

THE BOTTOM LINE

As countries generate more energy from renewable sources, that energy must be taken into account in the power-system planning process. However, because renewable sources such as wind and solar are variable and geographically dispersed, specific procedures are needed to ensure that the grids into which they are integrated can continue to meet demand reliably every minute of every day, now and in the future. With appropriate adaptations, the variable output of renewable energy sources can be incorporated into commonly used power planning models.

Incorporating Energy from Renewable Resources into Power System Planning

Why is this issue important?

As countries generate more energy from renewable sources, that energy must become part of the power-system planning process

Many countries are scaling up their investments in renewable energy. In 2004, investments in all forms of clean energy represented about 20 percent of total global investment in generation capacity. By 2011, that share had topped 40 percent (Bloomberg New Energy Finance 2012). Energy from renewable sources is sought for various reasons—chief among them to reduce climate-altering carbon emissions, to diversify generation portfolios, and to decrease dependence on and exposure to volatile fossil fuels. However, renewable sources—notably wind and solar power—have unique characteristics that require specific operational and planning procedures to ensure that the grids within which they are integrated can continue to meet demand reliably every minute of every day, now and in the future.

With appropriate modifications, the output of renewable energy sources (RES), even wind and solar, can be incorporated into commonly used power planning models.

What is the key challenge?

Resource variability complicates traditional least-cost planning

In power sector planning (often referred to as investment planning or capacity expansion planning), demand forecasts are compared against the existing power infrastructure to determine the type, size, and timing of the additions to generation, transmission, and distribution capacity that are required to meet the forecasted demand

at minimum costs, while also meeting established technical, social, financial, political, geographical, and environmental constraints. The most common method is the least-cost planning approach, in which the planning problem is formulated as a mathematical optimization problem that minimizes the costs of investments and power system operation over the planning horizon:

$$\begin{aligned} & \text{Min } \sum (investment\ cost_{jk} + operating\ cost_{jk}) \\ & \text{subject to} \\ & imports_k - exports_k + \sum_j generation_{jk} \geq demand_k \\ & reliability \geq minimum\ reliability\ standard \\ & environmental/technical\ constraint\ A_{jk} \leq technical\ parameter_{jk} \\ & \leq environmental/technical\ constraint\ B_{jk} \end{aligned}$$

where j and k represent technology and time period

Existing planning methods and approaches, such as least-cost planning, must now be adapted to account for the distinctive characteristics of RES, including variability, geographic dispersion, and a cost curve that differs from that of fossil-fuel generation. Variability means that the output wind and solar of generators varies from hour to hour and from day to day. RES are geographically dispersed because generation must occur where the water flows, the wind blows, and the sun shines.

Resource variability is of particular concern to power planners in ensuring long-term supply adequacy.¹ Thermal power plants can generally guarantee supply (they are “dispatchable”). Hydropower

¹ The short-term movement of RES power output (intra-hourly variation) also affects operations. Dispatch studies have shown that additional supply is needed to compensate for the frequent changes in RES output. The intra-hourly variation of RES output is not covered in this brief, but Troy, Flynn, and O’Malley (2012) provide additional information.



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“Several simple methods can help planners incorporate resource variability into conventional long-term power sector planning using the least-cost-planning approach.”

plants are subject to seasonal variation, but otherwise are dispatchable as well. Wind and solar power, by contrast, is generated only when the wind blows or when the sun shines. The change in power output from day to day (intra-daily variation) must be taken into account when planning the expansion of generation, because there is no guarantee that RES will be available at any given time to help ensure reliability and adequacy of supply.

Although sophisticated new planning tools have been developed to incorporate renewables (Welsch and others forthcoming), they may not be readily available to planners, or planners may simply want a first-order estimate of how a generation expansion plan may be affected by the introduction of renewables. Several simple methods can help planners incorporate resource variability into conventional long-term power sector planning using the least-cost-planning approach.

What solutions are available?

