Western Interconnect Energy Analysis - Towards Senate Bill 100

Athira Nirmal, Soundarya Ketharaman

Abstract

This paper examines the energy landscape of the Western Interconnect region of the United States, focusing on the implications of Senate Bill 100 (SB 100) for renewable energy integration and transmission infrastructure. The study analyzes the current generation mix, transmission networks, and energy demand, highlighting the critical role of the Western Electricity Coordinating Council (WECC) in ensuring a reliable and competitive power market. By employing a comprehensive approach that includes data preprocessing and exploratory data analysis, the research aims to identify strategies for minimizing system costs while maximizing the utilization of renewable energy sources such as solar, wind, and hydro power. The findings underscore the importance of optimizing energy production to significantly reduce carbon dioxide emissions and promote the adoption of renewable energy, ultimately contributing to a sustainable energy future in the Western Interconnect.

1. Introduction

The Western Interconnect region of the United States represents a complex and dynamic energy landscape characterized by diverse energy resources, regulatory frameworks, and evolving consumer demands. As the nation increasingly shifts towards sustainable energy practices, the implementation of policies such as Senate Bill 100 (SB 100) has become paramount in guiding the transition to a cleaner energy future. SB 100 mandates that California achieve 100% renewable energy by 2045, setting a precedent for other states within the Western Interconnect to follow suit.

This paper explores the structure and regulation of the energy sector in the Western Interconnect, with a particular focus on the generation mix, transmission networks, and the key policies that shape the region's energy dynamics. The Western Electricity Coordinating Council (WECC) plays a crucial role in maintaining a reliable electric power system, supporting competitive power markets, and ensuring open access to transmission networks. As the demand for renewable energy sources continues to rise, it is essential to analyze the challenges and opportunities associated with integrating these resources into the existing energy infrastructure.

Through a detailed examination of the current state of energy consumption, generation, and transmission, this study aims to identify effective strategies for minimizing system costs while maximizing the utilization of renewable energy. By addressing the pressing need to reduce carbon dioxide emissions and reliance on fossil fuels, this research contributes to the ongoing discourse on sustainable energy practices and the future of the Western Interconnect.

2. Background and Research Question

The Western Interconnect is a vast electrical grid that spans 14 states in the western United States, serving millions of customers and playing a critical role in the nation's energy landscape. This region is characterized by a diverse mix of energy resources, including fossil fuels, nuclear power, and an increasing share of renewable energy sources such as solar, wind, and hydroelectric power.

In recent years, California has emerged as a leader in the transition to a low-carbon energy future, setting ambitious goals to achieve 100% clean electricity by 2045. This commitment is part of a broader movement across the Western Interconnect to reduce greenhouse gas emissions and promote the use of renewable energy. The state's policies, such as the Renewable Portfolio Standard (RPS), aim to increase the share of renewables in the energy mix, thereby reducing reliance on fossil fuels and minimizing the carbon footprint of the electricity sector.

Transition to a low-carbon energy system while maintaining reliability, affordability, and universality of electricity service

Decarbonization pathways for the Western Interconnect involve analyzing scenarios for reducing greenhouse gas emissions by integrating renewable energy sources, implementing energy storage solutions and promoting demand response strategies (National Renewable Energy Laboratory, 2020). Ensuring grid resilience and reliability is critical, as renewable energy penetration increases, grid stability and reliability may be impacted (Western Electricity Coordinating Council, 2022).

Engineering and economic implications of achieving California's 2045 carbon neutrality goal, and market reforms and transmission planning designed to address these challenges

Engineering implications of achieving California's 2045 carbon neutrality goal involve analyzing the required scale and pace of renewable energy deployment, energy storage, grid modernization and demand response. Economic implications include assessing costs, investment requirements and job creation, with benefits encompassing reduced greenhouse gas emissions, improved air quality and economic growth.

Market reforms are essential for accommodating increased renewable energy penetration, involving market design changes, pricing mechanisms and capacity markets. Transmission planning approaches prioritize reliability and efficiency, including infrastructure upgrades, new transmission lines, smart grid technologies and microgrids.

3. Motivation

3.1 Importance of Decarbonization

Decarbonization is crucial for mitigating climate change impacts. The Western Interconnect must transition to a low-carbon energy system to achieve California's 2045 carbon neutrality goal. Decarbonization helps avoid catastrophic climate change consequences, ensuring global temperature rise remains below 1.5°C (International Energy Agency, 2021). This transition reduces greenhouse gas emissions.

3.2 Challenges in the Western Interconnect

The Western Interconnect faces unique challenges integrating intermittent renewable energy sources while maintaining grid reliability (National Renewable Energy Laboratory, 2020). Upgrading aging transmission infrastructure supports renewable energy integration (Western Electricity Coordinating Council, 2022). Managing peak demand requires advanced grid management systems.

