Balancing Seasonality in Decarbonizing Electricity Systems Worldwide

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Context

Decarbonizing electricity grids across the world will be increasingly impacted by systematic seasonal variation in wind speed and solar irradiance as well as seasonally varying patterns of demand, more so in the context of progressive decarbonization of energy services such as wintertime heating. These seasonal variations are governed by local meteorology which also has large-scale manifestations impacting entire electricity grid systems.

Objectives

- Characterize patterns of seasonally varying electricity demand across the world
- Consider whether within-country wind and solar variability are well matched with seasonal electricity demand patterns
- Examine the role and prospects of excess renewables capacity and long-duration storage in bridging generation imbalance relative to seasonal patterns of electricity demand

Seasonality: Generation and Demand

The month of wind & solar generation peak (Figure 1) as well as electricity demand maximum (Figure 2) varies systematically, with timings differing substantially within and across countries.

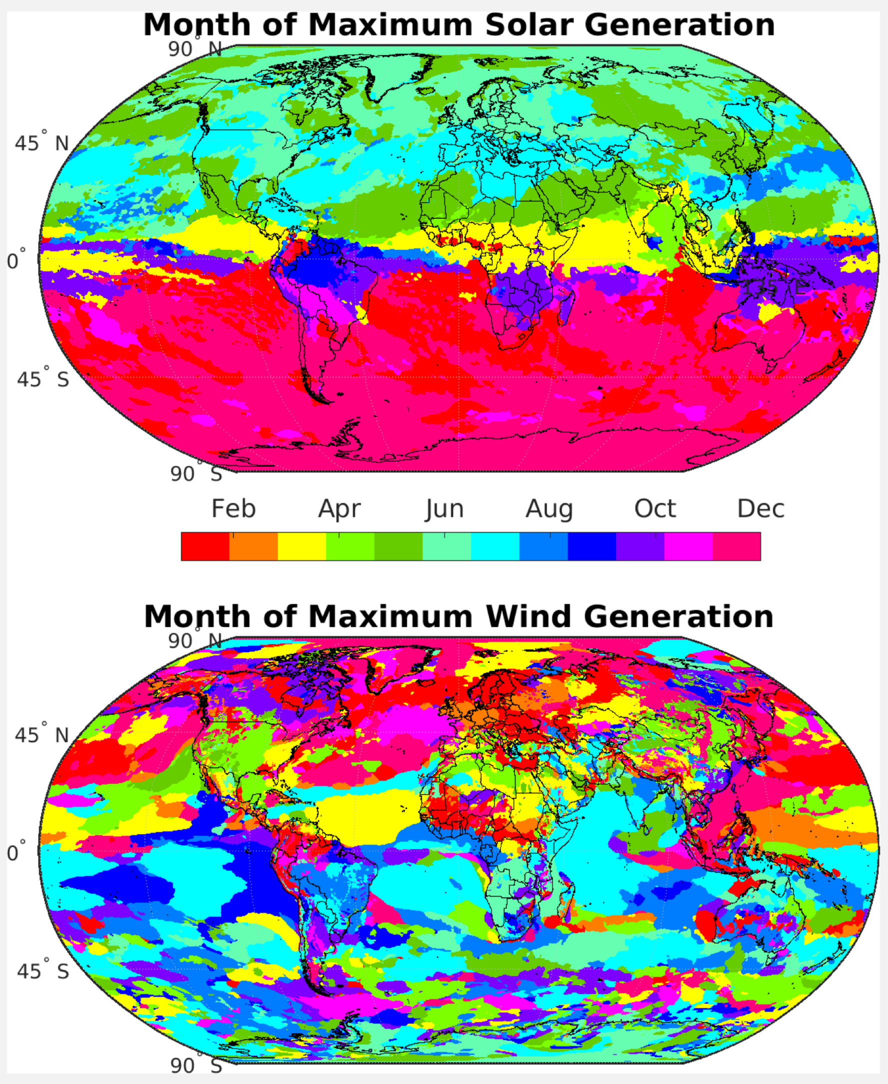

Figure 1. Month of wind and solar generation peak

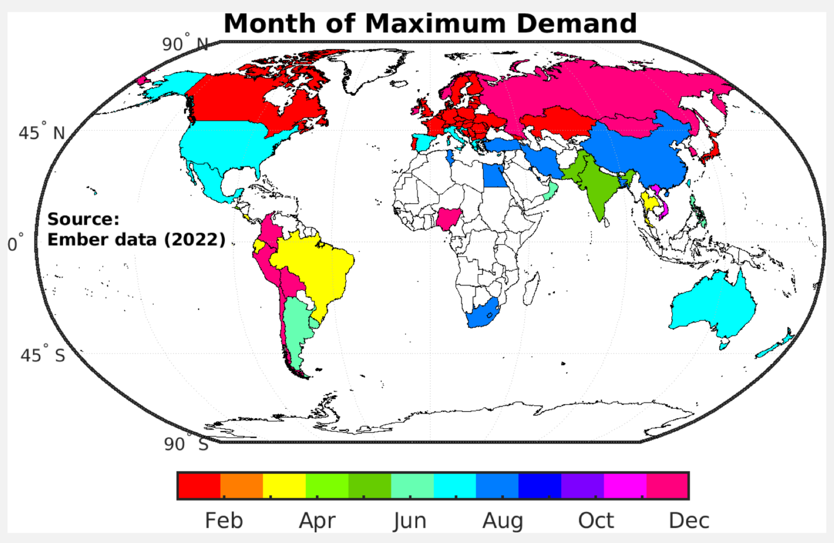

Figure 2. Month of electricity demand maximum

- Large electricity consumers (e.g., *China, US, India, and Brazil)* experience peak electricity during northern summer.
- Most *high latitude northern* countries experience higher demand in northern winter.
- Many large electricity consumers experience nearly 40 percent variation in electricity demand between seasons.

