RECAP
Probabilistic Loss of Load Model

Documentation

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Energy+Environmental Economics

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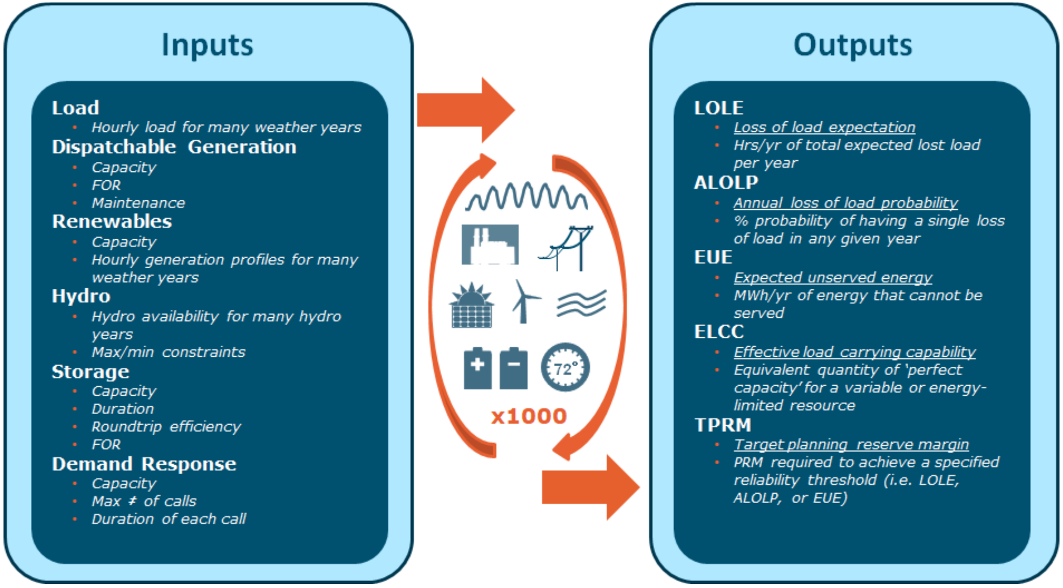
1 Background

E3's **Renewable Energy Capacity Planning Model (RECAP)** is a loss-of-load-probability model designed to evaluate the resource adequacy of electric power systems, including systems with high penetrations of renewable energy and other dispatch-limited resources such as hydropower, energy storage, and demand response. RECAP was initially developed for the California Independent System Operator (CAISO) in 2011 to facilitate studies of renewable integration and has since been adapted for use in many jurisdictions across North America.

RECAP evaluates resource adequacy through time-sequential simulations of thousands of years of plausible system conditions to calculate a statistically significant measure of system reliability metrics as well as individual resource contributions to system reliability. The modeling framework is built around capturing correlations among weather, load, and renewable generation. RECAP also introduces stochastic forced outages of thermal plants and transmission assets and time-sequentially tracks hydro, demand response, and storage state of charge.

Figure 1.1 provides a high-level overview of RECAP including key inputs, Monte Carlo simulation process, and key outputs.

Figure 1.1. RECAP model overview



Inputs

Load
- *Hourly load for many weather years*

Dispatchable Generation
- *Capacity*
- *FOR*
- *Maintenance*

Renewables
- *Capacity*
- *Hourly generation profiles for many weather years*

Hydro
- *Hydro availability for many hydro years*
- *Max/min constraints*

Storage
- *Capacity*
- *Duration*
- *Roundtrip efficiency*
- *FOR*

Demand Response
- *Capacity*
- *Max ≠ of calls*
- *Duration of each call*

Outputs

LOLE
- *Loss of load expectation*
- *Hrs/yr of total expected lost load per year*

ALOLP
- *Annual loss of load probability*
- *% probability of having a single loss of load in any given year*

EUE
- *Expected unserved energy*
- *MWh/yr of energy that cannot be served*

ELCC
- *Effective load carrying capability*
- *Equivalent quantity of 'perfect capacity' for a variable or energy-limited resource*

