Power System Planning: Advancements in Capacity Expansion Modeling

What Is Capacity Expansion Modeling?

An electricity capacity expansion model (CEM) is a tool or suite of tools used in long-term planning studies for the power sector. CEMs are used to identify the least-cost mix of power system resources, taking into consideration factors such as new policies, technological advancement, changing fuel prices, and electricity demand projections, among other factors. In many power systems globally, CEM analysis serves as a key tool for the development of power sector master plans or integrated resource plans. **Figure 1** shows results from a recent CEM study for the state of Tamil Nadu.

The Role of CEMs in Long-Term Planning

A CEM is one tool in the broader power sector planning process. CEMs are not suited for planning the technical details of grid operations. Other tools, including production cost models, power flow models, and power system dynamic stability simulations are needed alongside CEMs to capture the full spectrum of grid planning and operations. Also, questions related to the social justice and environmental impacts of power sector development are outside the scope of CEMs. These factors can be addressed with a robust stakeholder engagement process that includes diverse perspectives from civil society organizations and public advocates.

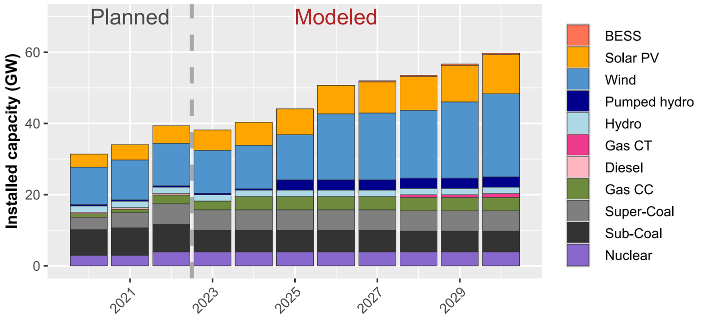


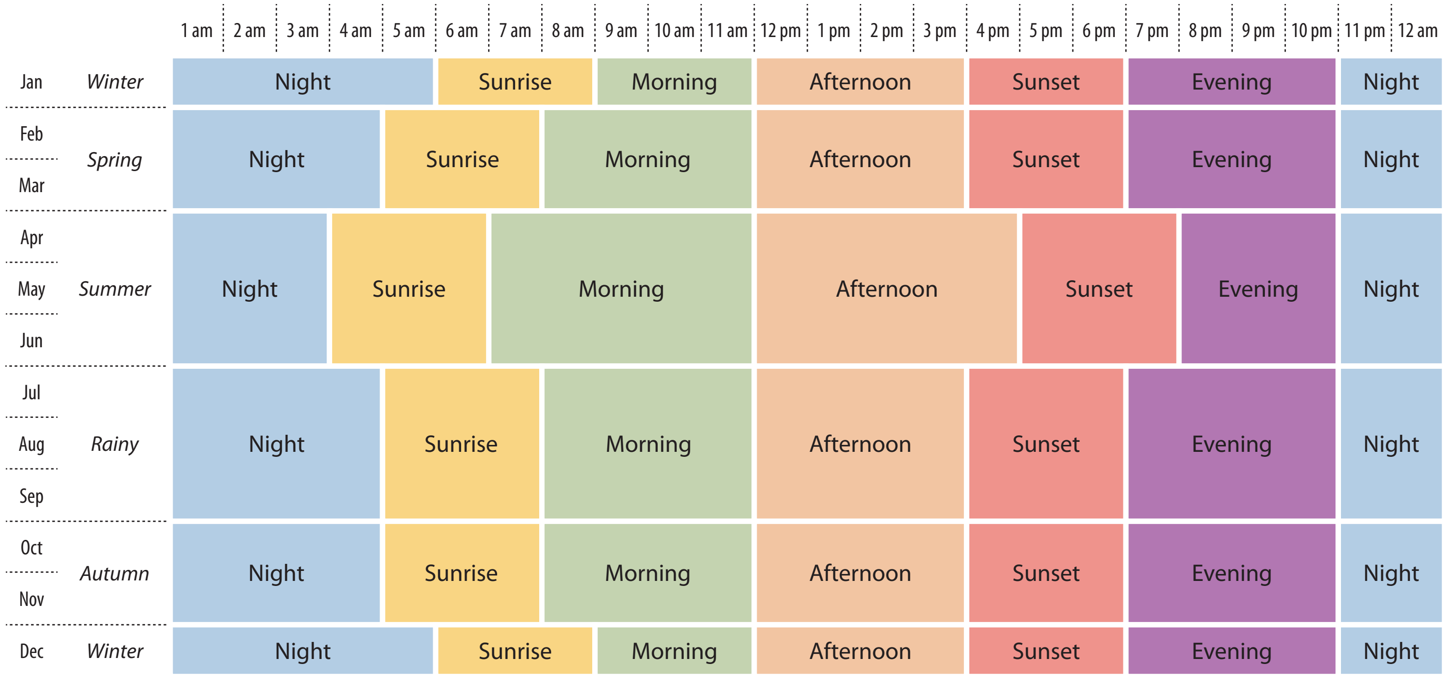
Figure 1. Example CEM results (Rose et al. 2021)