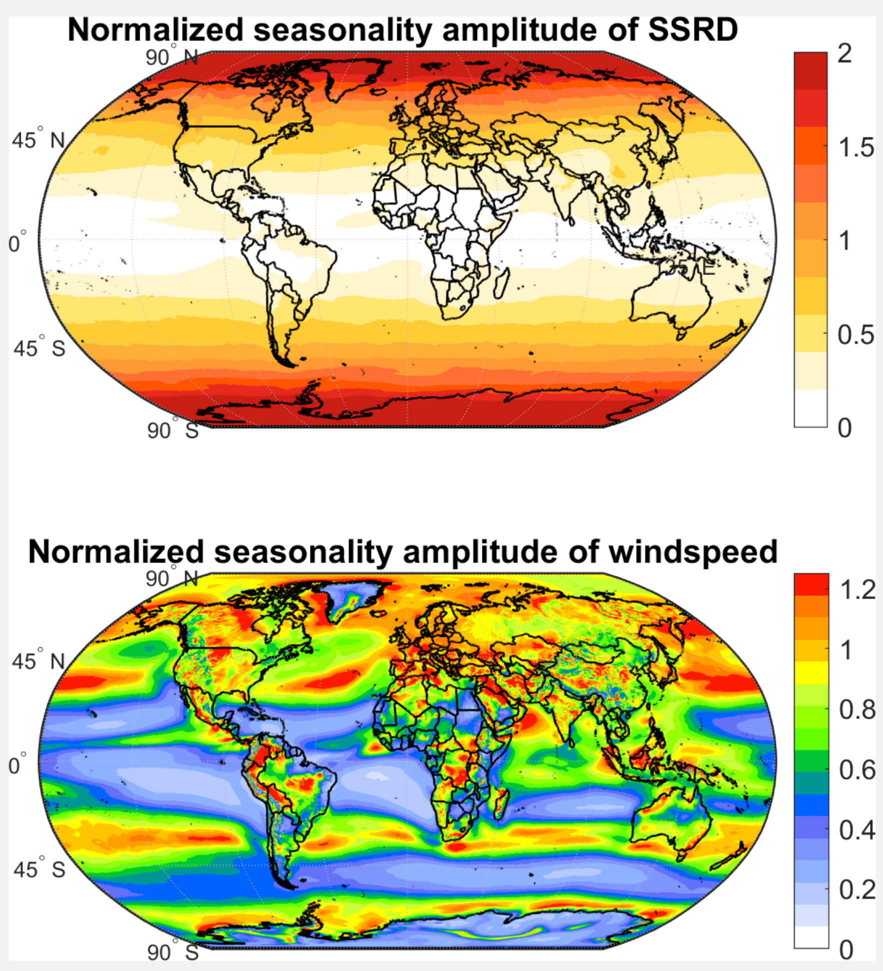

Figure 3. Seasonality amplitude of wind and solar

- Large amplitude seasonal cycle of surface downward solar insolation (SSRD) (Figure 3) at higher latitudes occurs due to the seasonal evolution of solar insolation.
- The potential for solar generation during the *summer* is high at *higher latitude regions*.
- The spatial structure of wind seasonality is complicated by various coupled feedbacks in the Earth's climate system.
- Despite that, large seasonal amplitudes are also present in wind generation (Figure 3), with tropical regions experiencing high winds during summer associated with monsoons.
- In the *high-latitude regions*, windspeed and corresponding wind generation is largest during the *winter season.*

Solutions: Wind:Solar:Storage

Solutions to bridge large seasonal variations in demand and generation present critical challenges. A few options are,