TPRM
- *Target planning reserve margin*
- *PRM required to achieve a specified reliability threshold (i.e. LOLE, ALOLP, or EUE)*

2 Model Inputs

RECAP is designed to allow loss of load probability simulation on a wide range of electricity systems that may comprise a diverse mix of generating resources, each with different constraints and characteristics that affect their availability to serve load at different times. The input data for RECAP, summarized in **Table** 2.1, enables a robust evaluation of loss-of-load-probability that can account for a broad variety of technologies and resource types, including:

- **Firm resources** capable of producing at their full rated capacity when called upon by operators (except during periods of maintenance and unforced outages)
- **Variable resources**, typically wind and solar, whose availability will vary on an hourly basis as a result of weather and solar irradiance patterns
- **Hydroelectric resources** that can be dispatched relatively flexibly but have constraints related to streamflow and underlying hydrological conditions
- **Pumped hydro resources** that operate similarly to hydroelectric resources with an additional, dynamically constrained pumped that will be dispatched to maximize reliability value, subject to underlying hydrological conditions, pump efficiency, and storage pond limits
- **Storage resources** that can be dispatched flexibly but have limited durations across which they are available due to limits on state of charge
- **Hybrid resources** that model renewables + storage paired operations, optionally allowing renewable-only charging and modeling of the resource behind a single interconnection point

- **Flexible loads** that can shift loads up/down to reduce unserved energy within a defined “shifting window”
- **Demand response programs** that can be called upon as a last resort by operators to maintain reliability but typically have limits on the frequency and duration of calls that vary depending on the type of program

Table 2.1. RECAP model inputs

Module	Inputs Needed
Load	• Annual energy demand • Annual 1-in-2 peak demand • Hourly profiles corresponding to a wide range of weather conditions (20+ years)
Firm Resources (e.g. nuclear, coal, gas, biomass, geothermal)	• Installed capacity by resource • Forced outage rate by resource • Maintenance profiles by resource
Variable Resources (e.g. wind, solar, run-of-river hydro)	• Installed capacity by resource • Hourly profiles for multiple years, ideally including multiple years of overlap with hourly load profile data
Imports/Market Purchases	• Assumed level of imports available from external markets available to contribute to portfolio reliability needs
Hydroelectric Resources	• Installed capacity by resource • Monthly/daily energy budgets across a range of plausible hydro conditions • Minimum output levels by month/day • Sustained peaking limitations by month/day
Pumped Hydro Resources	• Installed capacity by resource • Monthly/daily energy budgets across a range of plausible hydro conditions • Minimum output levels by month/day • Sustained peaking limitations by month/day • Pump efficiency • Storage pond limit
Storage Resources **(e.g. batteries, pumped storage)**	• Installed capacity by resource • Storage reservoir size by resource • Charging & discharging efficiency by resource
Hybrid Resources	• Installed storage charging & discharging capacity by resource • Installed storage reservoir size by resource • Charging & discharging efficiency by resource • Paired variable resource (from variable resources above) • Interconnection configuration (single interconnection or separate)

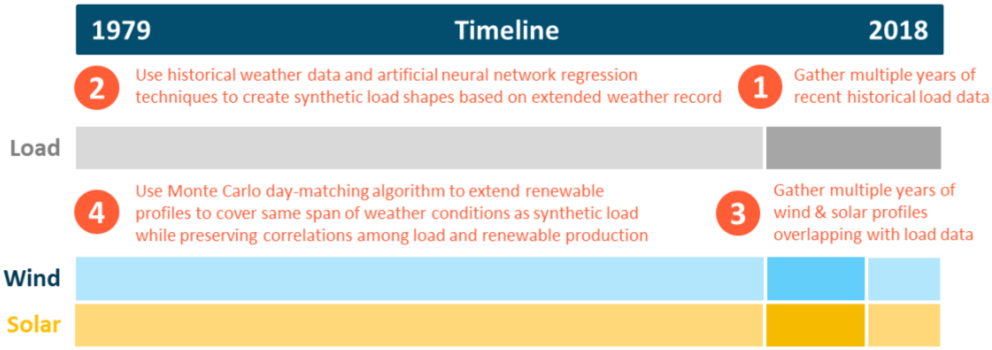
	• Interconnection rating (either single interconnection or storage & paired generation interconnections) • Grid-charging allowed
Flexible Loads	• Program size by program • Max shift hours • Rebound factor (similar to storage roundtrip efficiency loss)
Demand Response Resources	• Program size by program • Limits on program calls (e.g. number of calls per year/month/day, length of calls) • Load shift window (e.g., hours before/after call to shift energy from, only applicable to “shifting” DR resources)