Advancements in CEMs

Emergence of cost-effective clean energy and energy storage technologies, increasing opportunities for demand-side management, increasing availability of low-cost computational resources, and improved access to high-quality data in the last two decades have led to increasing complexity in CEM analysis. These advancements allow CEMs to more precisely answer questions about where, when, and what types of power sector investments will be cost-effective. The list below presents nine key areas in which CEMs are improving to answer more complex power system questions.

1. Increased Temporal Resolution

Increased temporal resolution is a key advancement that helps CEMs to better represent the potential contribution of wind, solar, and hydropower resources and to capture changing patterns in electricity demand. Some state-of-the-art CEMs use multiple periods, also known as **time-slices**, to capture changing system conditions throughout the day and between seasons. The ReEDS-India CEM model developed by NREL uses a total of 35 time-slices per year that represent different times of the day and year



Month	Season	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm	12 am
Jan	*Winter*	Night					Sunrise			Morning			Afternoon				Sunset			Evening				Night	
Feb Mar	*Spring*	Night				Sunrise			Morning				Afternoon				Sunset			Evening				Night	
Apr May Jun	*Summer*	Night			Sunrise			Morning					Afternoon					Sunset			Evening			Night	
Jul Aug Sep	*Rainy*	Night				Sunrise			Morning				Afternoon				Sunset			Evening				Night	
Oct Nov	*Autumn*	Night				Sunrise			Morning				Afternoon				Sunset			Evening				Night	
Dec	*Winter*	Night					Sunrise			Morning			Afternoon				Sunset			Evening				Night	

Figure 2. Example of temporal resolution in a CEM

to capture important chronological relationships between power system components (see **Figure 2**). The sunset time-slice, for example, can capture when solar generation is waning and other resources are needed to ramp up to meet evening peak demand.

Other approaches include using representative chronological periods and using randomly sampled periods to better capture system conditions that drive investment decisions. In general, increasing the temporal resolution helps CEMs better capture the contribution of variable resources and reliability considerations and can ultimately result in a more robust plan for the power sector.

2. Increased Geographic Resolution

Representing multiple geographic areas in a CEM can help capture synergies and challenges related to location-specific patterns of wind speeds, solar resources, hydropower availability, and electricity demand. Conventional resources can also be location-specific. In India, for example, charges for coal fuel transportation make coal-fired power plants more expensive to run in states that are far from major coal mines. In general, geographic resolution in a CEM should, at minimum, reflect the scale at which decisions are made. State-level planning, for example, can represent multiple control areas, also known as **balancing areas**, within the state to inform local planning decision by state agencies. National-level planning, on the other hand, can have a coarser geographic resolution but cover a larger geographic scope. In more advanced CEMs, the geographic resolution can be split into multiple levels (see **Figure 3**). The ReEDS-India model, for example, has six regions comprising 34 balancing areas, each representing a state or union territory with aggregated electricity demand, conventional generation capacity, and transmission. Balancing areas are further divided into renewable energy (RE) resource regions, each providing a unique supply curve and representative generation profile for wind and solar resources within the given geographic area.