3.3 Reliable 100% Zero-Carbon Electricity

A reliable 100% zero-carbon electricity grid requires renewable energy integration, advanced energy storage and enhanced grid resilience (National Renewable Energy Laboratory, 2020). Grid modernization upgrades infrastructure, implements smart grid technologies and manages peak demand (International Energy Agency, 2021).

3.4 Environmental and Economic Benefits

Decarbonization mitigates climate change impacts, improves air and water quality and drives innovation in energy storage. Renewable energy sectors create new job opportunities.

4. Problem Statement

The Western Interconnect faces significant challenges in transitioning to a low-carbon energy system while ensuring reliability and affordability. The key problems to address are:
Cost Optimization: Minimizing total system costs is crucial. Fixed costs, including generation, storage and transmission infrastructure, must be balanced with variable costs, such as generation and non-served energy costs.
Renewable Integration: Maximizing renewable energy utilization from solar, wind and hydro power sources is vital to reduce fossil fuel reliance.
CO2 Emission Reduction: Significantly decreasing carbon dioxide emissions through optimized energy production and renewable energy adoption is essential.

Achieving these objectives simultaneously poses an optimization problem that can be solved by the complex expansion model with Julia and HiGHs model optimizer.

5. Data Description

The dataset provided consists of 5 files:

1. Generators: Describes different technologies used with respect to each region along with the various costs and cap
2. Demand: Describes demand for various zones at each time index
3. Variability: Describes time-series data for capacity factor and resource availability
4. Fuels data: Describes cost and CO2 content for each fuel type
5. Lines: includes data on transmission fixed costs, capacity parameters, and loss parameters.

5.1 Data Cleaning and Preprocessing

Each of these files contain relevant and dependent information that must be extracted and saved in single data frames before building upon the complex expansion model. The data contains missing information on RPS eligible resources. In accordance with this, the data is pre-processed with the objectives of integrating renewable energy policies such as RPS. Figure 1 depicts the flowchart of the applied data cleaning and preprocessing stage.

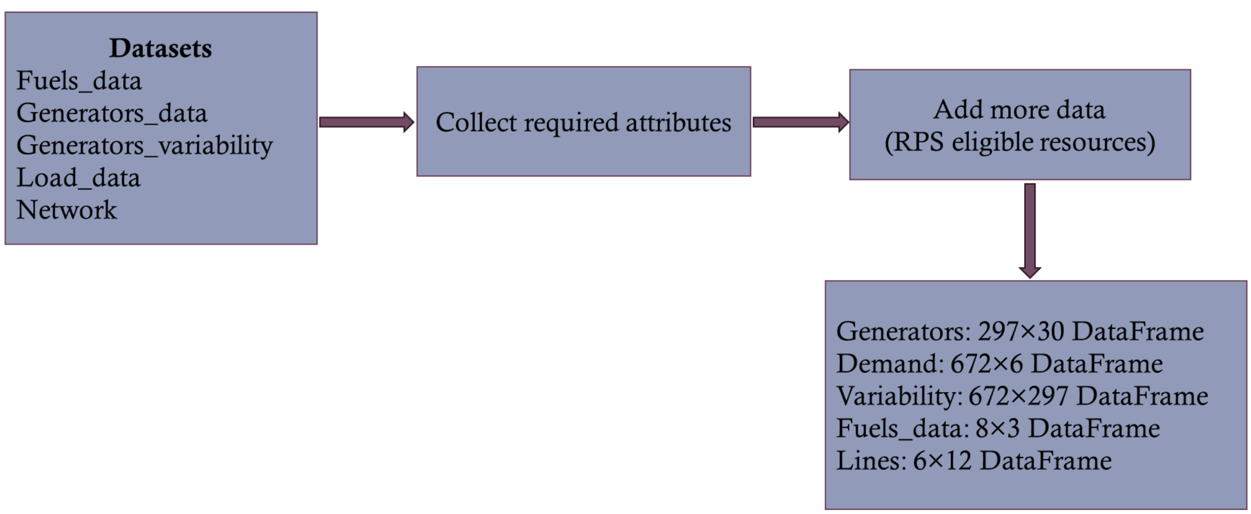

Figure 1: Data cleaning and preprocessing steps

5.2 Exploratory Data Analysis

On the dataset, visualisations are obtained in Julia for the energy statistics distribution as shown in Figure 2.