3 Methodology Description

3.1 Load & Renewable Simulation

Generating an extensive record of load and renewable profiles that capture both the range of variability of each as well as the key correlations between them is a necessary but challenging step in reliability modeling. To generate such a record, RECAP relies upon historical time-synchronous load and renewable profiles but also uses statistical approaches to extend what is typically a limited historical record. The four-step process used in RECAP is shown in **Figure** 3.1.

Figure 3.1. Illustration of processes used to generate load & renewable profiles for RECAP



Step 1. Gather historical load data for multiple recent years

The hourly and seasonal patterns of load are typically captured in RECAP through the actual observed patterns of hourly load metered by utilities, RTOs, or others. In general, multiple years of recent historical load data (5-10 years) is collected to provide a reasonable breadth of potential underlying weather conditions.

Step 2. Use neural network regression to simulate hourly loads across long-run weather record

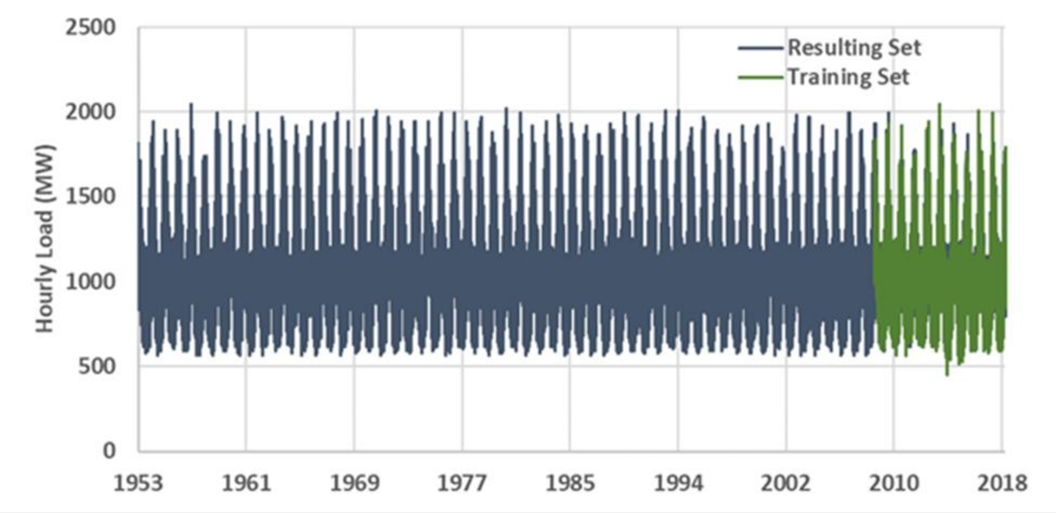
Typically, the availability of historical hourly load data that can be practically incorporated into RECAP is limited—both by data availability and by the fact that historic load shapes from previous years may not appropriately reflect the composition of end uses and customers that make up today's system (an issue that becomes increasingly pronounced farther back in time). At the same time, a rigorous approach to measuring reliability requires consideration of a breadth of potential weather conditions.

