Capacity and Reliability Planning in the Era of Decarbonization

August 2020

Energy+Environmental Economics

This whitepaper is prepared by:

Nick Schlag

Zach Ming

Arne Olson

Lakshmi Alagappan

Ben Carron

Kevin Steinberger

Huai Jiang

Recommended Citation:

N. Schlag, Z. Ming, A. Olson, L. Alagappan, B. Carron, K. Steinberger, and H. Jiang, "Capacity and Reliability Planning in the Era of Decarbonization: Practical Application of Effective Load Carrying Capability in Resource Adequacy," Energy and Environmental Economics, Inc., Aug. 2020

Available at: https://www.ethree.com/elcc-resource-adequacy/

Introduction

Around the world, policy and economics are driving a transition towards low-carbon electricity systems. These systems will increasing rely on intermittent renewable resources (wind, solar) and energy-limited resources (storage, demand response) to provide energy and essential grid services. While these resources are poised to transform our energy supply, their inherent characteristics and limitations add significant complexity to electricity system planning and operations. Nowhere is this truer than in the administration of resource adequacy. Capacity procurement processes designed to ensure sufficient reliability must evolve to effectively integrate renewables, storage, and other resources into frameworks originally conceived in an era where most resources were "firm" – available at full capacity except in the event of forced outages.

To date, a wide range of approaches and conventions have been used to incorporate these "non-firm" resources into resource adequacy programs. Increasingly, the industry has turned to "effective load carrying capability" ("ELCC") as the preferred method for measuring the resource adequacy contribution of intermittent or energy-limited resources. ELCC is derived directly from the loss-of-load probability modeling that system planners have long utilized to determine the Planning Reserve Margin ("PRM") that is necessary to ensure reliable electric service. As such, it is a natural extension of those methods to the problem of non-firm resources.

Developing a fair, efficient, and practical framework to apply ELCC to renewables, storage, and other non-firm resources is complex yet essential to the future viability of resource adequacy programs and capacity markets

Proper use of ELCC is critical to ensuring both reliability and economic efficiency in regulated and deregulated markets. Inaccurate measurement of the resource adequacy value of non-firm resources will lead to a system that fails to meet reliability targets or, alternatively, one that is overly reliable and saddled with unnecessary costs. However, complex interactions between non-firm resources make this a challenging exercise. For example, saturation causes the total capacity contribution from two solar resources to be less than the contribution of each resource alone, whereas the combined contribution from solar and battery storage resources might be greater than the standalone contributions.

Accounting for these interactive effects is especially important, and particularly complex, in the context of centralized capacity markets where accreditation methods can have momentous financial impacts for market participants. As renewable, storage, and flexible demand resources grow to very large scales in response to favorable economics and increasingly urgent government policies, developing fair, accurate, and practical methods of evaluating their capacity contributions will become critical to the functioning of these markets. This paper identifies and discusses various challenges and considerations that naturally arise with increased reliance on ELCC in resource adequacy programs and proposes a framework for the effective incorporation of ELCC into centralized capacity markets that is durable as non-firm resources evolve towards a preponderant share of electricity generation.

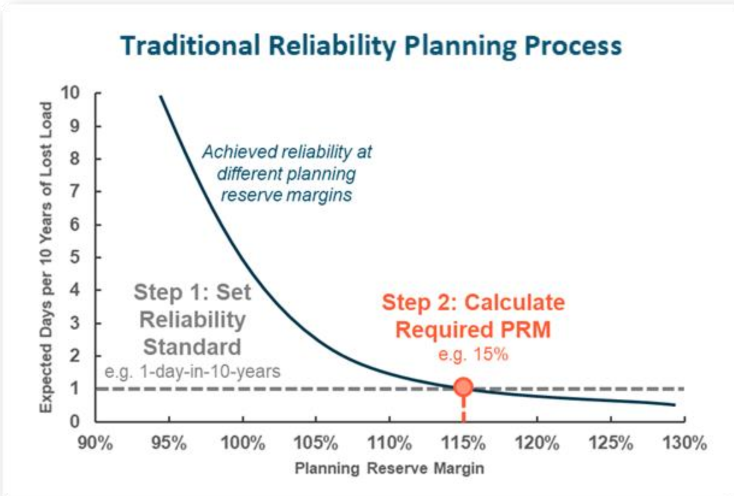
Background

Electric system reliability is of paramount importance to modern society. Stable and reliable provision of electric energy enables us to meet essential needs within the home and to operate businesses that provide services to maintain our quality of life. As adoption of electric vehicles increases, electric reliability will also become essential to mobility, while electrification of other end uses will further increase our reliance on electricity to meet critical energy needs such as heat during cold weather events. In many cases, power outages are more than a mere inconvenience, particularly when they impact the ability to work, communicate, or in the most severe cases health, life, and death.

There are many different aspects of electric reliability, from wide-scale reliability events like the Northeast blackout of August 2003 to localized events caused by trees, cars, or even squirrels. Within the context of generation resource procurement, system planners focus on the dimension of "resource adequacy": the ability of the bulk generation and transmission system to meet electric demands across a broad range of weather and system operating conditions. Many factors affect resource adequacy, including the characteristics of load (magnitude, seasonal patterns, weather sensitivity, hourly patterns) and resources (size, dispatchability, forced outage rates, and other limitations on availability).

In North America, there is no unified standard or method for determining resource adequacy. Rather, each power system defines its own resource adequacy requirements, acting under oversight from state, provincial or local authorities, based on a variety of factors including, in some cases, evaluations of the costs and benefits of achieving higher or lower reliability standards. In the event that a power system's resources are inadequate to serve all of its loads, North American Electric Reliability Council ("NERC") standards require it to proactively curtail service in order to protect against the possibility of an interconnection-wide reliability event.

Utilities use many metrics to quantify the frequency, magnitude, and duration of loss-of-load events. While there is no continent-wide requirement for resource adequacy, many power systems in North America are planned based on a standard of "1-day-in-10-years". This standard requires that there be sufficient generation and transmission resources to serve load during all but one day every ten years. It is frequently implemented as requiring a loss-of-load expectation ("LOLE") of 0.1 days per year. Because directly measuring the LOLE reliability of a system is data-intensive and computationally complex, loss-of-load studies are often used to define a planning reserve margin ("PRM"), measured as the quantity of capacity needed above the median year peak load to meet the LOLE standard, to serve as a simple and intuitive metric that can be utilized broadly in power system planning.



Historically, PRM accounting frameworks have used the maximum rated or "nameplate" capacity of firm resources such as coal, gas or nuclear power plants as the measure of a resource's contribution to resource adequacy requirements (in some cases with adjustments due to forced outages or temperature-related performance degradation). Non-firm resources are different from firm resource in important ways, for example due to variable availability or limitations on how long they can be dispatched, but they can still make important contributions to resource adequacy and reliability. To address these differences, system planners have had to devise new methods to incorporate these resources into the traditional paradigm.

As renewables and storage resources have gained market share, the PRM framework has been criticized as an antiquated, "peak-focused" requirement that is no longer relevant in a world where other hours may be more difficult for system operators to manage due to ramping events or lack of renewable energy production. However, these criticisms fail to recognize that a PRM requirement does not literally represent a requirement for capacity during the peak hour, but rather a requirement for capacity throughout the year that, for simplicity, is expressed in relation to a system's expected peak demand. This convention originated in the era of firm resources: so long as a system had sufficient capacity to meet peak demand, those same resources would also be available to meet demand under all other conditions. The integration of increasing levels of renewables and storage does not render the PRM framework obsolete, but it does require more advanced techniques to measure the contribution of different types of resources towards that capacity requirement.