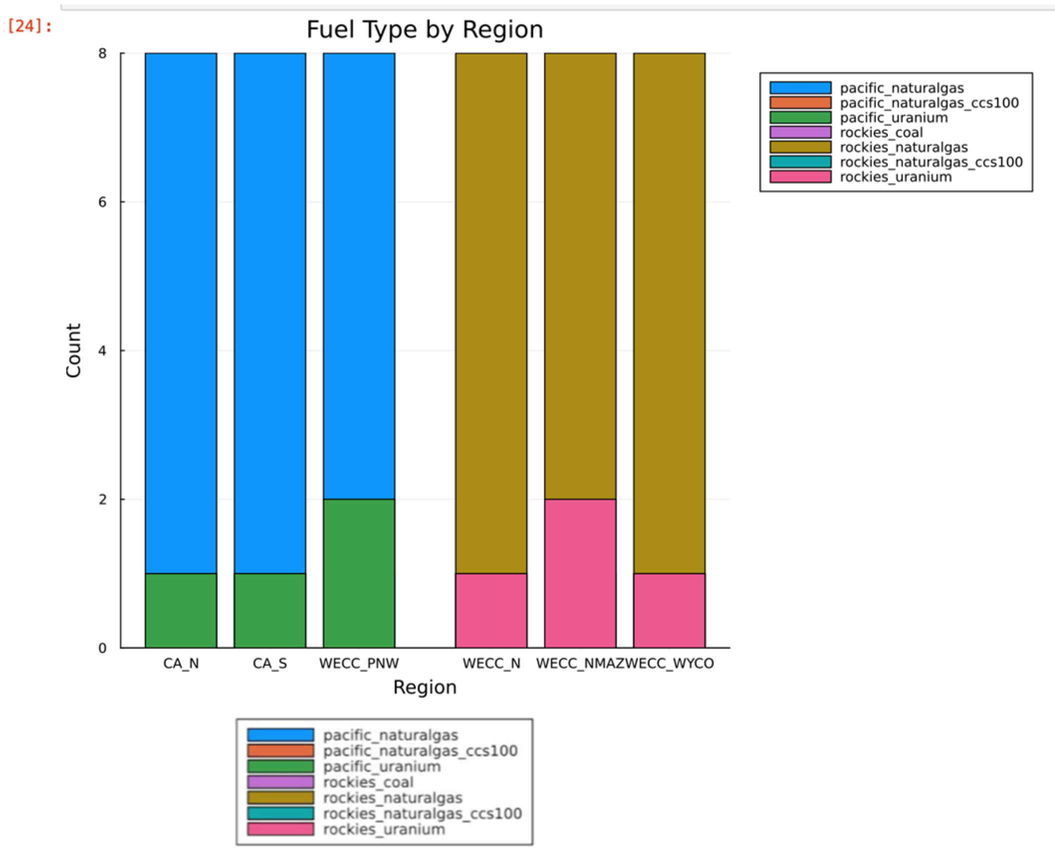

Figure 2: Distribution of different fuel types by region in western interconnect

The analysis on fuel data for CO2 content drawn in Sheets is a good indication of the fuel types that could be eliminated or avoided in the model as depicted in Figure 3.

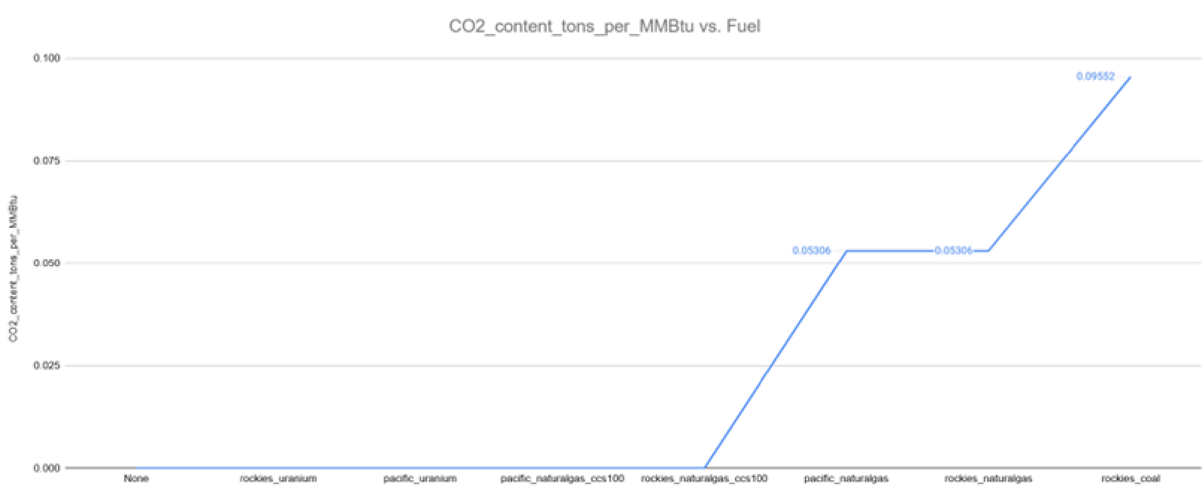

Figure 3: CO2 content (tons per MMBtu) for each fuel type

Further the load data for one day in January is drawn in Sheets to understand the peak demands, as illustrated in Figure 4.