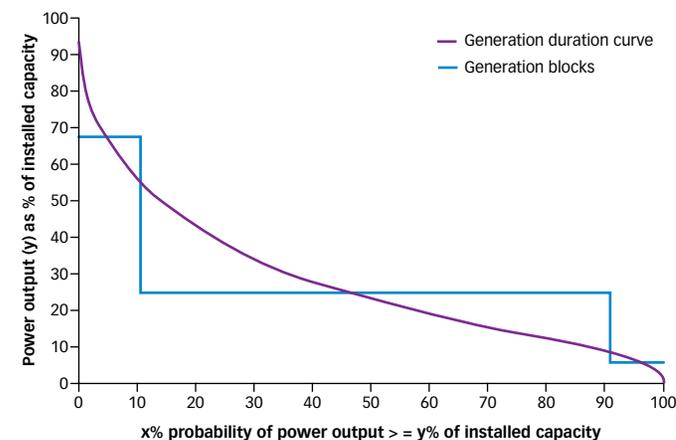
Simple techniques can be used to account for variability

Although limited in the level of detail they can capture, least-cost-planning models can be modified to incorporate RES variability into power sector planning. This can be achieved by (i) carefully representing supply or demand and (ii) modifying long-term adequacy constraints.

Supply-side approaches. The first supply-side approach is a simple one in which the renewable resource is represented as an “unreliable” thermal unit (Koritarov 2010). The forced outage rate of the unit is specified to be very large so that the unit’s generation matches the expected generation of the renewable resource, and the planned outage rate for maintenance is set to zero because RES units such as wind and solar typically require very little maintenance. (This can be modified to suit each case.) Fuel costs are set to zero, and operations and maintenance costs should capture the true costs of the RES unit. In the least-cost-planning model, dispatch is simulated for each load level of each period. Because the running costs of the RES unit are low, the unit will be dispatched when available.

The second approach treats the RES unit as a run-of-river hydropower plant (Koritarov 2010). Run-of-river hydro, like wind and

Figure 1. Determining the probability of RES output using the generation duration curve



Source: Synthetic data generated by AWS Truewind LLC.

solar resources, present an additional level of uncertainty related to hydrological, wind, or sun conditions, and typically energy storage is not available. The rationale for this representation, as contrasted with the approach used with thermal plants, is that it can capture the seasonal variation of RES units in addition to representing their nondispatchable nature. Seasonal variation is represented by specifying the expected generation and available capacity of the unit by period, and, if multiple hydrological conditions can be modeled within the framework, the probabilities of expected RES generation can be specified as well.

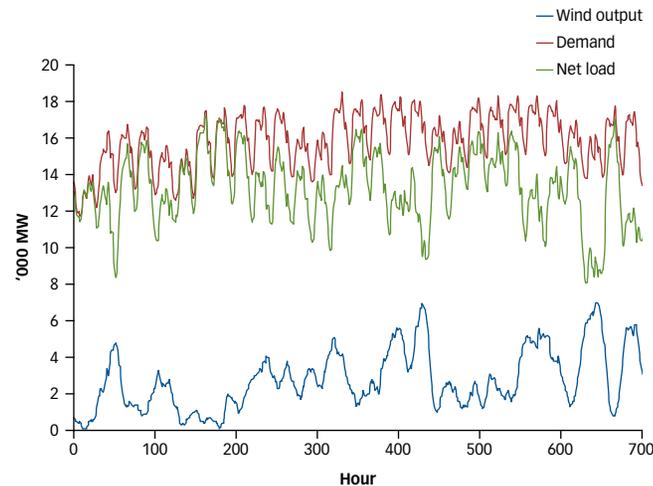
Using energy production data over a given period, it is possible to determine a “generation duration curve” for RES generation that depicts the frequency with which RES power output exceeds a certain level versus RES power output (as a fraction of installed capacity).² Figure 1 corresponds to simulated wind generation in

² Extensive, high resolution data are needed to provide certainty when developing generation duration curves. For example, one year’s worth of data measurements at 15-minute intervals following international practices is needed. ERCOT provides this information for Texas (United States) at the following site: <http://www.ercot.com/gridinfo/generation/>. NREL provides an extensive dataset for the eastern United States at http://www.nrel.gov/electricity/transmission/eastern_wind_methodology.html.