The integration of increasing levels of renewables and storage does not render the PRM framework obsolete, but it does require more advanced techniques for measuring the contribution of different types of resources towards that capacity requirement

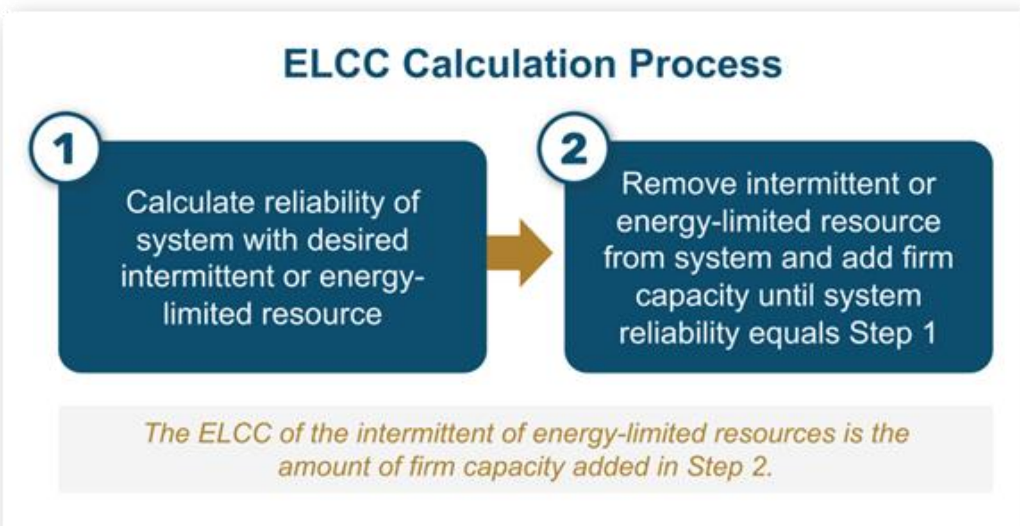
Reasonably characterizing each resource's contribution towards meeting system capacity needs is critical to ensuring the system meets its target reliability standard and will only become more significant as states and utilities add renewables and storage to their electricity portfolios. Historically, simple and practical heuristic methods have been used to assign capacity credits to individual intermittent or energy-limited resources. These simplifications have been adequate in many places due to the low penetration of renewables and energy storage. However, they do not appropriately capture the reliability dynamics of the system at higher penetrations, when the need for accurate representation of their characteristics is most critical.

Effective Load Carrying Capability

The ELCC metric is broadly viewed as the key to extending existing resource adequacy programs into a future where intermittent and energy-limited resources will represent major portions of the electricity portfolio. First introduced as a concept in the 1960's, ELCC has gained popularity in recent years as a method to express the capacity contribution of intermittent and energy-limited resources in in terms of equivalent "perfect" capacity (capacity that is always available). In this respect, ELCC is technology-agnostic: a system with a given quantity of ELCC megawatts will achieve the same level of reliability, regardless of what types of resources are providing those megawatts. For example, if the ELCC of solar is 50%, then an electricity system with 100 megawatts of solar (i.e., 50 megawatts of ELCC) would achieve the same reliability as an electricity system with 50 megawatts of a perfect resource.

Enhancing existing resource adequacy programs to incorporate ELCC-based approaches to measure resources' capacity contributions to system needs will allow those programs to continue to function efficiently and effectively even as the system transitions away from reliance on firm resources. The more broadly the construct of ELCC is applied across resources within a resource adequacy program, the more adequately prepared that program will be to accurately capture the effects of future portfolio changes, and the more level a playing field it will create for all resources that can contribute to resource adequacy needs.

The calculation of ELCC relies on sophisticated "loss-of-load-probability" modeling, which simulates the electricity system under many decades of different load and resource conditions. These models, which allow system planners to calculate the expected frequency, duration, and magnitude of reliability events on a system with a given portfolio of resources, can be used to compare the reliability contributions of intermittent and energy-limited resources to perfect capacity. Despite the rigor and complexity of its derivation, ELCC produces capacity value calculations that intuitively capture many of the most significant challenges that will arise with increased penetrations of renewables, storage, and other resources.