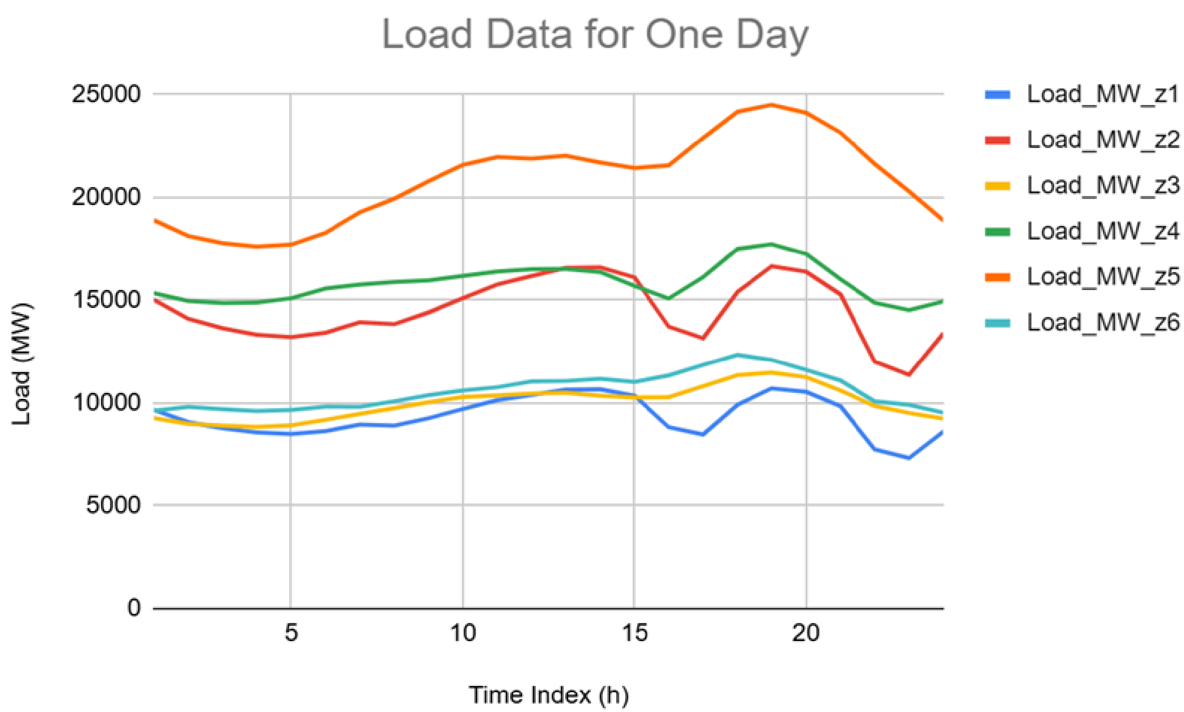

Figure 4: Load data for each day for different zones

6. Methodology

6.1 Assumptions

When modeling the expansion problem, following key assumptions are made:

1. Geographic diversification scenario – "Expanded regional transmission allowing for greater energy exchanges between California and the rest of the WECC" – is considered (California Energy Commission, 2018)
2. Dataset as part of SR01 is sufficient for the capacity expansion model
3. RPS eligible resources for California are biomass, small hydroelectric, geothermal, wind, and solar
4. RPS target value is set to 1 in alignment with SB100 policy for the year 2045

6.2 Model Creation

The complex expansion model is created for the dataset in the Western Interconnect using Julia for a period of 4 weeks. Figure 5 represents different phases utilised during building of the model. A three phase iterative approach was employed. The base model was built with the basic constraints necessary for the expansion model. The CO2 emission transmitted cap constraint model (CT Model) builds upon the Base Model to include the cap on CO2 emission. Finally, the Renewable Portfolio Standard (RPS) policy is added as a constraint into the CT model to get the RPS model.