“The traditional least-cost-planning framework can be used with both of the supply-side approaches described above by representing demand in the normal way and RES units as either thermal or hydropower units.”

Figure 2. Calculating the net load duration curve

a. Demand and wind generation record



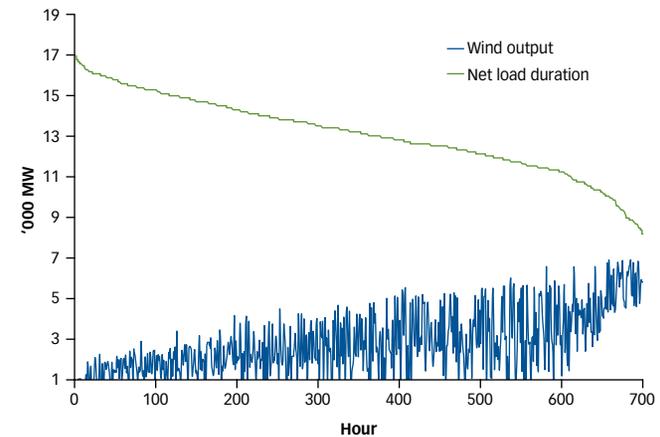
Source: Synthetic data generated by the authors.

Ontario from 2002 to 2006.³ Based on this curve it is possible to define three wind-generation blocks that correspond to high (with a probability of 10 percent), medium (80 percent), and low (10 percent) wind-power production. If the periods are monthly, it can be assumed that high winds occur 10 percent of time, that is, for three days; medium winds (80 percent) for 24 days; and low winds (10 percent) for three days. More importantly, the wind-generation duration curve is used to define the power that may be available with some degree of probability. For instance, based on the figure, approximately 5 percent or more of the installed capacity is available 95 percent of time.

The traditional least-cost-planning framework can be used with both of the supply-side approaches described above by representing demand in the normal way and RES units as either thermal or hydro-power units (specifying the technical and economic parameters of the unit accordingly). The advantages of this approach are that the RES units are included in dispatch simulations, while seasonal variability and some uncertainty are also captured. The disadvantages

³ Wind output simulation by AWS Truewind LLC was commissioned by the Ontario Power Authority. The data can be found at <http://www.powerauthority.on.ca/integrated-power-system-plan/simulated-wind-generation-data>.

b. Net load duration curve



of these methods are that (i) the stochastic nature of RES output is misrepresented (Koritarov 2010) because neither intra-hourly nor intra-daily output variation is represented, (ii) chronological power output information is not captured, and, (iii) in the case of the first approach, it is difficult to specify the generating capacity available during peak demand periods. Representing the RES unit as a thermal unit may be more appropriate for concentrated solar power and biomass units; however, this approach is less appropriate for wind and solar photovoltaic units.

Demand-side approach. Typically, variable RES output must be absorbed by the power system once produced, with output acting like a sort of negative demand. Thus, the final approach commonly used to represent RES in least-cost-planning models has been termed the “net load” approach (De Jonghe and others 2011). It requires modification of the so-called demand load duration curve. In this approach, net load is determined as the hourly load less RES generation for a given period; the net load duration curve is then generated by graphing net load data in descending order of magnitude. (The largest value is plotted on the left; the smallest value on the right.)

“Unlike the supply-side approaches described above, the net load approach does not include RES units in dispatch simulations—in other words, the contribution of RES units to long-term adequacy requirements is neglected, resulting in somewhat “fictitious” results.”

Figure 2 depicts this process. Figure 2(a) shows a month of actual demand, wind power generation, and demand minus the wind power contribution. This last curve describes the load to be supplied by sources other than wind. Figure 2(b) depicts the net load duration curve. The wind generation corresponding to each hour is also shown.

