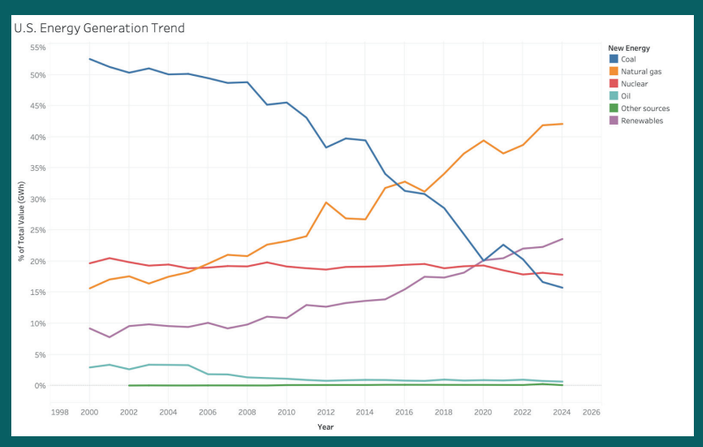
MODELING ENERGY TRANSITION DYNAMICS IN THE U.S.: 25 YEARS OF SHIFTS FROM FOSSIL TO RENEWABLE POWER

dohui.kim@concordiahanoi.org | Daisy Kim | Big Data (Ms. Hien) 2025/26

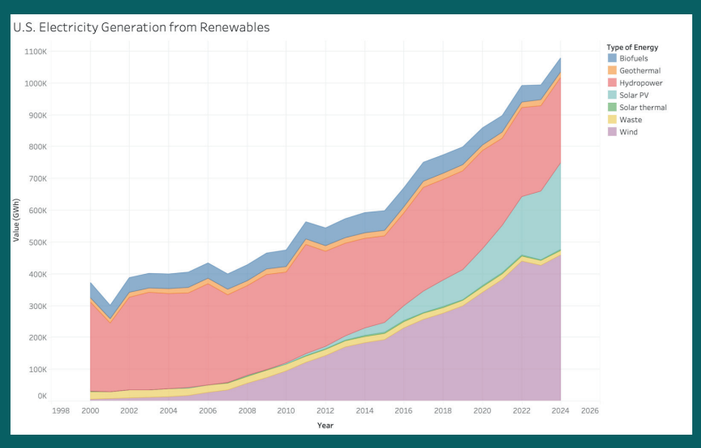
Abstract—The U.S. electricity sector is undergoing a significant transformation as the nation gradually shifts from fossil fuel–dominated generation toward renewable energy sources. Understanding how this transition unfolds over time is essential for evaluating changes in electricity production, energy composition, and emissions patterns. This paper analyzes long-term trends in U.S. electricity generation to model energy transition dynamics over the past 25 years and to examine how different components of the power sector evolve in relation to one another.

U.S, ENERGY GENERATION BY TYPE FROM 2000 TO 2024



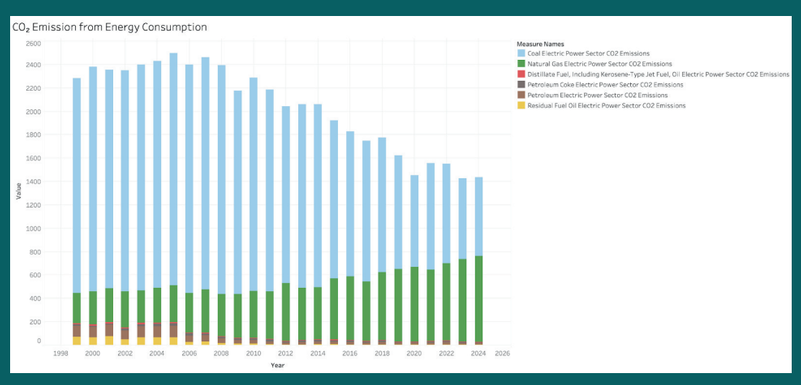
The long-term trend in U.S. electricity generation (Figure 12) shows distinct shifts in the energy mix over the past 25 years. Coal's share of total generation declines steadily from above 50% in the early 2000s to below 20% by the early 2020s. In contrast, natural gas exhibits a sustained increase in generation share, rising from roughly 15–17% to over 40% of total generation, reflecting its growing role in meeting U.S. electricity demand [8]. Renewable energy sources also show a strong upward trend; although renewables start as a relatively small share of total generation (below 10%), their contribution increases steadily, surpassing nuclear power in the early 2020s. Nuclear power, by comparison, remains stable throughout the period, with its share fluctuating in a narrow range, indicating limited structural change relative to other sources.