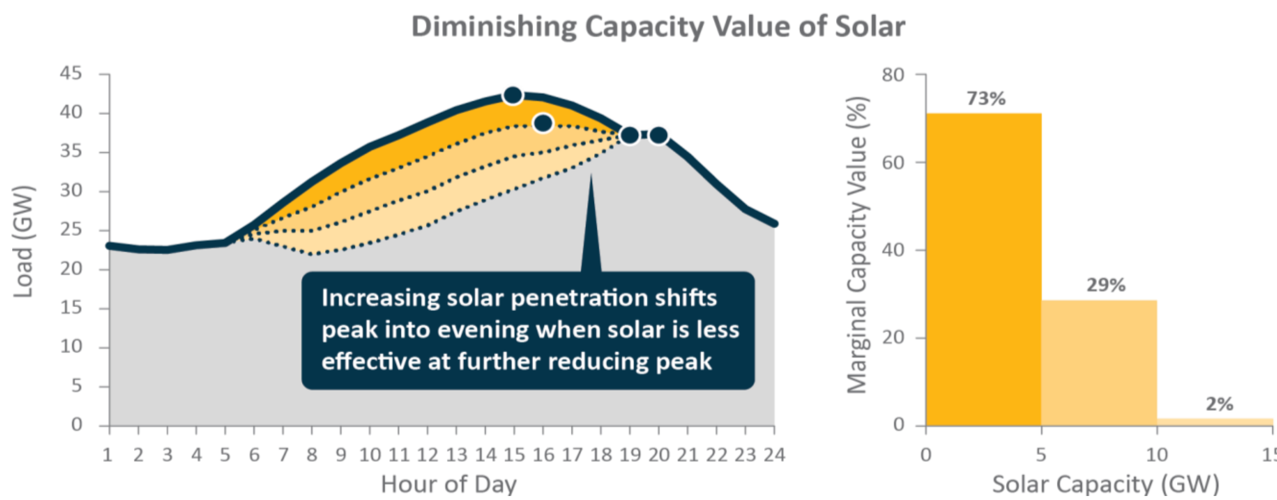


ELCC Dynamics

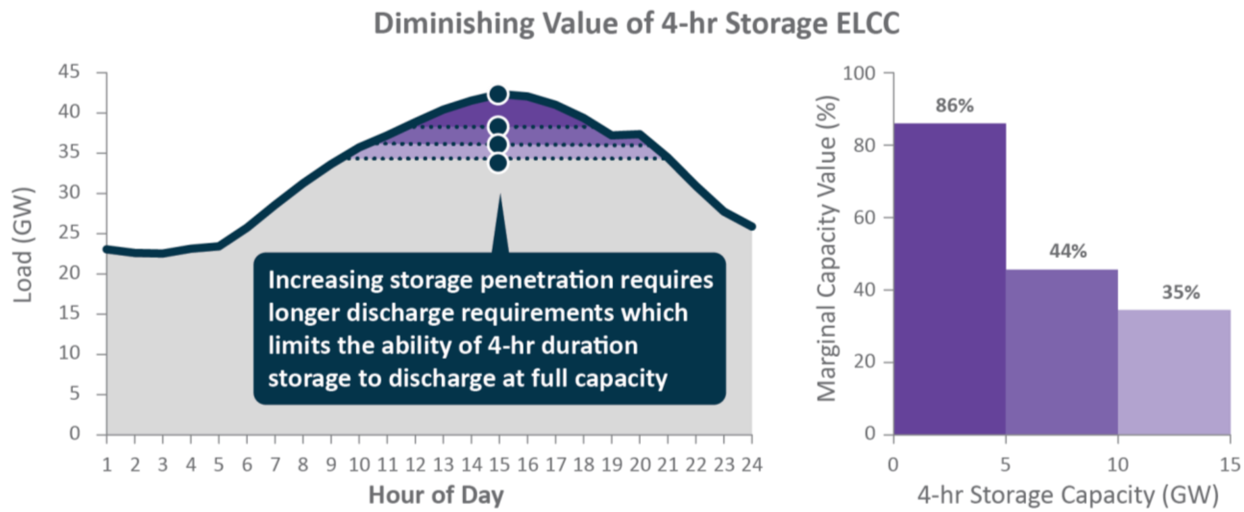
One of the strengths of the ELCC approach is that it captures how intermittent and energy-limited resources can interact to meet resource adequacy needs. Clearly, an electricity system cannot reliably serve load with only solar energy (there would be no energy at night), nor can it reliably serve load with only battery storage (there would be no energy to charge the batteries). However, an electricity system with both resources can serve load across a broader range of conditions. Because of interactions like these, it is not a straightforward exercise to calculate the ELCC of an individual resource within the context of a much larger portfolio of intermittent and energy-limited resources.

Saturation Effects at Increasing Penetration

One of the key dynamics captured by ELCC is the diminishing marginal returns of a specific resource with increasing scale – that is, continuing to add more and more to an electricity system will produce lower and lower marginal resource adequacy benefits. This effect has been widely recognized through the impact of increasing solar penetrations on net peak demand, an effect that jurisdictions such as California have already encountered at today's penetration of solar and is illustrated below.

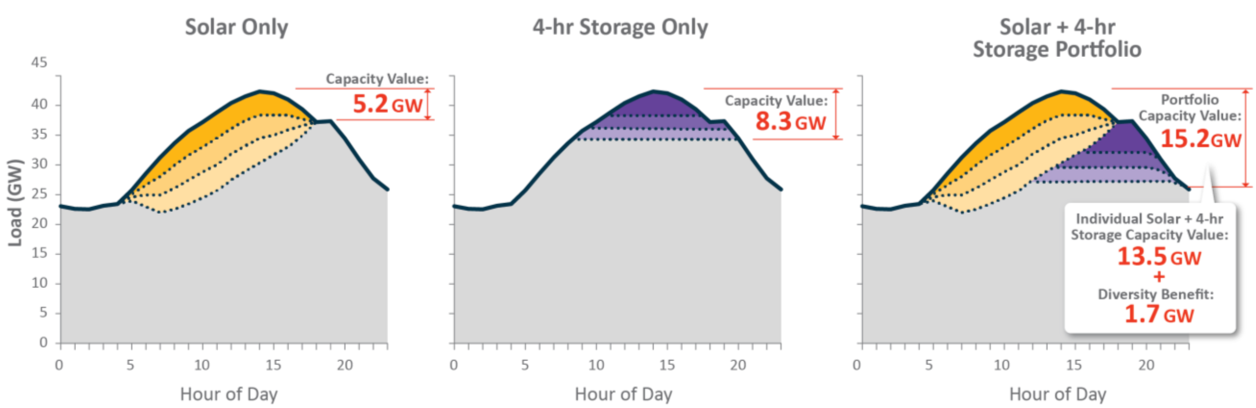


This same principle applies to energy-limited resources like energy storage, though for different reasons: the finite duration limits the ability of energy storage to meet demand across extended periods. This effect can be interpreted in multiple ways: either (1) the marginal ELCC of storage with a fixed duration will continue to decline as more is added to the system, or (2) storage with progressively increasing duration is needed to sustain a high capacity value.



The Benefits of Resource Diversity

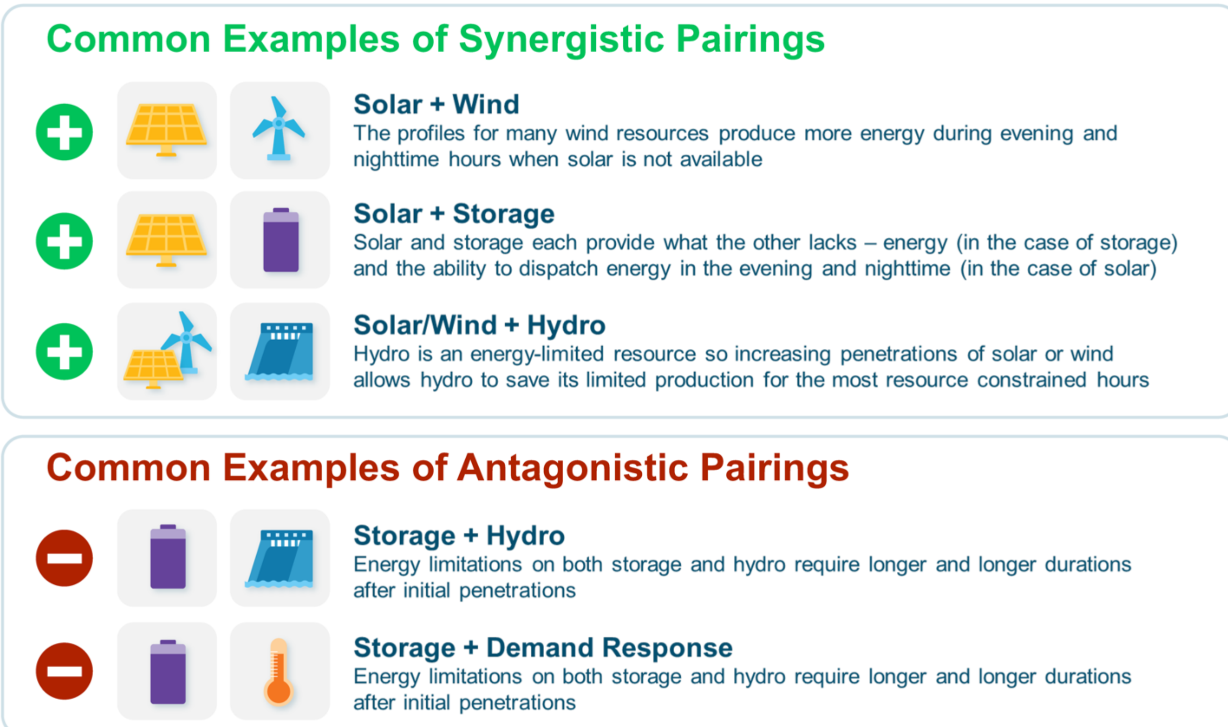
While resources with similar operating characteristics yield diminishing returns, combining resources with complementary characteristics can produce the opposite effect, a total ELCC that is greater than the sum of its parts. This effect has commonly been described as a "diversity benefit" in jurisdictions that have explored ELCC implementation. There are many combinations of resources that will produce such an effect; solar and storage provide an intuitive illustration. This is because solar acts to "sharpen" the shape of the net peak demand, reducing the length of the period during which storage must discharge to reduce the peak, in addition to providing a source of energy for charging. This is illustrated in the figure below.