- Long-duration bulk energy storage
- Excess of wind and solar capacity
- Renewable portfolio design
- Demand-side management

$$Demand_{monthly} = a \times Wind_{generation} + b \times Solar_{generation} + \varepsilon \quad ...Eq. (1)$$

To explore the necessity of long duration storage, we develop a simulation model (Eq. (1)). Based on daily generation, the model aims to meet the existing electricity demand in 73 countries using wind, solar and storage for a typical year (2022) (Figure 4).

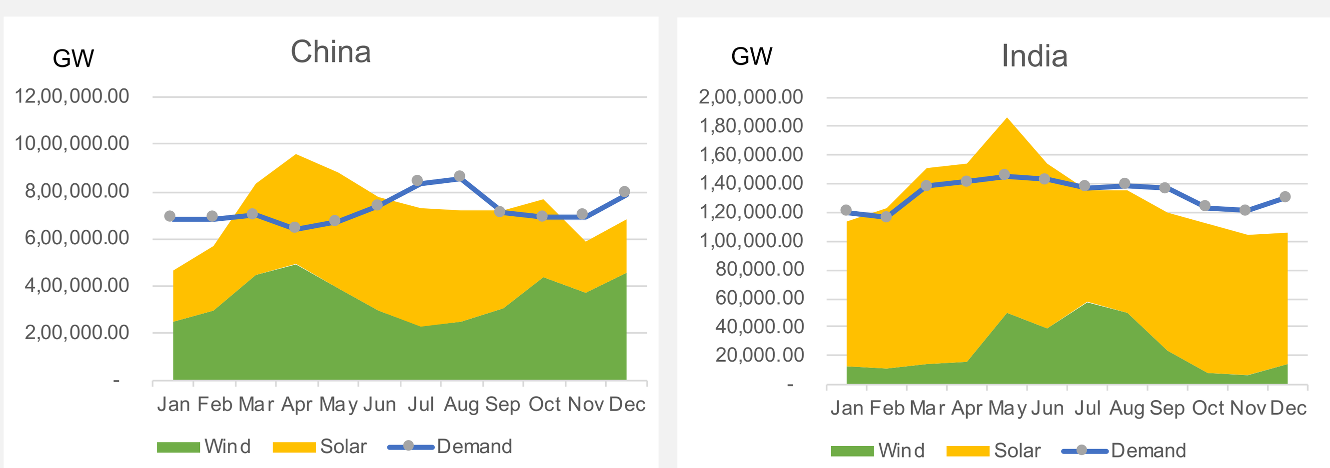

Figure 4. Excess – deficit balance

Solutions: Scenarios

The optimal wind-solar ratio that helps achieve excess-deficit balance for the year using minimum long-duration storage varies from country to country (Figure 5). While the optimal energy mix in tropics is solar heavy, wind becomes vital for countries in extra tropics. Figure 6 shows the normalized storage requirement in optimal scenario.