This approach does not capture uncertainty and assumes that the same chronological wind pattern will prevail in the future; however, the approach is able to capture the variability of RES power output. Therefore, when using this approach it is important to incorporate greater time discrimination in the least-cost-planning model to capture as much variability as possible. Consequently, the approach requires extensive data and the use of renewable resource assessments. Additionally, this modeling method reflects how supply interacts with the load pattern and sharpens estimations of the costs of the generation required to supply demand when RES generation changes.

Unlike the supply-side approaches described above, the net load approach does not include RES units in dispatch simulations—in other words, the contribution of RES units to long-term adequacy requirements is neglected, resulting in somewhat “fictitious” results. When employing this approach, therefore, it is particularly important that long-term adequacy constraints, or reliability, should be modified as described below.

Modification of long-term adequacy constraints. In order to ensure that current and future demand is met despite resource variability, forecasting errors, and unanticipated events, long-term adequacy requirements are expressed using both deterministic and probabilistic metrics. The simplest deterministic approach to addressing this concern requires a planning reserve, whereby a pre-specified level of excess “firm” capacity must be available above and beyond what is required to meet peak demand levels. The planning reserve accounts for both the operating reserve requirements for peak periods and uncertainty in projections of load growth. In most systems, regulators require reserve margins to be 10–20 percent in order to ensure that, in case of generator breakdowns or sudden increases in demand, the power grid is still operational.

A common probabilistic metric is the loss of load probability (LOLP), defined as the probability over some period of time that the

power system will fail to provide uninterrupted service to customers. This approach uses the characteristics of system components to predict the likelihood that demand will be served and provides a meaningful representation of the random events that can affect supply and demand. Another probabilistic metric is the loss of load expectation (LOLE), which is similar to LOLP and specifies the expected amount of time during which demand will not be met over a given period.

Ensuring that a system comprising RES units will be reliable requires the modification of the long-term adequacy constraints as described above. In particular, assuming that reliability constraints are implemented using reserve margins, it is important to update and increase the reserve requirements beyond the 10–20 percent typically required in most power systems and to determine the firm generating capacity of RES units offline (external to the model) to ensure that sufficient capacity is available to meet demand. For further detail on this topic, see Matos and others (2009).

Reserve requirements. Integrating renewables in the grid necessitates an increased reserve margin to meet standard reliability criteria. One rule of thumb often used when incorporating renewables into planning models is to increase the reserve requirement by the fraction of firm generating capacity supplied by RES units. For example, if the reserve margin requirement was originally determined as

$$R_o = \frac{(P_G - P_D)}{P_G}$$

Then the new reserve requirement should be calculated as

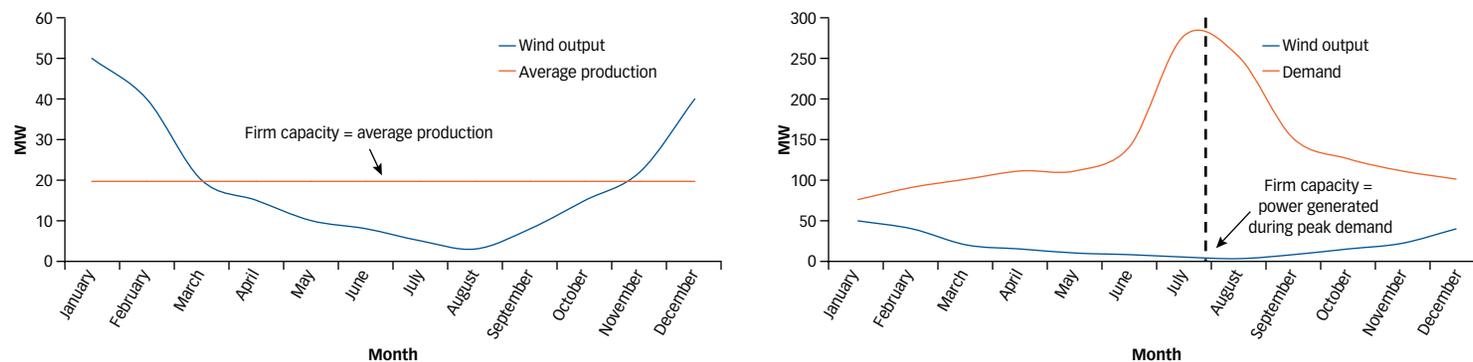
$$R_n = \frac{(P_G + C_{RES} - P_D)}{P_G}$$