Interactive Effects: Synergistic and Antagonistic Combinations

The examples above illustrating saturation effects and the benefits of resource diversity are just three examples of what may be more broadly described as the **"interactive effects"** between resources in a portfolio. Characterizing these interactions is critical to understanding how these uses of ELCC relate to one another. Interactions between resources may either be ***synergistic***—producing a diversity benefit when paired with one another—or ***antagonistic***—in which the whole is less than the sum of its parts.

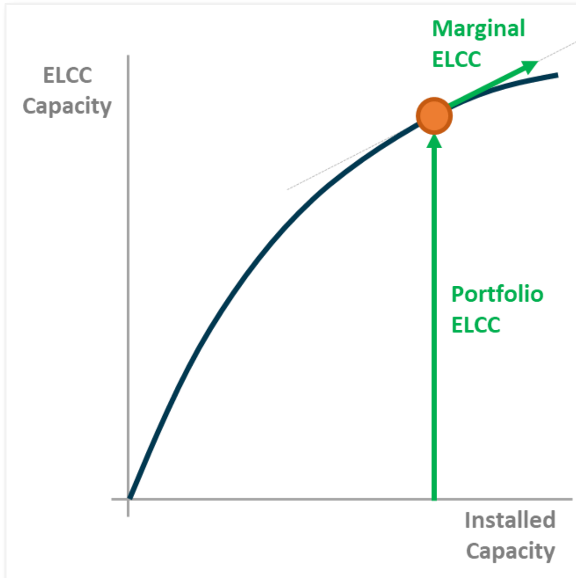
Ultimately, what determines the nature of interactions within a portfolio as synergistic or antagonistic is the degree of diversity among the constituent resources. Scaling up a single resource type yields the fastest diminishing returns since no resource can be more similar than the resource itself. But different resources with similar limitations can also interact antagonistically with one another, while resources with sufficiently different characteristic limitations can interact synergistically. Common examples of such pairings are shown in the figure below.



In any system with more than two types of resources, all intermittent and energy-limited resources will interact with one another to some degree in their contributions to reliability needs. The multiplicity of interactions and dimensions become increasingly difficult to disentangle from one another, a sign of the challenge inherent in the accreditation of ELCC values to individual resources. As the penetrations of these resources grow to represent significant shares of the electricity system across the U.S., these interactive effects cannot be ignored or rounded away. Rather they must be addressed head-on to ensure that electricity systems continue to provide both reliability and economic efficiency.

Effective load carrying capability is a property of a portfolio of resources, not of the individual resources

These features of ELCC—namely, its ability to capture saturation effects, diversity benefits, and other interactions between resources—derive from an axiomatic characteristic of ELCC, namely, that the quantity provided is a property of a portfolio of resources, not of the individual resources themselves. Because of the interactions between resources in a portfolio, there is no single value that accurately captures the contribution of an individual resource toward the reliability of the portfolio at all times and under all circumstances. Instead, there are two types of ELCC values that can be uniquely defined and calculated, from which all practical applications of ELCC must be derived:



+ **Portfolio ELCC:** the combined capacity contribution of a combination of intermittent and energy-limited resources. Because all resources are evaluated together, this method inherently captures all interactive effects and combined capability of the resources.
+ **Marginal ELCC:** the incremental capacity contribution of a specific resource (or combination of resources), measured relative to an existing portfolio.

Firm Resources, ELCC and UCAP

The concept of ELCC may also be applied to traditional firm resources to account for the fact that, due to the risks of unplanned outages, their capacity value is lower than 100%. In many organized capacity markets, "Unforced Capacity" (UCAP) has been adopted to account for this effect; in a large electricity system with many generators, UCAP provides a reasonable approximation of a more detailed ELCC calculation for firm resources. Further, in such systems, firm resources typically do not exhibit the same types of interactive effects as intermittent and energy-limited resources. However, in smaller systems where large generator outages may have an outsized impact on reliability, ELCC can more accurately measure the contribution of firm resources towards system capacity needs.

Application of ELCC in a Resource Adequacy Framework

The very features of ELCC that make it the preferred metric to measure the capacity contributions of resources towards resource adequacy needs also create challenges for its implementation. The application of ELCC in resource adequacy planning requires a carefully considered framework, both for vertically integrated utilities responsible for meeting their own resource adequacy needs and for centralized resource adequacy programs and capacity markets.

The very features of ELCC that make it the preferred metric to measure the capacity contributions of resources towards resource adequacy needs also create challenges for its implementation.

Vertically Integrated Utilities

The simplest example of an application of ELCC is in the context of a vertically integrated utility that is responsible for meeting its own resource adequacy requirement with a single portfolio of resources. For such a utility, accrediting capacity value to individual resources is not strictly necessary—what matters is whether the utility's total portfolio meets its total needs. In this case, the application of ELCC may reasonably rely directly on the two "measurable" ELCC values: portfolio and marginal. Both are directly useful to the utility:

- To assess whether a given combination of resources is sufficient to meet a utility's PRM target, the **portfolio ELCC** provides a measure of the combined capacity contribution of the intermittent and energy-limited resources in its portfolio.
- To evaluate potential resource additions, the **marginal ELCC** for each resource provides a measure of how much that resource will increase the total ELCC of the utility's portfolio, offering a means of comparing the relative capacity value of resource alternatives to identify the least-cost resource among a discrete set of options.

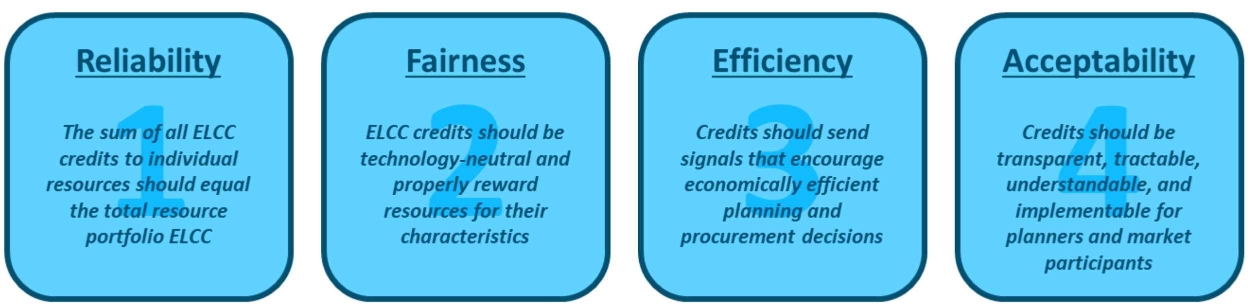
Within this framework, once a new resource has been procured, it is no longer necessary for the utility to ascribe a capacity value to that specific resource, and it may be treated as part of the portfolio ELCC calculation. Together, these two constructs can allow a utility to simultaneously ensure the reliability of its existing portfolio of resources and make economically efficient decisions in the procurement of new capacity resources to meet incremental need.