Importantly, CEMs with more balancing areas can better represent the transmission system. Capturing transmission constraints can provide important insights for long-term planning, both for generation and transmission investment decisions. However, increasing the number of transmission linkages in a CEM can significantly increase the computational resources and time required to complete a study. This trade-off should be carefully considered when selecting the geographic resolution of a CEM.

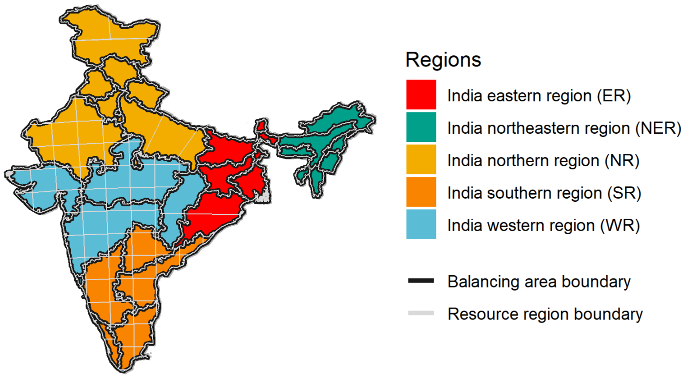


Figure 3. Example of geographic resolution in a CEM

3. Representing RE Resource Variability

Modern CEMs can capture the energy value and capacity contribution of variable RE resources as a function of RE penetration and evolving grid composition. Accounting for the energy and capacity contribution of RE to meet system requirements is important for two reasons: (1) failure to include their contribution can lead to an overbuilt system where other resources are deployed—but not necessarily needed—to meet system needs; and (2) as more variable RE is added in the system in the same location, the contribution of each additional unit to meet energy and capacity needs declines (Denholm et al. 2016).

For system energy requirements, the declining value of variable RE is related to the timing of energy supply and demand. For example, in the middle of the day when solar energy is highest, overgeneration from solar photovoltaics (PV) can cause electricity supply to exceed demand. This results in **curtailment** (i.e., when excess RE cannot be used). Typically, some amount of curtailment will be cost-effective in most power systems. The goal of a CEM is not to achieve a zero-curtailment scenario. Instead, a CEM can identify the level of curtailment that can be expected given the least-cost mix of resources for a particular power system.

CEMs also help ensure that future investment decisions will meet system adequacy requirements. Conventional resources like coal- and gas-fired power plants typically have a **capacity credit** close to 100%, meaning most of their installed capacity counts towards system adequacy and reliability requirements. The capacity credit of wind, solar, and some hydropower resources, on the other hand, is location- and time-dependent and requires more sophisticated approaches to quantify accurately. State-of-the-art CEMs can capture these trends to assess the most cost-effective mix of capacity resources needed to ensure system adequacy in the future.

Variability of RE resources can also impact the **operating reserves** needed to maintain grid reliability during normal operations and contingency events. Power systems with a high share of wind generation, for example, can require additional grid operating reserves during high-wind periods to manage short-term variability and uncertainty due to generation forecast errors. In some systems, it may be necessary to represent multiple types of operating reserves that are needed at different timescales, including spinning, non-spinning, and contingency reserves, or other categories. Advanced CEMs can represent multiple categories of operating reserves and dynamically adjust the required levels based on the contribution of RE. This capability helps power system planners avoid over- or under-investment in generation capacity that will provide operating reserves.

4. Energy Storage Technologies

Energy storage presents new complexities for CEMs because it is a source of both electricity demand and supply, and because storage operations are energy-limited (i.e., limited duration). Full representation of energy storage grid services, also described as **value streams**, is an active and ongoing effort in state-of-the-art CEMs. Importantly, the value of energy storage for providing different grid services changes both with the amount of storage deployed and with the amount of RE, particularly solar PV, on the grid. These competing factors are increasingly important to represent in long-term planning studies as the cost of both storage and solar PV technologies continues to decline.