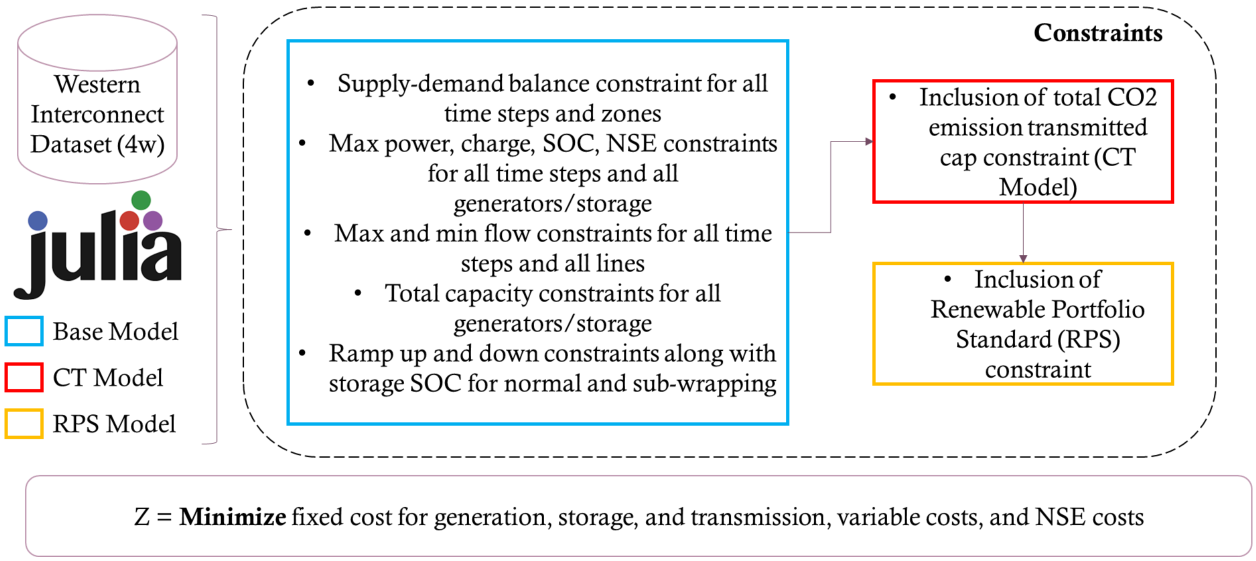

Figure 5: Implementation steps for the model

6.2.1 Base Model

The objective is to minimize the total cost and increase renewable sources. The following were the constraints added:

1. Demand Balance: Ensures that generation, storage, and transmission meet demand in every time step and zone
2. Capacity Limits: Restricts generation, storage, and transmission within their maximum capacities
3. Storage Constraints: Limits on charging, discharging, and state-of-charge (SOC) of storage units
4. Transmission Flow: Ensures flows on transmission lines respect capacity and directionality
5. Ramp Constraints: Limits how quickly generators can increase or decrease their output between time steps
6. Coupling of Time Periods: Links variables across time steps to account for ramp rates, storage SOC, and sub-period wrapping

6.2.2 CT Model

The objective is to minimize the total cost, increase renewable sources, and decrease CO2 emissions. CO2 emission calculations are done as shown in Equation 1 and Equation 2.

CO2 emissions rate = fuel CO2 content * heat rate (1)
Start-up CO2 emissions = fuel CO2 content * start up fuel use (2)

Based on these equations, the constraints were created. Figure 6 shows the mathematical equation for CO2 emissions.

$$Total\_CO2\_emission = \sum_{t \in T, g \in G} sample\_weight[t] * \left(vGEN[t,g] \cdot generators.CO2_{Rate[g]} + vSTART[t,g] * generators.CO2\_Per\_Start[g]\right)$$

Figure 6: Mathematical equation for CO2 emissions

Hence, the code addition into Julia for modeling the CT model requires code update as depicted in Figure 7.

```
@expression(Expansion_Model, Total_CO2,
    sum(sample_weight[t] * (vGEN[t,g] * generators.CO2_Rate[g] +
    vSTART[t,g] * generators.CO2_Per_Start[g]) for t in T, g in G)
)

@constraint(Expansion_Model, Total_CO2 <= 0)
```

Figure 7: Julia implementation for CO2 emissions

6.2.3 RPS Model

The objective is to minimize the total cost, increase renewable sources, and decrease CO2 emissions with the RPS policy. CO2 emission calculations are done as shown in Equation 1 and Equation 2.

Based on the RPS requirement, the constraints were created. Figure 8 shows the constraint equation.

$$\frac{\sum_{g \in RPS} GEN_{t,g}}{\sum_{g \in G} GEN_{t,g}} \geq RPS_{target_t}, \forall t \in T$$

Figure 8: Mathematical equation for RPS target value

Hence, the code addition into Julia for modeling the CT model requires code update as depicted in Figure 9.

```julia
# Now let us try to add the RPS constraint. For carbon neutrality, we w
rps_target = 1
@constraint(Expansion_Model, cRPS[t in T],
    sum(vGEN[t,g] for g in RPS) >= sum(vGEN[t,g] for g in G)
)
```

Figure 9: Julia implementation for RPS constraint

7. Results Analysis

7.1 Cost Result Analysis

The Base Model, CT Model and RPS Model differ significantly in their cost structures. The Base Model minimizes total costs by reducing fixed generation and non-served energy (NSE) costs. In contrast, the CT Model incurs higher fixed costs due to increased generation and storage expenditures. The RPS Model has the highest total costs, driven by high fixed generation costs and elevated NSE costs. Visualization is seen in Figure 10.