To allow consideration of a broad range of potential weather conditions observed across multiple decades in spite of the lack of useful historical load data during most of that period, RECAP uses a neural network regression algorithm to extend a relatively shorter sample of actual historical load data across a longer period based on key weather indicators and drivers across that longer period. The neural network algorithm is trained with a set of historical loads and associated underlying weather data and then used to simulate load levels that reflect the composition of end uses and the underlying economic conditions that reflect today's electricity demands while also capturing the underlying weather conditions across a much broader record. The key variables included in the neural network regression include:

- Daily minimum and maximum temperatures at multiple weather stations;
- An indicator for month (+/- 15 days);
- A flag for day-type (weekend vs. weekday);
- A day index to account for any growth observed during the training period.

Figure 3.2 shows an example of the results of this process. The resulting shape can be scaled upward or downward to the appropriate level of annual and peak demand to match a future system's expected demand growth.

Figure 3.2. Example of results of neural network regression to extend load across long weather record



Step 3. Gather historical (or simulated) renewable profiles for multiple recent years

Multiple years of actual and/or simulated hourly profiles for wind and solar resources are a key input to RECAP. Whenever possible, actual historical metered data is preferred, but in its absence (given the relatively small amount of renewable generation existing today), simulated hourly profiles from sources like NREL's WIND Toolkit and NREL's System Advisor Model provide coverage across multiple historical years (2007-'12 and 1998-'18, respectively). Several considerations are important in developing this data set:

- Hourly profiles should capture multiple years. The potential variability of renewable generation, particularly during periods of extreme load, is high enough that a single year may not appropriately capture its expected production during those periods. Therefore, multiple years (typically at least four) are needed.
- Hourly profiles should correspond to a period for which load data is also available. Developing a dataset of load and renewables that is weather-matched based on actual historical conditions allows the modeling to account for the actual observed correlations between load and renewables.
- Hourly profiles for wind and solar should (ideally) cover the same historical period. Like above, this allows the model to preserve actual observed correlations

between wind and solar—not just between load and each renewable technology independently.

Step 4. Use a probabilistic day-matching algorithm to match renewable profiles to extended weather record

A stochastic rolling day-matching algorithm is used to match the limited sample of renewable profiles with the extended record of simulated load data using the observed relationship for years with overlapping data i.e., years with available renewable data. The day matching algorithm, illustrated in **Figure** 3.3, selects a renewable profile for each day of the simulation based the corresponding level of load in that day and the level of renewable generation in the prior day(s).[1] The potential sample of renewable profiles from the historical record that are considered as potential matches for each day in the extended record is also restricted to days within +/- 15 calendar days of that day to ensure that seasonal factors (e.g. variations in patterns of insolation, which affects solar production on a seasonal basis) are also accounted for in the process. Ideally, this day matching algorithm can be run on both wind and solar profiles simultaneously—this is possible when the historical records for wind and solar profiles are contiguous—but the algorithm can also be run independently on wind and solar if overlapping records are not available.