Centralized Resource Adequacy Programs

Most competitive electricity markets today have some type of resource adequacy program administered either through centrally cleared capacity markets (ISO-NE, NYISO, PJM) or through some combination of self-supply and bilateral exchanges (SPP, CAISO) with centrally-administered need determinations. While the structures of these programs vary widely, one common element across programs is the need to assign capacity credits to individual resources. This is necessary so that resource owners may be appropriately compensated for their contributions to resource adequacy and so that program participants may demonstrate that their portfolios adhere to the required standard.

Successfully implementing ELCC in these types of programs will require a method to credit ELCCs to individual resources. However, there is no single ELCC value that accurately describes the capacity contribution of a given resource under all circumstances due to the complex interactive effects. As a result, designing the most appropriate method for resource accreditation will require program administrators to exercise judgment to identify and balance several guiding principles. In many ways, the principles that underpin a sound framework for ELCC accreditation parallel the principles that guide electricity ratemaking; here, we express those principles as Reliability, Fairness, Efficiency, and Acceptability. As in rate design, these principles will inevitably come into conflict with one another.

1. **Reliability:** The sum of all ELCC credits to individual resources should equal the total resource Portfolio ELCC. To the extent that this principle is not met, the system will under or over procure capacity, resulting in a system that either fails to meet reliability targets or, alternatively, one that is overly reliable and saddled with unnecessary costs.
2. **Fairness:** ELCC credits should be technology-neutral and properly reward resources for their characteristics. In other words, the ELCC credit for a specific resource should be purely a function of its inherent capability and not a product of an arbitrary classification by the system administrator that unduly creates different credits for similar resources. Additionally, resources should be fairly credited for their interactions with other resources, either positive or negative.
3. **Efficiency:** Credits should send signals that encourage economically efficient planning and procurement decisions. To both minimize societal costs and encourage efficient entry and exit from the capacity market, new resources should be sent an ELCC credit signal that aligns with their marginal contribution to resource adequacy.
4. **Acceptability:** Credits should be transparent, tractable, understandable, and stable for planners and market participants. This principle ensures that theoretical purity is not held in higher regard than the practical aspects of implementation. The system administrator must be able to reasonably manage any system and resource owners must be able to reasonably understand and forecast the market signals in order to respond appropriately.



The question of how to accredit resources using an ELCC framework has often been framed as a choice between accrediting resources based on "marginal" and "average" ELCC: the former provides the correct signal to the market for the need for new capacity, and the latter ensures the accreditation results in the correct total capacity value for the portfolio. While this dichotomy is useful to frame the tradeoff between economic efficiency and reliability, it belies the complexity of practically implementing an ELCC accreditation framework in a system with a diverse portfolio of intermittent and energy-limited resources. Multiple frameworks for ELCC implementation have been considered that generally fall into four categories: (1) **marginal**, (2) **vintaged marginal**, (3) **class average**, and (4) **adjusted class average**. The advantages and disadvantages of these approaches highlight the inherent tension among the guiding principles of ELCC accreditation.

In a **"marginal"** accreditation framework, all resources are credited an ELCC based on their marginal contribution to system resource adequacy needs. While this approach has been recognized for the feature that it provides the most appropriate signal to the market for the procurement of least-cost capacity resources (satisfying the efficiency principle), it does not appropriately credit a portfolio of resources for its contribution to resource adequacy. Because the marginal ELCCs of most resources will decline with increasing penetration, this approach will eventually lead to procurement of excess capacity beyond what is needed to meet system needs (failing the reliability principle) unless resource adequacy requirements are also adjusted dynamically.

A **"vintaged marginal"** approach is closely related to the marginal approach but locks in the marginal ELCC of each resource at the time it is added to the system. This credit is thereafter retained by the resource, either for its lifetime or for a predetermined period of sufficient duration to enable a degree of revenue certainty. In this respect, it provides additional stability and certainty that a marginal approach will not and also ensures that the total accredited ELCC will sum to the portfolio total. However, in doing so, it introduces differences in the treatment of otherwise identical resources simply due to their construction date, thereby undermining a foundational goal of fair competition in the marketplace (failing the fairness principle).[1] Locking in ELCC values for too long a period may push market design towards a model that resembles long-term contracting more than today's competitive markets, diluting liquidity and inhibiting competition. Finally, there may be practical difficulties defining the ELCC lock-in period, given the potential for owners to modify their resources through upgrades or partial retirements.

"Class average" accreditation frameworks have been implemented in several jurisdictions. In this framework, a total ELCC is calculated for a class of resources (e.g. wind, solar) and averaged across all resources within the class. This total ELCC is akin to a Portfolio ELCC but only for all resources within the class. In applying this approach, the program administrator faces a choice of whether to calculate the ELCC for each class with or without the other classes on the system; the two approaches will yield different results. This approach is appealing in simple applications of ELCC—namely, when it is being applied to a single relatively homogeneous group of resources. The concept of calculating a single average ELCC across a diverse portfolio of resources will obviously fail to capture significant differences in the characteristics (failing the fairness principle) and contributions of the constituent resources, and yet, if resources are separated into distinct classes, the average ELCCs for each class will not capture the significant interactive effects among classes (failing the reliability principle).

"Adjusted class average" approaches have been explored as a means of adapting class average approaches to incorporate interactive effects among classes. These methods generally involve multiple sequential steps: (1) the calculation of the Portfolio ELCC, (2) the calculation of total ELCCs for different

[1] It is important to note that the value of existing resources for other electricity market products, such as the day-ahead energy market, are also impacted by the entry of new resources but there is no vintaged value ascribed to them to protect them in this regard. At the same time, there is a vintaged element to the method in which access to transmission is allocated in the industry.

classes of resources within the portfolio (described above), and (3) a uniform adjustment of each class' total ELCC such that the sum across all resources matches the Portfolio ELCC. While satisfying the reliability principle, this approach does not satisfy several dimensions of the fairness principle as described below.

Adjusted class average approaches function reasonably in a system with two distinct resource classes, but extension of this logic to a system with more resource diversity will be challenging. New resources with increasing degrees of heterogeneity (renewables across broader geographies, storage of multiple durations, hybrids with various configurations) will also merit incorporation into an ELCC-based framework, and ELCC may be extended to encompass other existing energy-limited resources as well (demand response, hydro). Invariably, this will require further segmentation of new classes just as the distinctions between many of them will blur with hybridization.

Importantly, this definitional challenge not only presents an administrative headache but will have a significant impact on the resulting ELCC accreditation to resources, leading to arguably arbitrary and unfair outcomes for specific resources and creating obvious opportunities for regulatory arbitrage. These issues stem from two factors:

The shortcomings inherent in existing methods of ELCC attribution are fundamental and will become increasingly pronounced, presenting a major barrier to their usefulness in the decarbonization era

- **Defining increasingly segmented classes will lead to inconsistent treatment of resources in classes of different relative sizes.** The adjusted class average approaches treat interactive effects among resources within a class differently from interactive effects between technology classes. While well-intentioned choices to define new classes may appear unbiased, resources that end up in smaller classes where the class average ELCC and the marginal ELCC are relatively close will be treated differently than resources in larger classes, where the class average ELCC is farther from the marginal ELCC. In short, individual resources may be either penalized or rewarded simply on the basis of the artificial construct of their assignment to technology classes.
- **Applying a uniform adjustment to all resources classes to account for interactive effects does not faithfully capture the nature of the interactions between technologies.** As a simple example, consider a portfolio with three classes, two of which are strongly synergistic and the third of which has no interactive effects with the first two. In this case, the uniform adjustment would reward all three classes with an upward adjustment of all three classes despite the fact that the synergistic effects were the product of only two.