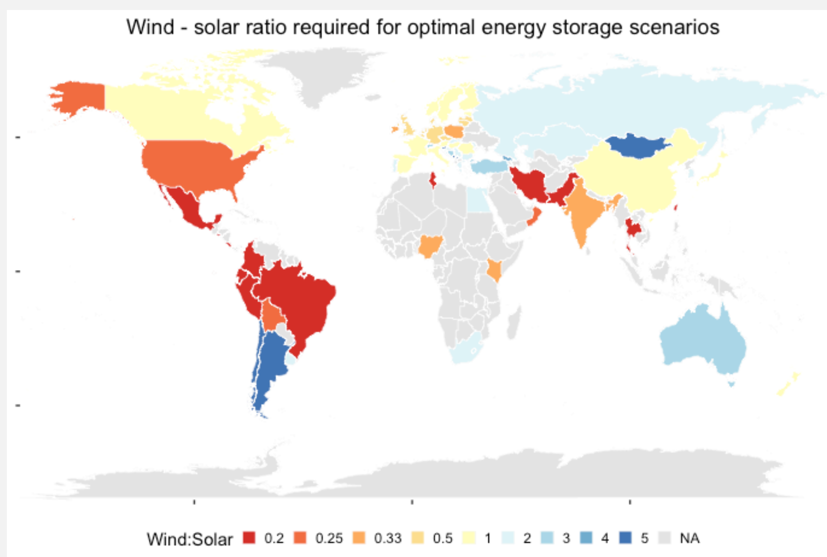

Figure 5.Optimal wind-solar ratio to minimize long-duration storage

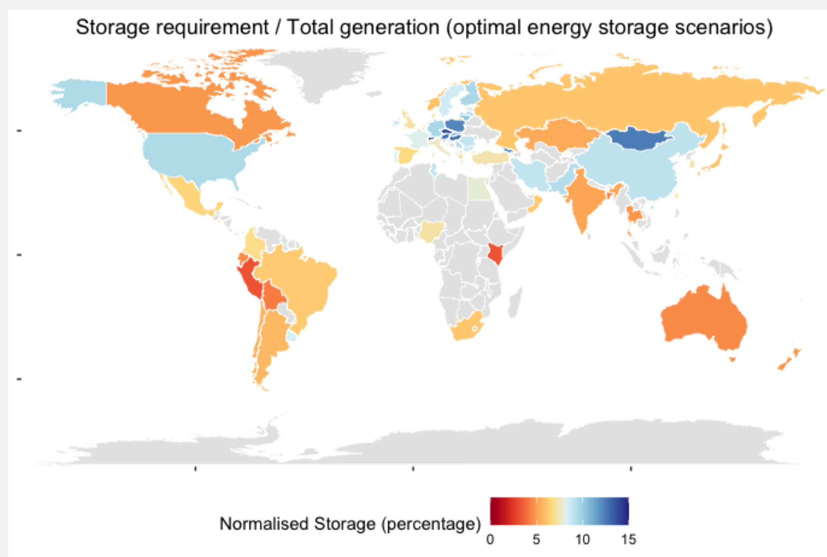

Figure 6. Normalized storage requirement (Storage requirement / Total generation, in percentage) in optimal scenario