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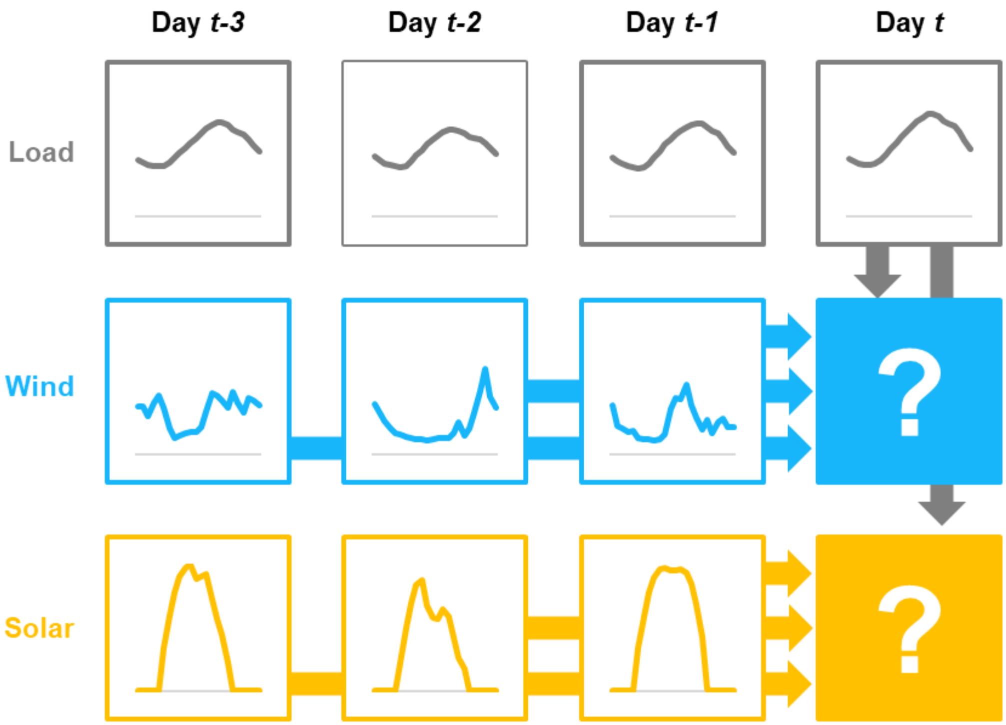
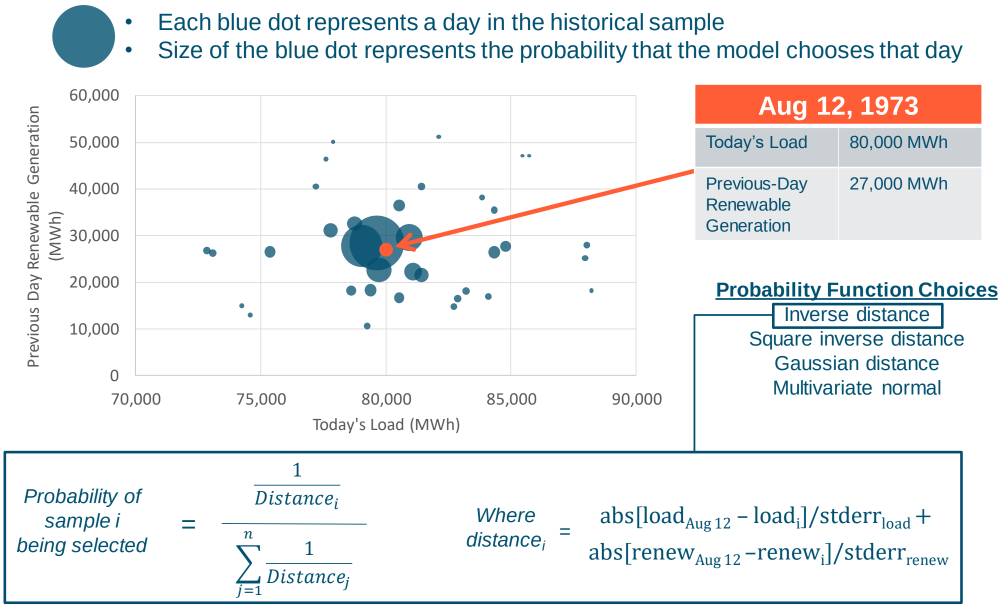
[1] The number of prior days' renewable generation included in the matching algorithm can be varied as needed to ensure that extended weather events observed in the historical record (e.g. multi-day storm systems) occur within the stochastic simulation.

Figure 3.3. Illustration of day-matching algorithm used to extend record of renewable profiles to match loads



The algorithm used to select renewable profiles is a probabilistic one that allows for stochastic pairings of load and renewable shapes—in other words, multiple plausible combinations of load and corresponding renewable profiles are generated for the extended weather record. The probability that any specific day from the historical weather record will be selected as a match is based on an inverse distance algorithm that measures the similarity between each possible day of renewable profiles in the historical record and the desired day in the longer record and assigns a probability to each one. **Figure** 3.4 illustrates the assignment of probabilities for a specific individual day; the days in the historical record that are "closest" to that day (in terms of that day's load and the previous day's renewable generation) are assigned the highest probability.