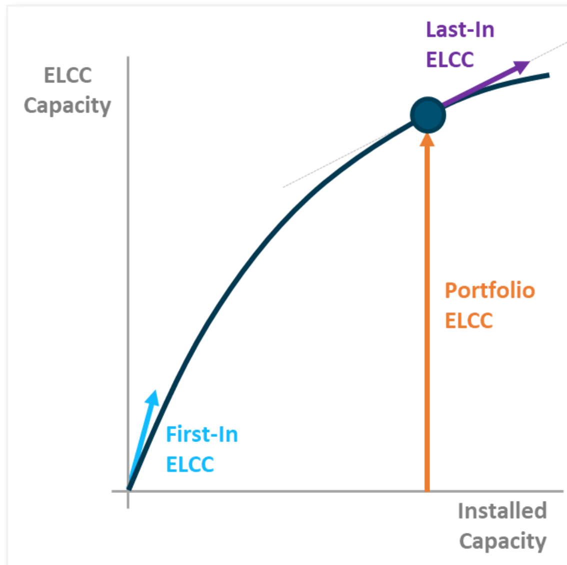
The shortcomings inherent in existing methods of ELCC attribution are challenging and will become increasingly pronounced, presenting a major barrier to their usefulness in the decarbonization era.

The Delta Method: A New Approach for ELCC Accreditation

The following framework introduces a method to credit ELCC values to individual resources in a manner that adheres to the principles outlined above. This method relies on several measurable ELCC values:

- The **Portfolio ELCC**, as presented earlier, is the total ELCC provided by a combination of intermittent and energy-limited resources;
- The **First-In ELCC** for each resource, the marginal ELCC of each individual resource in a portfolio with no other intermittent or energy-limited resources; and
- The **Last-In ELCC** for each resource, the marginal ELCC of each individual resource when taken in context of the full portfolio.

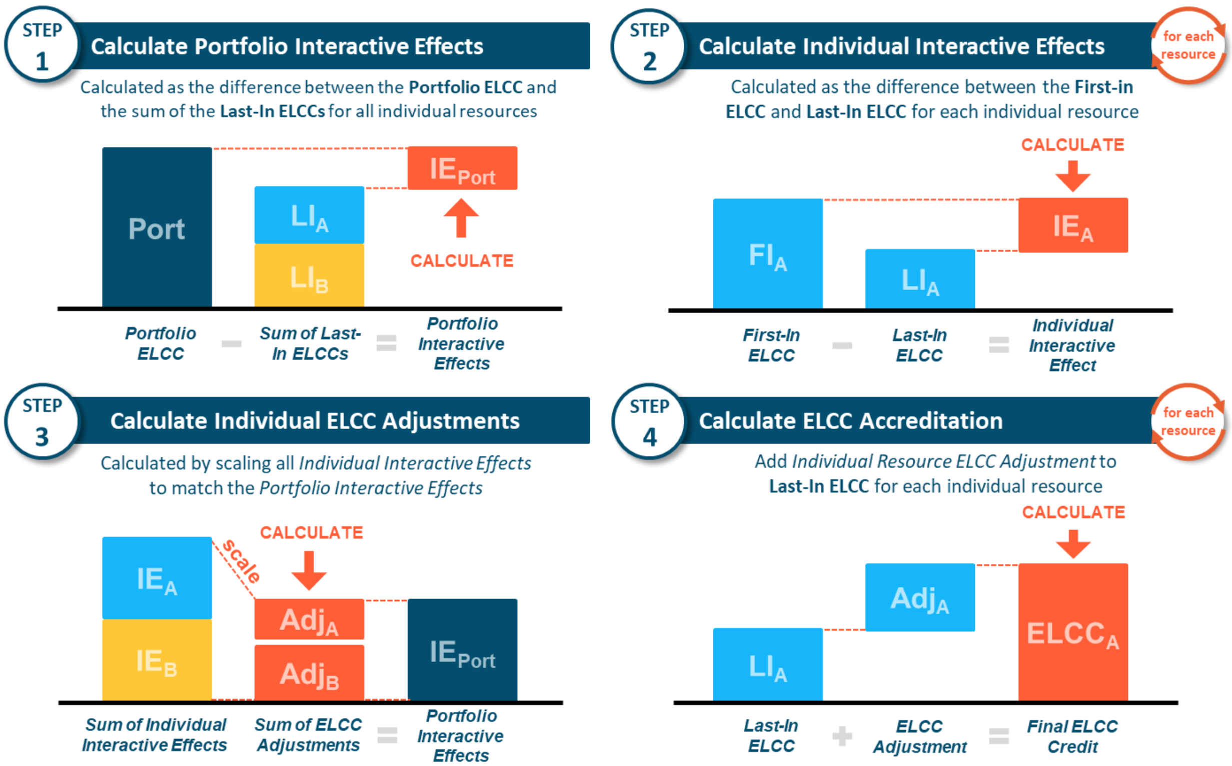
While neither the First-In ELCC nor the Last-In ELCC alone serve as an appropriate means to credit resources, together, they provide a natural means to characterize synergistic and antagonistic interactions within a portfolio. If a resource's Last-In ELCC exceeds its First-In ELCC, its contribution to resource adequacy is greater when considered in the context of the entire portfolio than on its own; this resource can be described as synergistic with the rest of the portfolio. If, on the other hand, a resource's Last-In ELCC is lower than its First-In ELCC, its contribution to resource adequacy is lower in the context of the entire portfolio than on its own; this resource is antagonistic with the rest of the portfolio. Note that any portfolio comprising three or more resources may include both synergistic and antagonistic resources.



Under the proposed method, herein referred to as the "Delta Method," each resource's Last-In ELCC is adjusted either upward or downward according to the difference between its Last-In and First-In ELCCs in a manner such that the sum of accredited ELCCs to all resources equals the ELCC of the portfolio. This approach ensures that the interactive effects between a resource and the portfolio are credited to resources in a manner that captures the effects of their interactions on resource adequacy. This method will naturally result in an accredited ELCC for each resource in between its First-In ELCC and Last-In ELCC.

Described in the graphic below, the method consists of the following steps. In Step 1, the total portfolio interactive effect (positive or negative) is derived as the difference between the total portfolio ELCC and the sum of the individual resource Last-in ELCCs. In Step 2, each resource's contribution toward the portfolio interactive effects is calculated as the difference between its First-in and Last-in ELCC. This value is then used in Step 3 as an allocator for the total portfolio effects calculated in Step 1. Then in Step 4, the allocated portfolio effects calculated in Step 3 are added to the Last-in ELCC to derive the final accredited value. The accredited ELCC value is thus composed of two parts: (1) a marginal ELCC based on the total portfolio, and (2) an allocated share of the portfolio effects caused by the aggregated non-firm resources.

