patterns and change in weather conditions in order to forecast grid collapse with a view to reducing curtailment and enhancing penetration of renewable energy. The use of XAI approaches will provide information on mining grid data and thus inform operators on how to reduce the risk of such measures and increase the adoption of green energy systems that will facilitate increased economic activities within the regions.

Summary of Literature Review:

1. "Artificial Intelligence-Based Prediction and Analysis of the Oversupply of Wind and Solar Energy in Power Systems"

This study by Shams et al. (2021) aimed to address the economic and operational challenges posed by renewable energy curtailment due to oversupply in power systems. Using historical data from the California Independent System Operator (CAISO), the authors developed a machine learning-based framework to predict wind and solar power curtailments (WSPCs). Several machine learning methods were evaluated, including regression trees, gradient boosting, random forests, neural networks, and long shortterm memory networks. Among these, the random forest model performed best in predicting WSPCs. This predictive approach, validated with both holdout and crossvalidation methods, provided a robust tool to enhance the utilization of renewable resources by minimizing curtailments. The study's findings underscore the importance of accurate curtailment prediction in optimizing renewable energy usage and planning for future grid operations.

2. "Integration of Renewable Energy Sources in Future Power Systems: The Role of Storage"

Weitemeyer et al. (2014) explored the integration of high shares of renewable energy sources (RES) like wind and solar into power systems, focusing on the role of storage. Using a modeling approach, they analyzed how different storage sizes and efficiencies affect RES integration in a 100% renewable energy scenario for Germany. The study found that up to 50% of electricity demand could be met with a mix of wind and solar, without storage or curtailment, if flexible power plants are available. However, higher renewable penetration levels require efficient, albeit modestly sized, storage solutions to stabilize the grid. Only when RES meets more than 80% of demand are larger seasonal storage solutions necessary. The findings highlight the importance of balancing additional generation with storage capacities to optimize RES integration, providing insights for policymakers and energy planners on efficient storage deployment strategies.

3. "Artificial Intelligence-Based Approaches for Renewable Energy Curtailment Prediction and Optimization"

This study focuses on the utilization of machine learning techniques to predict renewable energy curtailments in power systems. Through a mix of data-driven approaches, including regression and classification algorithms, the authors aimed to understand the patterns and drivers of curtailments in systems with significant renewable penetration. The findings revealed that predictive models can help system operators preemptively adjust energy dispatch to minimize curtailments, ensuring more efficient use of renewable resources. The study suggests that incorporating real-time weather and generation data into these models could further improve accuracy, supporting better decision-making in renewable power systems. Future work will focus on refining models to include more granular weather data and investigating the economic impacts of optimized curriculum management.

Novelty Approach:

The current research aims to provide a comprehensive overview of the issue of integration of renewable energy on the grid, taking into account the problems related to the changes in the grid. So it is a three-pronged approach: an examination of the reasons for increased power consumption during peaking load months, an exploration of the possibilities for back-to-back low output days and automation of their calculations in different scenarios, and an investigation of the methods to eliminate the low demand cost of generating power while many sources are generating renewable energy. The new approach allows combining the factors of demand, supply, and losses. At the same time, it gives an opportunity to increase the resilience and efficiency of the system and to increase the production of renewable energy.

Research Questions:

Research Question 1: How do weather conditions and energy generation factors influence electricity demand during peak load seasons, and what key drivers significantly impact these fluctuations?

For this question, the approach will focus on analyzing the relationship between key environmental factors (such as temperature, humidity, combined renewables, and imports) and electricity demand during peak load periods. We aim to determine which specific conditions are most influential in driving these fluctuations. This analysis will assist in understanding and anticipating changes in energy demand during critical load times, enabling more efficient resource allocation. Historical weather data and grid load information will be used to gain insights into patterns that drive peak energy usage, thereby supporting better decision-making for demand management and optimizing the energy supply mix.

Research Question 2: How can the risk of consecutive days with low renewable energy generation be effectively predicted based on weather patterns, and what measures can be implemented to maintain reliability during such events?

The approach here is to leverage weather data to predict the risk of prolonged periods with low renewable generation, focusing on solar and wind. Key features, such as temperature, windspeed, and solar radiation, will help in understanding how weather patterns contribute to the occurrence of consecutive low-output days. The goal is to provide actionable insights for grid operators to anticipate such situations, ensuring reliability through proactive planning. This could include scheduling increased imports or tapping into traditional energy reserves ahead of expected dips in renewable production, thus mitigating potential energy shortages and ensuring grid stability.

Research Question 3: What strategies can be implemented to minimize renewable energy curtailment during periods of high renewable output and low demand, ensuring grid stability and optimal resource utilization?

For this question, the approach will focus on examining the conditions that lead to renewable energy curtailment—specifically during times of high renewable output but low demand. Using features like wind gusts, solar radiation, and contributions from different generation sources, the project aims to identify scenarios where curtailments are more likely and develop strategies to minimize them. This would involve optimizing the energy dispatch schedule to balance renewable contributions and traditional generation effectively. Ultimately, by reducing curtailment rates, this approach aims to increase the efficiency of renewable energy usage and ensure the stability of the grid, even during periods of high renewable production.

Preliminary Implications:
The potential outcomes of this initiative are vital for improving electric grid reliability and increasing renewable energy use. By enhancing energy dispatch strategies during peak demand, generation can better align with needs. During periods of low renewable generation, operators can adjust energy supply schedules by using reserve load levels, which helps maintain grid support and protects consumers from energy shortages. Techniques to prevent curtailment also help utilize energy efficiently, leading to increased sustainability. Locally, the combination of stakeholder attitudes, technology, and capital can improve energy services, fostering further adoption of renewables. This project aims to reduce dependence on fossil fuels and address inefficiencies in renewable energy use, contributing to broader environmental goals. Overall, these efforts promote renewable integration into existing infrastructure, enhancing sustainability and reducing the negative impacts of fossil fuel dependency.

Conclusion:
The integration of renewable energy is essential for a sustainable future but presents significant challenges related to grid stability and energy management. This project addresses these challenges by proposing a comprehensive machine learning-based framework aimed at predicting grid instability, minimizing renewable curtailments, and optimizing energy dispatch. By leveraging CAISO energy production data, curve events, and weather information, the proposed model will provide actionable insights to enhance grid resilience. Explainable AI will also be used to reveal key drivers of curtailments and instabilities, thus supporting informed decision-making for both operational and strategic purposes. The ultimate goal is to ensure a more efficient, resilient, and sustainable power grid that maximizes the use of renewable resources while maintaining reliability. This research will contribute to a more balanced approach to renewable energy integration, leading to reduced emissions, improved resource utilization, and enhanced energy security.

References:

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