Figure 3.4. Renewable profile selection process



- Each blue dot represents a day in the historical sample
- Size of the blue dot represents the probability that the model chooses that day

Aug 12, 1973	
Today's Load	80,000 MWh
Previous-Day Renewable Generation	27,000 MWh

Probability Function Choices

Inverse distance
Square inverse distance
Gaussian distance
Multivariate normal

$$\text{Probability of sample } i \text{ being selected} = \frac{\frac{1}{Distance_i}}{\sum_{j=1}^{n}\frac{1}{Distance_j}}$$

$$\text{Where } distance_i = \mathrm{abs}[\mathrm{load}_{\mathrm{Aug\,12}} - \mathrm{load}_i]/\mathrm{stderr}_{\mathrm{load}} + \mathrm{abs}[\mathrm{renew}_{\mathrm{Aug\,12}} - \mathrm{renew}_i]/\mathrm{stderr}_{\mathrm{renew}}$$

3.2 Loss of Load Probability Simulation

Based on the inputs described above, RECAP simulates the loss of load probability for an electric system using a Monte Carlo approach to capture plausible combinations of load, variable renewables, and outages across hundreds of potential years. For each broad class of resource enumerated above, RECAP includes a module that evaluates the ability of each resource in that class to contribute to load in each hour of the simulation. The methodology used in each module is presented in **Table** 3.1.

Table 3.1. Overview of methodology used to compare load and resource availability

Module	Methodology
Load	The hourly profile of electricity demand is determined based on an hourly load shape that covers a broad range of historical weather conditions (multiple decades) that is scaled to the desired level of annual and peak demand. The underlying load shape itself is a result of a pre-processing neural network regression that simulates hourly load shapes for the full available weather record based on recent historical loads and a longer record of weather data.
Firm Resources (e.g. nuclear, coal, gas, biomass, geothermal)	Available dispatchable generation is calculated stochastically in RECAP using forced outage rates (FOR) and mean time to repair (MTTR) for each individual generator. These outages are either partial or full plant outages based on a distribution of possible outage states. Over many simulated days, the model will generate outages such that the average generating availability of the plant will yield a value of (1-FOR).
Variable Resources (e.g. wind, solar, run-of-river hydro)	Availability of variable renewable resources is simulated stochastically based on the rolling probabilistic day-matching algorithm described above. This results in an hourly timeseries profile for all variable resources that aligns with the hourly load profile.
Imports/Market Purchases	Availability of generic resources from external areas (i.e. assumed wholesale market purchases) can be specified at an hourly, monthly, or annual level. This is an input to RECAP.
Hydroelectric Resources	To determine hydro availability, the model uses a monthly historical record of hydro production. For every simulated load year, a hydro year is chosen stochastically from the historical database. Associated hydro budgets are typically assigned on either a weekly or daily basis and then "dispatched" to minimize net load (load less variable resources and hydro) during that period while accounting for a number of constraints, including: • Minimum output levels that capture the lower limit on the level of generation that a system may produce when considering hydrological and other physical constraints on the system