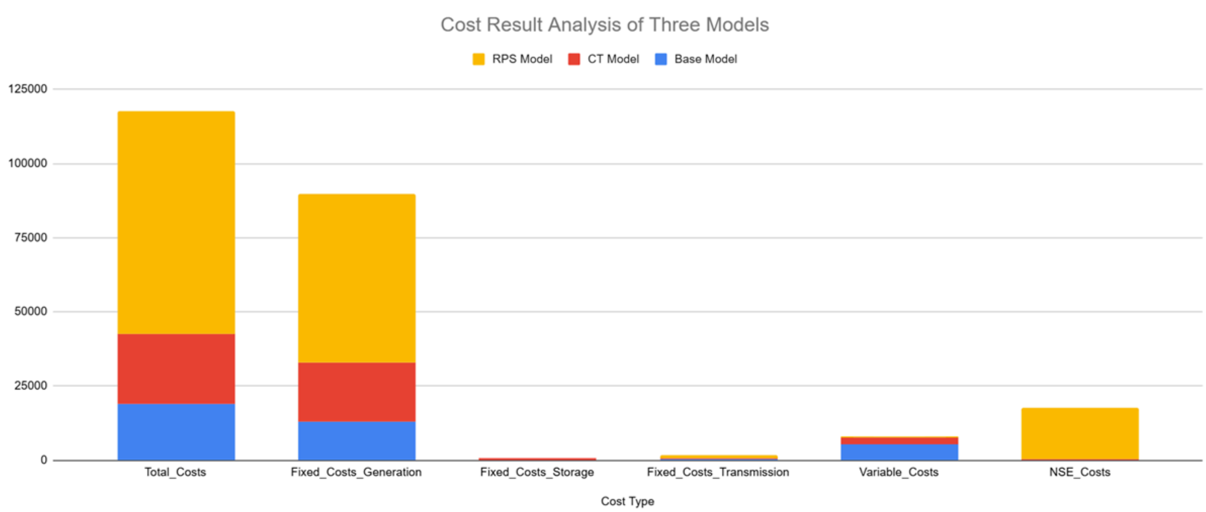

Figure 10: Cost result analysis comparing the three models

7.2 Generators Result Analysis

The RPS Model generates significantly higher total megawatts (MW) but produces lower total gigawatt-hours (GWh), indicating inefficiency in energy utilization due to renewable integration. This suggests suboptimal resource allocation. In contrast, the CT Model strikes a balance between moderate MW capacity and the highest GWh output, implying improved operational efficiency compared to the Base Model. Visualization is seen in Figure 11.

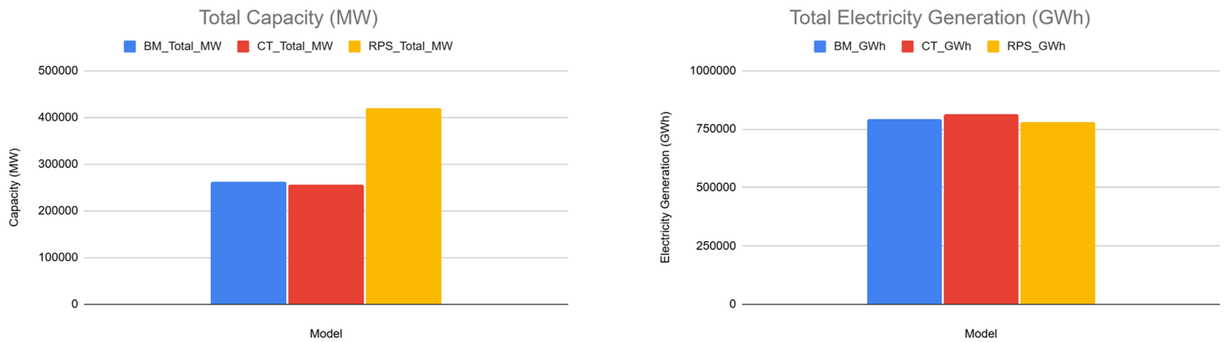

Figure 11: Generator results analysis comparing the three models

7.3 NSE Result Analysis

The RPS Model exhibits the highest non-served energy (NSE) across all segments, indicating significant challenges in meeting demand despite its higher megawatt (MW) capacity. This suggests that the model struggles to effectively utilize its resources to match energy supply with demand. In stark contrast, the Base Model demonstrates reliable energy delivery, achieving near-zero NSE. Visualization is seen in Figure 12.