Also, recent advancements in CEMs provide insights about the cost-effective duration for energy storage. The duration of an energy storage device is the amount of time the system can discharge from storage at full power output capacity. CEMs that represent different durations of energy storage can indicate which durations of energy storage are cost-effective in the near-term, when and where longer-duration devices may be advantageous, how much RE curtailment can be recovered, as well as their contribution to meeting capacity adequacy requirements.

5. Demand Response, Electric Vehicle, and Distributed Energy Resource Representation

Recent advancements in CEMs are enabling power system planners to consider even greater changes to future electricity supply and demand stemming from **demand response** and the adoption of **electric vehicles** (EVs) and **distributed energy resources** (DERs). Demand response is the voluntary reduction and/or shifting of electricity demand by end users, whether they be industrial, commercial, or residential. In some cases, rather than build new generation resources to meet growing electricity demand, it may be more cost-effective to incentivize end users to reduce their demand for certain hours. Incorporating demand response in CEMs requires detailed data and assumptions about the potential for and cost of demand response in a given area. Adoption of EVs can also have significant implications for future electricity demand and supply. Growing demand for EV charging can shift the pattern of electricity demand and can drive higher rates of growth in total electricity demand. It will be increasingly important for CEMs to capture the impacts of EVs on future electricity demand, as well as potential opportunities for EVs to provide demand response and other grid services.

On the supply side, increasing adoption of DERs such as rooftop PV systems or behind-the-meter battery storage by utility customers can offset the need for centralized, utility-scale resources. However, because decisions about demand response, EV adoption, and DER investments are made by end-use customers, CEMs must extend their scope or rely on inputs from other modeling tools that can capture and aggregate individual customer investment decisions. This type of cross-sectoral model linkage, between models of the bulk power system, the distribution grid, and individual customers, will be increasingly important as costs for EVs and DER technologies continue to decline.

6. Climate Change Impacts

Climate change can have significant impact on power sector resources. Hydropower generation in India, for example, is projected to be impacted by increased streamflow, earlier snowmelt, and increased seasonal variability of hydro resources due to climate change (Ali et al. 2018). Other potential impacts include increased frequency of extreme weather events, increased cooling demand, increased climate variability (i.e., extreme dry and wet years), and increased fire risk, among others. CEMs that include the potential impacts of climate change on the power sector can help to identify investments that promote **climate resilience** (i.e., the ability to maintain reliable power supply during extreme events as well as longer-term climate impacts).

7. Technologies for Deep Decarbonization

Emerging technologies can play a crucial role in reducing the carbon intensity of power systems as legacy fossil-fueled power plants are retired. To meet future power sector decarbonization targets, CEMs can include various emerging technology options, such as:

- Alternative fuels including green hydrogen, biofuels, and synthetic methane
- Seasonal energy storage
- Carbon Capture and Storage
- Direct Air Capture.

CEMs can help identify which decarbonization technologies will be cost-effective under various cost and performance assumptions. However, costs and performance characteristics for emerging technologies can be highly uncertain and will change over time as they become commercialized. Some emerging technologies may also have constraints that require other modeling tools or CEMs with extended scopes to fully capture **multisectoral interactions**. For example, green hydrogen and other alternative fuels may require new pipelines and storage fuel facilities to supply both power sector and industrial needs, and cost-effectiveness of green hydrogen production can depend on demand for hydrogen from different sectors of the economy. These interactions are discussed further in the next section.

8. Linkages Across Energy Sectors

As policymakers pursue increasingly low-carbon power systems, it is increasingly important to understand how the power sector interacts with other energy sectors that drive the economy. Energy sectors that have significant interactions with the power system include water, industry, buildings, and transportation. Prices for fossil fuels, for example, can depend on fuel demand in the power sector as well as demand from heavy industries, commercial and residential buildings, and the transportation sector. Linking electricity CEMs with modeling tools for other energy sectors can help achieve lower-cost pathways for **economy-wide decarbonization**.

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