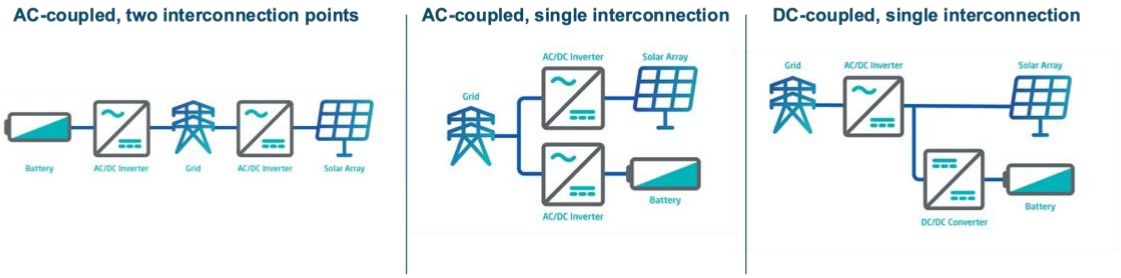
Module	Methodology
	• Sustained peaking limits, which limit the output of the hydro system across a range of rolling time windows (e.g. 1-hour, 2-hour, 4-hour, and 10-hour) to capture how hydrological factors may limit the ability to discharge water through a dam for sustained periods of time.
Pumped Hydro Resources	Pumped hydro resources may be modeled as storage resources (described in next line of the table). Alternatively, RECAP can model pumped hydro storage as two interrelated components, an underlying hydro resource and a dynamically constrained pump: 1. To determine hydro availability, RECAP stochastically selects a hydro year from the historical record to determine monthly hydro energy budgets. Associated hydro budgets are typically allocated on either a weekly or daily basis (RECAP can accommodate time periods of any length) and then dispatched to minimize net load (load less variable resources and hydro) during that period while accounting for a number of constraints (such as minimum output levels based on hydrological and other physical constraints on the system). 2. Once an initial hydro dispatch is determined based on applicable budget and operating constraints, RECAP calculates on an hourly basis whether there is residual generation capacity available to serve the incremental pumping load and whether there is additional output capacity in the dam to discharge pumped water, subject to pumping efficiency and maximum storage limits.
Storage Resources (e.g. batteries, pumped storage)	The model dispatches storage if there is insufficient generating capacity to meet load net of renewables and hydro. Storage is reserved specifically for reliability events where load exceeds available generation. It is important to note that storage is not dispatched for economics in RECAP which in many cases is how storage would be dispatched in the real world. However, it is reasonable to assume that the types of reliability events that storage is being dispatched for (low wind and solar events), are reasonably foreseeable such that the system operator would ensure that storage is charged to the extent possible in advance of these events. (Further, presumably prices would be high

<table>
<tr><th>Module</th><th>Methodology</th></tr>
<tr><td></td><td>during these types of reliability events so that the dispatch of storage for economics also would satisfy reliability objectives).</td></tr>
<tr><td>**Hybrid Resources**</td><td>

Hybrid resources in RECAP are modeled as two separate resources: (1) a paired “supply” resource (typically solar) and (2) a paired storage resource. These basic dispatch logic for each component remains the same as if they were standalone (described above), with additional operational constraints:

- If configured behind a single interconnection point, the total net generation of the system cannot exceed the shared interconnection.
- If configured to be grid-charging, the storage component is allowed to charge either from grid energy or from the paired supply resource. Otherwise, energy can only be stored by charging from the paired supply resource.

The input parameters available in RECAP are intended to model three common hybrid resource configurations:



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Module	Methodology
Flexible Loads	The model dispatches flexible loads as needed to further flatten the “net load” curve if there is still demand that has not been met by the previous resource classes. Flexible loads are able to shift energy for a certain number of hours based on the program definition and must be energy-neutral subject to rebound factor assumptions, which account for potentially higher MWh of loads shifted “up” relative to the amount of energy shifted “down” to reduce unserved energy in net load hours.
Demand Response Resources	The model dispatches demand response if there is still insufficient generating capacity to meet load even after storage. Demand response is the resource of last resort since demand response programs often have a limitation on the number of times they can be called upon over a set period of time.

To the extent the portfolio of resources whose availability is determined through the steps above is insufficient to meet demand in any hour, a loss of load event is recorded. After simulating hundreds of years of possible Monte Carlo outcomes, RECAP calculates the system's LOLE and a variety of other reliability statistics.