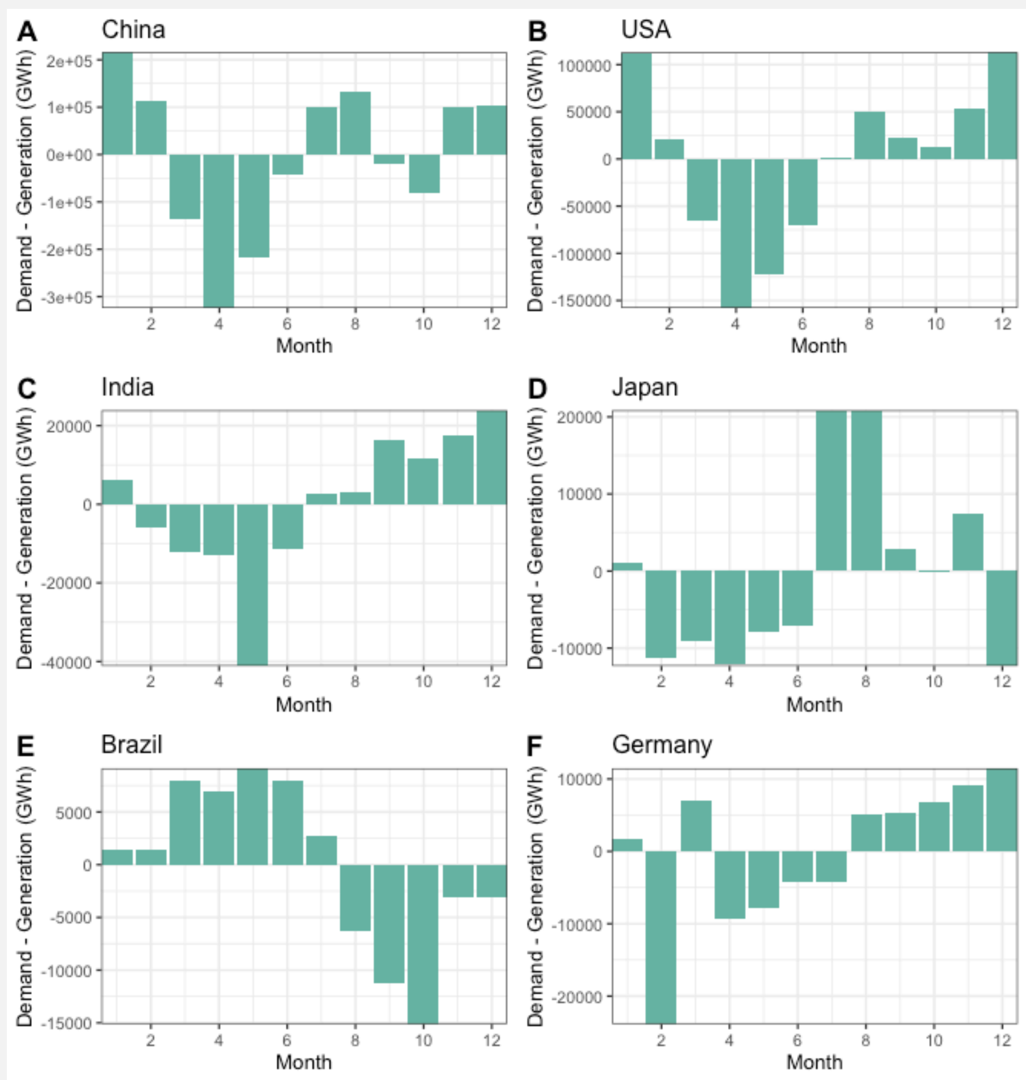

Figure 7. Energy excess and deficits occur in consecutive months even in the optimal storage scenario

Long-duration bulk storage is essential across countries, as there are consecutive months having excess generation with other consecutive months with deficit (Figure 7).

The model (Eq. (1)) shows that replacing bulk storage with installation of additional wind-solar is *extremely challenging*, needing *1.5 times* wind-solar capacity in more than *35% countries.*

Discussion

- Addressing seasonal variation in electricity demand with wind - solar generation alone is challenging.
- Modifying the electricity demand using Demand side management (DSM) is sector specific; can be useful at smaller time scales (hour or day) for smaller regions; DSM needs further analysis to ascertain its efficacy in seasonal scale at country level (Williams et al., 2023).
- Different technologies for bulk long-duration (seasonal) storage that must be modelled are Thermal storage, Hydrogen storage, Compressed air storage, and Battery storage.

Conclusion

Bridging seasonal-scale gaps and balancing the impacts of various manifestations of seasonality remains an important roadblock towards net zero electricity systems worldwide, and it is essential to survey and model the most promising long-duration storage solutions.

References

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