U.S. ELECTRICITY GENERATION FROM RENEWABLES



Renewable electricity generation has nearly tripled since 2000. Wind and solar energy have expanded most dramatically, as shown in the graph below. Wind began contributing substantially in the late 2000s, and solar PV's rapid expansion after 2015 sharply increased the slope of the total generation curve. Hydropower remains relatively stable throughout the entire period, indicating that most of the structural change in U.S. renewables comes from technologies capable of rapid scaling rather than from traditional sources. Smaller contributors such as geothermal, waste, and biofuels add to the layered increase but do not significantly alter the overall trajectory.

CO_2 EMISSION FROM ENERGY CONSUMPTION DATA

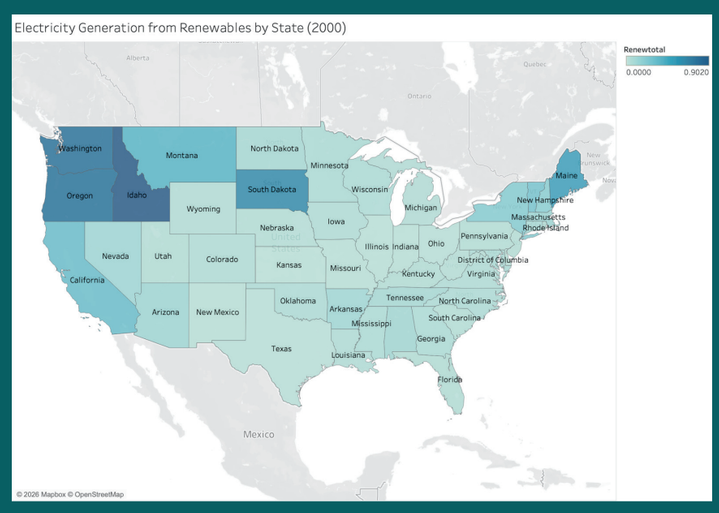


Overall, the close alignment between the downward trend in total CO_2 emissions and the decline in coal-related emissions underscores coal's continued statistical prominence in shaping aggregate emission patterns, even as its absolute contribution decreases over time. Concurrently, the sustained increase in natural gas–related emissions alongside this decline reflects a growing divergence between the two dominant sources, indicating a reconfiguration of the power-sector emissions profile.

FULL RESEARCH PAPER

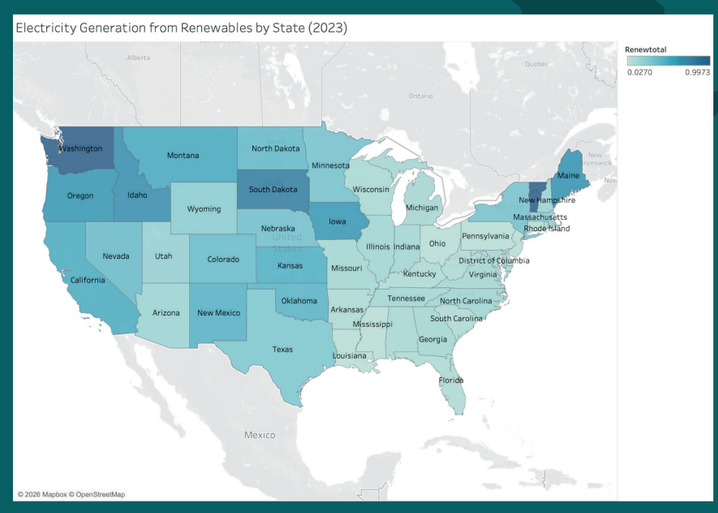
U.S. ELECTRICITY GENERATION FROM RENEWABLES BY STATE (2000 VS. 2023)

The two choropleth maps below, excluding Alaska and Hawaii, illustrate electricity generation from renewable sources across U.S. states in 2000 and 2023. When examined comparatively, the maps reveal clear spatial variation and temporal change, suggesting correlations between renewable electricity generation and regional characteristics such as prevailing climate conditions and geographic location.



2000

In 2000, renewable electricity generation was unevenly distributed across the United States, with higher values concentrated in a limited number of states. States in the Pacific Northwest and parts of the Mountain West exhibit relatively elevated renewable generation compared to the national average, while the majority of states display comparatively low levels. This spatial concentration suggests a correlation between renewable electricity generation and regional characteristics common to these areas, including geographic and climatic conditions favorable to certain renewable resources.