where P_G represents the firm generating capacity of conventional power sources (without variable renewables), P_D indicates peak demand, and C_{RES} is the firm generating capacity supplied by RES units (Madrigal 2012).

Firm capacity. Firm capacities are used to indicate the contribution of individual units to the supply of peak demand and to help planners determine if the integrated supply mix meets the planning reserve constraint. For thermal generation, firm capacity is expressed

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Figure 3. Determination of firm RES capacity using (a) average production and (b) power generated during peak demand



Source: Madrigal 2012.

as the time (in hours) that the unit is available to produce energy divided by 8,760, the number of hours in a year, scaled by maximum output capacity.⁴ For hydro power, it is calculated based on the power that the plant can guarantee at peak time with a given probability. For other RES, firm capacity is highly dependent on the type of technology and is determined using deterministic (figure 3) or probabilistic analysis.

The most common methods of deterministic and probabilistic analysis used to compute firm capacity are the average production, peak demand, and LOLE methods. Average production, the simplest deterministic approach, assumes that, for a given period, firm generating capacity is equal to the average power production of the unit. Another deterministic approach, peak demand assumes that the firm generating capacity is the available generating capacity of the RES unit at times of peak demand (Madrigal 2012).

The LOLE method is a probabilistic approach that determines what is commonly known as effective load carrying capability. It

⁴ For thermal units, firm capacity is determined as (100-FOR) multiplied by the rated capacity of the generator. For large hydro units, firm capacity is determined based on the probability of water inflows and production during times of peak demand when peak demand is the critical condition. Other measures simply refer to the power output that can be guaranteed with a given probability (for example, above 90 percent) in a given year.

assumes that firm RES capacity is equal to the increment in demand that can be met at the same level of LOLE after the renewable resource is added to the power system. The steps used to determine firm capacity using the LOLE method (Madaeni and others 2012) are outlined below:

- Determine $LOLE_0$, that is, LOLE without RES operating in the system.
- Forecast renewable production and determine the net load duration curve.
- Determine $LOLE_n$ based on the net load duration curve (that is, with RES in the system).
- Increase demand across all hours until $LOLE_0$ equals $LOLE_n$.
- Calculate firm RES capacity as maximum demand corresponding to $LOLE_n$ minus maximum demand corresponding to $LOLE_0$.

While deterministic methods provide simple approaches to approximating the firm capacity of RES units during peak demand, probabilistic methods better reflect the uncertainty of the contribution of the variable source to system reliability. The final probabilistic method described above is also able to reflect how generation interacts with the load pattern.

“With the global increase in renewable energy targets, power system planners must quickly learn to integrate RES into long-term generation expansion plans without increasing costs or compromising reliability or environmental values.”

Table 1. Taking RES units into account in least-cost planning

Method	Ease of use	Quality of approximation ^a	Data requirements	Pros	Cons
Represent RES as thermal units	Very simple	Rough first order	Expected generation of RES units; operations and maintenance costs of RES units	RES units are included in dispatch simulations.	Does not take into account stochastic nature, chronological power output, or firm capacity of RES.
Represent RES as run-of-river hydro unit	Simple	Good first order	Expected generation and available capacity of RES unit per period; the probabilities of expected RES generation	RES units are included in dispatch simulations; seasonal variation and nondispatchable nature of RES are taken into account.	Neither stochastic nature of RES output nor chronological power output is taken into account.
Net load approach	More complex	Good first order	Hourly demand; hourly, chronological RES generation for each period	Captures intra-hourly and intra-daily RES output variation; reflects how supply interacts with demand; allows more accurate estimation of system costs.	Does not capture uncertainty; assumes the same chronological pattern in the future.