This approach is naturally well-suited to account for synergistic, antagonistic, and neutral interactions simultaneously within a single portfolio; that is, the attribution of interactive effects may result in the accreditation of ELCCs that exceed the Last-In ELCC for some resources and are lower than the Last-In ELCC for others.



Most prior applications of ELCC in the context of organized markets have relied on average and adjusted class average approaches, arguably fulfilling several of our core design principles—most notably, reliability and acceptability—but exhibiting major shortcomings in promoting fairness and equitable treatment among resources. This is where the proposed Delta method offers a significant improvement upon these prior methods, namely:

- ✓ The approach is technology-neutral and does not rely on the potentially arbitrary definitions of technology classes, which could become increasingly problematic over time and unduly differentiate between similar resources that fall into different classes; and
- ✓ ELCC credits to individual resources directly reflect the nature of their synergistic, antagonistic, or neutral interactions with the portfolio by adjusting Last-in ELCC based on its difference from its First-in ELCC.

The following table summarizes a full scoring of both the Delta Method and the other existing methods introduced earlier in the paper.

	Reliability	Fairness	Efficiency	Acceptability
Marginal	Sum of individual capacity credits differs significantly from portfolio ELCC	Resources treated equitably based on marginal value to system	Provides the correct signal at the margin for new resource entry	Tractable and transparent, but subject to large year-to-year changes and value erosion
Vintaged Marginal	Sum of individual capacity credits equals portfolio ELCC	Resources with equal characteristics assigned different credits	Provides the correct signal at the margin for new resource entry	Volatility mitigated by vintaging, but tracking creates administrative complexities
Class Average	Sum of individual capacity credits differs from portfolio ELCC	Subject to bias due to class definitions; does not fully account for interactive effects	Deviates from true marginal throughout use of average credits	Tractable and transparent; volatility mitigated through averaging
Adjusted Class Average	Sum of individual capacity credits equals portfolio ELCC	Subject to bias due to class definitions; arbitrary treatment of interactions	Attributes interactive effects in a manner that may distort market signals	Tractable and transparent; volatility mitigated through averaging
Delta	**Sum of individual capacity credits equals portfolio ELCC**	**Credits assigned based on technical capability, agnostic to classification and vintage**	**Deviates from true marginal due to allocation of interactive effects**	**Tractable and transparent; volatility mitigated by allocation of interactive effects**

Market Considerations

While the Delta Method presents a theoretical framework for the accreditation of resource-specific ELCCs, there may be practical issues associated with implementing this method into existing markets. Addressing these issues will differ in each jurisdiction based on compatibility with existing market rules, but there are multiple additional questions that must be considered in implementation of an ELCC-based framework.

Question #1: What is the right level of granularity for calculation of ELCCs to balance tradeoffs among accuracy, computational burden, and administrative simplicity?

Capacity market administrators may find calculating the First-In ELCC and Last-In ELCC of each individual resource in the portfolio impractical for several reasons:

1. Running ELCC calculations for hundreds (or thousands) of individual resources is computationally intensive;
2. ELCC results for very small resources may not "converge" appropriately to the theoretically correct values due to conventions of existing modeling techniques; and
3. The historical production data for individual resources may not be of sufficient quality (at least years of historical hourly data) for the purposes of evaluating individual resource ELCCs.

A practical application of the Delta method may therefore require certain simplifications that preserve the key elements of the approach. Namely, instead of calculating a First-In ELCC and Last-In ELCC for each resource based on its individual production profile, a program administrator may calculate First-In ELCC and Last-In ELCC for a representative class of resources and then apply those representative values to each of the individual resources. Defining representative resource classes should capture a meaningful distinct set of characteristics such as plant design, age, and geography for renewable resources and duration and efficiency for energy storage. A resource class could be as small as three (wind, solar, and four-hour storage) or could encompass tens of representative resources. In other words, the Delta method is still compatible with a class-based approach, though it is crucial to distinguish it from the adjusted class average approaches, which calculate the ELCC of an entire class instead of a representative resource within that class, inadvertently capturing saturation effects due to overly large calculation intervals.

Question #2: How can markets be structured to mitigate risks to participants, considering the potential volatility and uncertainty inherent in the application of ELCC?

Capacity procurement mechanisms are designed to provide efficient price signals for investment and transparent and predictable capacity value to help developers finance these projects. Implementing ELCC accreditation into these mechanisms may reduce the transparency and predictability of capacity value relative to existing pre-defined approaches, which could serve as a barrier and increase financing costs of renewable and energy-limited resources. To combat this, capacity market administrators could consider the following:

+ **Consideration 1:** Conduct forward-looking studies using the same models to forecast how ELCCs for different types of resources would change under hypothetical future scenarios. This information would help to reduce some of the uncertainty associated with the complex computational mechanics of ELCC determination while still requiring the developer and investor communities to make their own projections of how the future system would change and with it, their potential capacity market revenues.

- **Consideration 2:** Allow new intermittent and limited-duration resources to lock in their ELCC or provide these resources a guaranteed floor to ensure their ELCC will not be credited below a certain value for a limited period of time. This could be accomplished by applying the Vintaged Marginal approach described above for an initial time period, after which all resources would revert to the pool and be accredited as part of the broader portfolio.
- **Consideration 3:** Use state administered "contracts-for-differences" whereby the state covers the financial implications of differences between forecasted ELCC and actual ELCC to reduce the uncertainty of market outcomes for resources that meet state-directed policy goals.

It is also important to consider that other energy market products (e.g. day-ahead and real-time energy, ancillary services, etc.) contain volume and price risk that is a function of other resources on the system, and that these values are not locked-in and must be forecasted by market participants. To the extent that market operators provide additional certainty to ELCC relative to other products, it is important that there is a strong justification for doing so.

Question #3: How should performance obligations and/or penalties be structured for resources whose contributions to the system are inherently limited (as captured by ELCC)?

Resources that participate in centralized capacity markets are typically subject to performance requirements. These requirements generally consist of:

- **Must-offer requirements** that require resources to offer their capacity into the day-ahead energy market so the system operator can schedule that resource as needed
- **Pay-for-performance structures** that occur in periods of low reserve availability on the system in which resources are penalized with high prices (often driven by "scarcity pricing")

These constructs were designed with dispatchable thermal generation in mind. These resources are generally required to offer their awarded capacity amounts into the day-ahead energy market for all 24 hours of the day and are expected to perform during pay-for-performance events—which may occur at any time. However, this would be an inappropriate standard to apply to intermittent and energy-limited resources, as the ELCC values for these technology types already account for lack of availability 24 hours a day. Therefore, several considerations for a different approach are warranted.

- **Consideration 4:** Any performance requirements of intermittent or energy-limited resources should be closely aligned with the modeled performance from which the ELCC was determined. Performance requirements must consider the fundamental operating characteristics of those resources (e.g., time-dependent hourly profiles, dispatch duration limits) that are already accounted for in their ELCC. If a resource's performance in the market exactly matches its performance in the loss-of-load model, it should be neither penalized for non-performance nor rewarded for excess performance. As a simple example, a solar resource should not be penalized for lack of performance during nighttime hours, not only for the obvious reason that it cannot perform without sunlight, but also because the ELCC value accredited to it is a function of both its expected performance during daytime hours (high) and its expected performance during nighttime hours (zero). Instead, resources should only be penalized if they are generating below expected output due to factors outside of their control and not considered in the ELCC accreditation process, such as forced outages or poor upkeep.