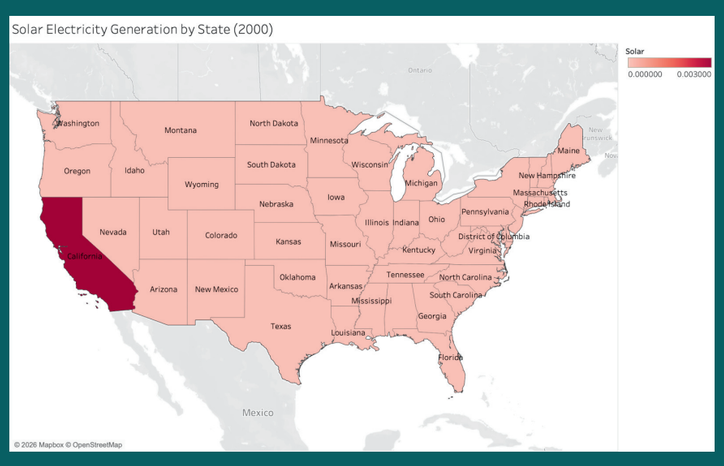


2023

In 2023, electricity generation from renewable sources exhibits a substantially more differentiated distribution across U.S. states than in 2000. States such as Washington, Oregon, California, Idaho, Montana, North Dakota, South Dakota, Iowa, Kansas, and Maine display relatively high levels of renewable electricity generation, while Florida, Mississippi, Louisiana, Kentucky, and West Virginia remain at comparatively lower levels. This contrast highlights pronounced interstate variation that was not clearly observable in earlier years, when renewable generation levels were uniformly low across most states.

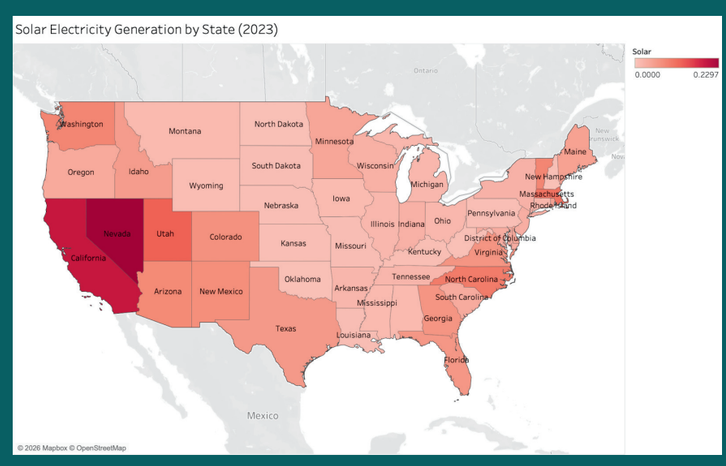
U.S. SOLAR ELECTRICITY GENERATION BY STATE (2000 VS. 2023)

Building on the previous U.S. electricity generation from renewables graph displaying the gradual increase in total with net solar energy—Solar PV and Solar thermal—exhibiting a pronounced growth, the following state-level maps shift the focus from national-level trends to a more specific examination of how this rapid expansion in solar power is distributed across individual states.



2000

In 2000, solar electricity generation was minimal across nearly all states; California is the primary exception, exhibiting higher solar output relative to other states. While California benefits from high solar irradiance and a generally warm climate, comparable solar resource levels were present in several other southwestern states by 2000. However, solar electricity generation remained overwhelmingly concentrated in California at that time, suggesting that spatial patterns of early solar output aligned more closely with the distribution of early policy adoption and technological deployment than with climatic conditions alone [10].



2023

By 2023, the association between climate characteristics and solar electricity generation becomes more apparent. States located in warmer, high-insolation regions, particularly in the Southwest and Southern United States—including California, Nevada, New Mexico, Texas, and parts of the Southeast—exhibit higher levels of solar electricity generation relative to many cooler or lower-insolation states. These regions are characterized by longer annual sunlight exposure and higher average solar intensity, and the spatial clustering of elevated solar output in these areas is consistent with a positive correlation between warmer climates, higher insolation levels, and solar electricity generation.

Conclusion—Overall, a clear and singular relationship between renewable electricity expansion and changes in the U.S. power-sector emissions profile was not isolated. When national trends in renewable electricity generation were compared with total electricity generation, a strong upward alignment was observed, indicating that renewable growth occurred within an expanding electricity system rather than replacing demand outright. When the composition of electricity generation was further examined, a consistent decline in coal generation alongside increases in renewable energy and natural gas was observed, suggesting a restructuring of the electricity mix rather than a uniform transition away from fossil fuels. At the state level, solar electricity generation displayed increasing geographic dispersion over time, with higher levels of output clustered in warmer, high-insolation regions by 2023.

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