Source: Authors.

a. The quality of the approximation depends on the quality of data available. Higher resolution data and more time-series data improve quality.

What are the key lessons?

Trade-offs exist between simplicity of method and accuracy of results

With the global increase in renewable energy targets, power system planners must quickly learn to integrate RES into long-term generation expansion plans without increasing costs or compromising reliability or environmental values. The variability of renewable resources can be captured in long-term planning using classical least-cost-planning models. This is achieved through a two-pronged approach: First, RES units are represented as if they were thermal or hydro plants, or the net load duration curve is used to represent demand (excluding RES from dispatch). Second, long-term adequacy constraints are modified by taking into account the estimated firm generating capacity of renewables in one of several ways. Tables 1 and 2 provide a comparative overview of the approaches presented,

indicating the data needed for implementation as well as the advantages and drawbacks of each method.

The methods described here and summarized in tables 1 and 2 have been used in various cases. For example, the regulator in Mexico issued an ordinance that determines the amount of energy from RES (specifically wind) that should be used for planning purposes, referencing the contribution of these sources to peak demand. Argonne National Laboratory in the United States has used the LOLE method as a way to incorporate wind power into the Wien Automatic System Planning capacity-expansion model. The Argonne model is used in various developed and developing countries.⁵ Additionally, the net load approach to incorporating RES units and

⁵ Presentation can be found at <https://www.ferc.gov/EventCalendar/Files/20100608141145-Koritarov,%20Argonne%20NL%20-%20Modeling%20Wind%20in%20Expansion%20Planning.pdf>.

“The methods described in this note provide a first-order estimate of the generating capacity needed to meet demand over time. To improve the quality of the results and obtain a more holistic view of the system, least-cost-planning models must be complemented by additional analyses to capture the intra-hourly variation of RES output as well as the geographic dispersion and dynamic costs of the renewable sources.”

Table 2. Calculating the firm generating capacity of RES

Method	Ease of use	Quality of approximation ^a	Data requirements	Pros	Cons
Average production	Very simple	Rough first order estimate	Average RES production for a given period	Easy to calculate.	Results in gross over- or underestimation of firm capacity; does not capture uncertainty; not suitable for project closure feasibility analysis, as further assessment is required.
Contribution during peak demand	Very simple	Good first order	Power generated by RES units at peak demand	Easy to calculate; assesses RES output at time of peak demand.	Does not capture uncertainty; not recommended when RES make up a large share of total generation capacity.
LOLE approach	Complex	More sophisticated	Hourly load and RES generation for each period	Better reflects the uncertainty of the variable source’s contribution to system reliability; reflects how generation interacts with demand.	Is data intensive and requires proper modeling tools.

Source: Authors.

a. The quality of the approximation depends on the quality of data available. Higher resolution data and more time-series data improve quality.

the LOLE approach to estimating firm capacity are industry standards and used by very skilled planners and utilities worldwide.

The methods described in this note provide a first-order estimate of the generating capacity needed to meet demand over time. To improve the quality of the results and obtain a more holistic view of the system, least-cost-planning models must be complemented by additional analyses to capture the intra-hourly variation of RES output as well as the geographic dispersion and dynamic costs of the renewable sources. While not the focus of this brief, these features should be included in the planning process to ensure that a diverse supply mix meets demand in the short, medium, and long term. Executing multiple models and performing manual analysis can be tedious. Fortunately, new commercial tools have been designed to alleviate the planning burden (ESMAP forthcoming). These will be the subject of a forthcoming Live Wire.

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MAKE FURTHER CONNECTIONS

Live Wire 2014/1. "Transmitting Renewable Energy to the Grid," by Marcelino Madrigal and Rhonda Lenai Jordan

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