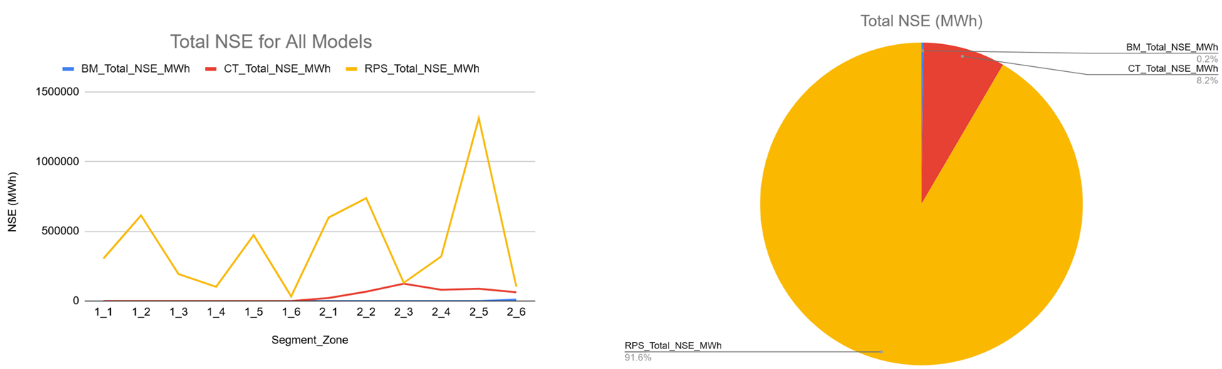

Figure 12: NSE results analysis comparing the three models

7.4 Storage Result Analysis

CT Model exhibits increased total storage utilization compared to the Base Model and RPS Model. This suggests that the CT Model effectively balances emissions trading with strategic storage deployment, optimizing its storage resources to mitigate emissions and ensure reliability. In contrast, the RPS Model fails to utilize additional storage capacity despite experiencing higher non-served energy (NSE), indicating missed opportunities for enhancing grid resilience and reliability. Visualization is seen in Figure 13.

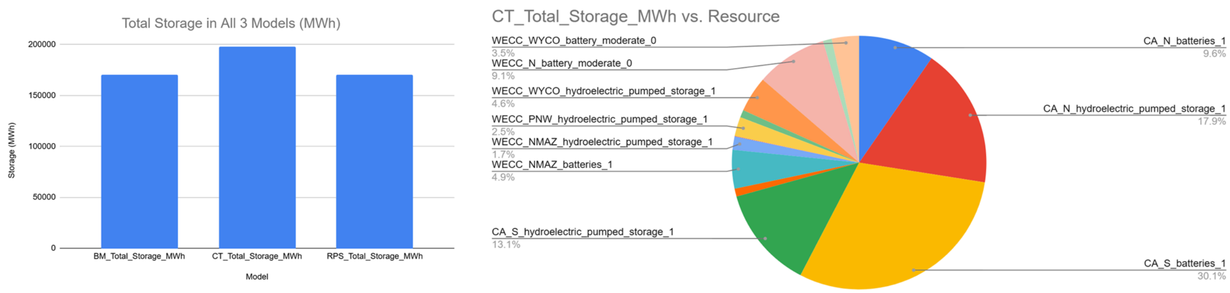

Figure 13: Storage results analysis comparing the three models

7.5 Transmission Result Analysis

The RPS Model exhibits the highest transfer capacity, implying the critical importance of a reliable and robust transmission infrastructure to meet the renewable energy standard. This suggests that a well-planned and resilient transmission network is essential for efficiently integrating renewable energy sources and ensuring grid reliability. Visualization is seen in Figure 14.