3.3 Effective Load Carrying Capability Calculation

The simulation of LOLE for a given electric system enables the calculation of "effective load carrying capability" (ELCC) for individual resources, or, in more colloquial terms, their capacity value: a measure of the equivalent amount of "perfect capacity" that could be replaced with the addition of a specified resource while maintaining the same level of reliability. ELCC for individual resources (or combinations of resources) is calculated through iterative simulations of an electric system:

1. The LOLE for the electric system without the specified resource is simulated. If the resulting LOLE does not match the specified reliability target, the system "adjusted" to meet a target reliability standard (most commonly, one day in ten years). This adjustment occurs through the addition (or removal) of perfect capacity resources to achieve the desired reliability standard.
2. The specified resource is added to the system and LOLE is recalculated. This will result in a reduction in the system's LOLE, as the amount of available generation has increased.
3. Perfect capacity resources are removed from the system until the LOLE returns to the specified reliability target. The amount of perfect capacity removed from the system represents the ELCC of the specified resource (measured in MW); this metric can also be translated to percentage terms by dividing by the installed capacity of the specified resource.

This approach can be used to determine the ELCC of any specific resource type evaluated within the model. In general, ELCC is not widely used to measure capacity value for firm resources (which are generally rated either at their full or unforced capacity) but provides a useful metric for characterizing the capacity value of renewable, storage, and demand response resources.

The ELCC of a resource depends not only on the characteristics of load in a specific area (i.e. how coincident its production is with load) but also upon the resource mix of the existing system (i.e. how it interacts with other resources). For instance, ELCCs for variable renewable resources are generally found to be higher on systems with large amounts of inherent storage capability (e.g. large hydro systems) than on systems that rely predominantly on thermal resources and have limited storage capability. ELCCs for a specific type of resource are also a function of the penetration of that resource type; in general, most resources exhibit declining capacity value with increasing scale. This is generally a result of the fact that continued addition of a single resource or technology will lead to saturation when that resource is available and will shift reliability events towards periods when that resource is not available. The diminishing impact of increasing solar generation as the net peak shifts to the evening illustrates this effect.

3.4 Planning Reserve Margin Calculation

The results of RECAP can also be translated into a simpler and more widely used planning reserve margin requirement (PRM), a target for system reliability expressed as a percentage requirement above expected peak demand. PRM requirements are used by many utilities and RTOs in their administration of resource adequacy requirements. Thus, RECAP also expresses its outputs in terms of the PRM:

- The “actual” PRM of a system is calculated based on the summation of capacity provided by all resources; firm resources are rated at nameplate capacity, while hydro, variable, and use-limited resources are rated based on ELCC endogenously calculated as described above. This total amount of capacity is divided by the expected peak to provide a planning reserve margin.

- The “target” PRM of a system (i.e. the PRM needed to achieve a corresponding specified LOLE target) is calculated by adjusting the starting system as needed with perfect capacity resources to achieve the desired LOLE. The PRM for this adjusted system then represents the reserve margin needed to meet the comparable LOLE standard.

4 Key Model Outputs

A primary benefit of the RECAP model is the ability to produce an array of summary results that give insight into system reliability and the nature of frequency, magnitude, and duration of loss of load events on an electric system. The summary reliability statistics produced include:

- **Loss of load expectation (LOLE, measured in days per year),** the expected number of days in which loss-of-load events occur in each year;
- **Loss of load hours (LOLH, measured in hours per year),** the expected number of hours of lost load in each year;
- **Loss of load events (LOLEV, measured in events per year),** the expected number of reliability events that occur within each year;
- **Annual loss of load probability (ALOLP, measured in %),** the probability that at least one loss-of-load event will occur within a year; and
- **Expected unserved energy (EUE, measured in MWh per year),** the expected amount of unserved load within each year.

RECAP also produces a number of metrics that help translate these detailed reliability statistics into a more typical planning reserve margin framework. If the user specifies a specific reliability target (for example 0.1 days/yr LOLE, or "one day in ten years"), the model calculates the required quantity of capacity necessary to achieve that level of reliability through an internal search algorithm. Comparing the required quantity of capacity to the median (1-in-2) peak load yields the target planning reserve margin while comparing it to the quantity of existing firm capacity on the system yields a net capacity shortage. Included in this measure of firm capacity is the effective load carrying capability

(ELCC) of all non-firm resources including wind, solar, hydro, demand response, and battery storage.