- **Consideration 5:** Market operators should carefully reexamine energy market price caps and consider lifting them to enable higher prices during scarcity events. Higher energy prices can reduce resources' need for capacity market revenues and thus the importance of the complex market design associated with it, while at the same time providing a more acute price signal in real time encouraging resources to perform according to their maximum capabilities during the periods that they are most needed. This need not raise costs to consumers, because capacity market participants will in theory incorporate the higher revenues anticipated in the energy market into their reduced forward capacity bids.

Conclusion

The inevitable transition to a decarbonized electricity system that is heavily dependent on non-firm resources has already begun and will continue to escalate with both policy and economic tailwinds. It is thus imperative that electricity markets are well-positioned to integrate these resources into the existing system in a way that fairly compensates all resources for the attributes that they provide. ELCC accreditation is a key component to a functioning centralized capacity market that provides fair and efficient signals to new and existing resources while maintaining acceptable standards of reliability.

Interactions among non-firm resources are an inherent characteristic of a deeply decarbonized electricity system and will grow to be of profound importance. These interactions must be addressed directly in any centralized capacity market design. The "Delta Method" proposes a framework to credit resource-specific ELCCs in a manner that fairly recognizes the synergistic and antagonistic interactions of each resource with the broader portfolio. When evaluated in comparison to other existing and proposed ELCC accreditation methods, the Delta Method outperforms along the key principles of reliability, fairness, efficiency, and acceptability. To the extent that the Delta Method is implemented into existing capacity market frameworks in North America, it is important to consider several practical implementation issues including administrative and computational tractability, potential volatility and uncertainty, price signals for efficient capital allocation, and performance obligations of resources.

Overall, the Delta Method provides an important step forward in the evolution of centralized capacity markets that are both consistent with and will enable a deeply decarbonized electricity system in a robust and durable manner.

References

[1] L. L. Garver, "Effective Load Carrying Capability of Generating Units," IEEE Trans. Power Syst., vol. PAS-85, no. 8, pp. 910-919, Aug. 1966.

[2] Probabilistic Assessment, Technical Guideline Document, Tech. Rep., North American Energy Reliability Corporation, Aug. 2016.

[3] G. E. Haringa, G. A. Jordan, and L. L. Garver, "Application of Monte Carlo simulation to multi-area reliability evaluation," IEEE Computer Applications in Power, vol. 4, pp. 21–25, Jan. 1991.

[4] Probabilistic Adequacy and Measures, Technical Reference Report, Tech. Rep., North American Energy Reliability Corporation, Apr. 2018.

[5] Methods to Model and Calculate Capacity Contribution of Variable Generation for Resource Adequacy Planning, Tech. Rep., North American Energy Reliability Corporation, Mar. 2011.

[6] R. Billinton, P. Harrington, "Reliability Evaluation in Energy Limited Generating Capacity Studies," IEEE Trans. Power Appl. Syst., vol. 97, no. 6, pp. 2076–2085, Nov. 1978.

[7] R. Billinton, R. Allan, Reliability Evaluation of Power Systems, 2nd edition, Spring Science + Business Media, New York, NY, pp. 10013–11578, 1996

[8] Reliability Requirement, CAISO. Available at: http://www.caiso.com/planning/Pages/ReliabilityRequirements/Default.aspx

[9] Planning Year 2019-2020 Wind & Solar Capacity Credit, MISO, Dec. 2018. Available at: https://cdn.misoenergy.org/2019%20Wind%20and%20Solar%20Capacity%20Credit%20Report303063.pdf

Technical Appendix

The Delta Method to ELCC accreditation can be represented using the following equations:

Consider a system with resources $r_1, r_2 \ldots r_n$ with installed capacities of $C_1, C_2 \ldots C_n$, respectively. The ELCC function for this system is given by $f(r_1, r_2 \ldots r_n)$. Then:

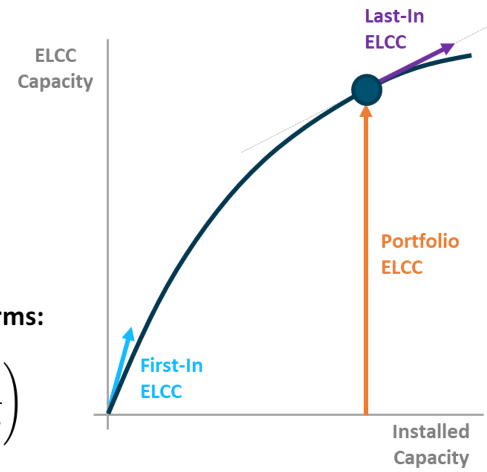
Portfolio ELCC: $P = f(C_1, C_2 \ldots C_n)$

First-In ELCC: $FI_i = C_i \cdot \frac{\partial f}{\partial r_i}(0, 0 \ldots 0)$

Last-In ELCC: $LI_i = C_i \cdot \frac{\partial f}{\partial r_i}(C_1, C_2 \ldots C_n)$

The ELCC attributed to each resource is calculated from these terms:

Resource ELCC: $ELCC_i = LI_i + \left(P - \sum_{j=1}^{n} LI_j\right)\left(\frac{LI_i - FI_i}{\sum_{j=1}^{n} LI_j - FI_j}\right)$



The following represents a simple and illustrative numeric example demonstrating how ELCC credits would be calculated using the Delta Method on a system with solar, wind, and storage resources. The illustrative portfolio is representative of the California electricity system, which has a peak load of approximately 50,000 MW.

Item	Units	Solar	Wind	Storage	Notes
# of Plants	*#*	200	50	10	
Representative Plant Size	*MW*	100	100	100	
Total Capacity	*MW*	20,000	5,000	1,000	Plant size * # of plants
First-In ELCC for Representative Plant	*MW*	50	30	80	Calculated in LOLP model
	%	50%	30%	80%	First-In ELCC / Representative Plant Size
Last-In ELCC for Representative Plant	*MW*	10	20	90	Calculated in LOLP model
	%	10%	20%	90%	Last-In ELCC / Representative Plant Size
Portfolio ELCC	*MW*	8,000			Calculated in LOLP model
Portfolio Interactive Effects	*MW*	4,100			Portfolio ELCC – Sum of Last-In ELCCs for All Resources 8,000 – (200 * 10 + 50 * 20 + 10 * 90)
Individual Interactive Effect	*MW*	+40	+10	-10	First-In ELCC MW – Last-In ELCC MW for Representative Resources Solar: 50 - 10 Wind: 30 - 20 Storage: 80 - 90
Sum of Individual Interactive Effects	*MW*	8,400			200 * 40 + 50 * 10 + 10 * -10
Individual Resource ELCC Adjustments	*MW*	20	5	-5	Individual Interactive Effect / Sum of Individual Interactive Effects * Portfolio Interactive Effects Solar: 40 / 8,400 * 4,100 Wind: 10 / 8,400 * 4,100 Storage: -10 / 8,400 * 4,100
Individual Resource ELCC Credit	*MW*	30	25	85	Last-In ELCC + Individual Resource ELCC Adjustment Solar: 10 + 20 Wind: 20 + 5 Storage: 90 – 5
Individual Resource ELCC Credit	*%*	30%	25%	85%	Individual Resource ELCC Credit / Representative Plant Size