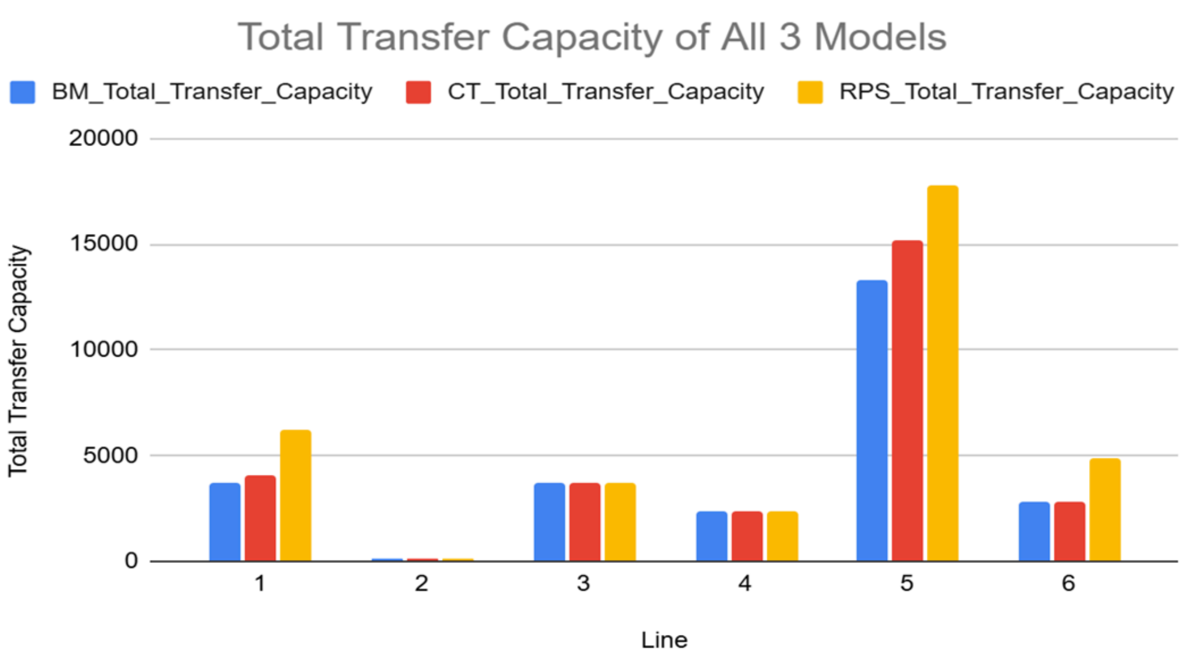

Figure 14: Transmission results analysis comparing the three models

8. Regulatory and Market Reforms

8.1. Reform 1: Cap and Trade Policy

The CT model implements a cap on CO_2 emissions, outperforming the Base Model by incorporating additional storage capacity resources. Furthermore, the CT model's effectiveness can be enhanced through the integration of emissions trading, as defined by the Cap and Trade policy (Center for Climate and Energy Solutions, 2022). Key components of this policy include:

1. Emissions Cap: Sets a limit on total emissions.
2. Allowances: Allocates emissions permits to companies or countries.
3. Trading: Enables entities to buy and sell excess allowances.

California already has the Cap-and-Trade Program, launched in 2013. This program aligns with the goals of SB100, making it a perfect reform to consider.

8.2. Reform 2: Renewable Portfolio Policy

Although the RPS Model performs less favorably compared to the CT Model, its inclusion is crucial for promoting renewable energy. To enhance its effectiveness, we should consider adding constraints to ensure a minimum number of storage components. Key features of the RPS policy include:

1. Renewable Energy Targets: Sets a minimum percentage of renewable energy sources.
2. Eligible Resources: Defines qualifying renewable energy technologies (e.g., solar, wind, hydro).
3. Compliance Mechanisms: Enforcement through renewable energy certificates, penalties or incentives.

By integrating storage requirements and refining RPS policy design, its performance can be significantly improved (California Public Utilities Commission, 2022).

9. Limitations

9.1 Socioeconomic Factors Ignored

The model employed in this research does not account for the socioeconomic impacts of energy policies, such as job creation, regional equity, or energy access. These factors are crucial for understanding the broader implications of transitioning to a renewable energy system, as they can significantly influence public acceptance and the overall success of decarbonization efforts.

9.2 Limited Emissions Scope

The focus of this study is primarily on carbon dioxide emissions from the power sector, which may overlook other greenhouse gases, such as methane and nitrous oxide, as well as emissions from other sectors, including transportation and industry. A more comprehensive analysis would require a broader emissions scope to fully understand the environmental impact of energy policies.

9.3. Absence of Consumer Behavior Considerations

The model does not incorporate potential changes in consumer behavior or the impacts of demand-side management strategies in response to carbon pricing or renewable energy policies.

Understanding how consumers might adapt to new pricing structures or incentives is essential for accurately predicting energy demand and the effectiveness of various policy measures.

9.4 Limited Policy Interactions

The interactions between different policies, such as cap-and-trade systems and clean electricity standards, are not analyzed in detail. This oversight may overlook potential synergies or conflicts between these policies, which could significantly affect the overall effectiveness of the transition to a low-carbon energy system.

10. Conclusion and Future Work

The complex expansion model was developed to evaluate the performance of the Western Interconnect grid in achieving 100% carbon-free operations by 2045, under three scenarios. By incorporating Cap and Trade policy alongside Renewable Portfolio Standard (RPS) policy, with a minimum storage capacity threshold, California can attain SB100 targets by 2045, leveraging the Western Interconnect grid's reliability.

However, this analysis has limitations:
1. Socioeconomic factors and consumer behavior are not considered.
2. Emissions scope is restricted to fuels and greenhouse gas sources producing methane, excluding industries like transportation.
3. Only limited policy interactions are included.

Some of the future work recommendations are as follows:
1. Run the model for a one-year period.
2. Conducting sensitivity analysis on storage resources to assess impact on Non-Served Energy (NSE).
3. Integrate trading incentives into the model to examine effects on total costs.

11. References

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