

Decomposition and Optimization in Constructing Forward Capacity Market Demand Curves

Feng Zhao, Tongxin Zheng and Eugene Litvinov

Abstract—This paper presents an economic framework for designing demand curves in Forward Capacity Market (FCM). Capacity demand curves have been recognized as a way to reduce the price volatility inherited from fixed capacity requirements. However, due to the lack of direct demand bidding in FCM, obtaining demand curves that appropriately reflect load’s willingness to pay for reliability is challenging. The proposed framework measures the value of reliability by the Cost of Unserved Energy (CUE), i.e., Expected Unserved Energy (EUE) multiplied by Value of Lost Load (VOLL). The total cost of capacity and CUE are then minimized, allowing economic tradeoffs between different reliability levels. EUE, a multivariate function of the total system capacity and its distribution among capacity zones, is decomposed into single-variable functions, which form the base for system and zonal demand curves. VOLL is implied from the Net Cost of New Entry (Net-CONE) based on long-term market equilibrium properties. The proposed framework is applied to a multi-zone ISO New England system to demonstrate its effectiveness.

Index Terms—Capacity demand curve, Cost of New Entry (CONE), decomposition, Expected Unserved Energy (EUE), Forward Capacity Market (FCM), market equilibrium, value of reliability, Value of Lost Load (VOLL).

I. INTRODUCTION

Forward Capacity Market (FCM) has been adopted in many regions (e.g., ISO-NE, MISO, NYISO and PJM) to address long-term resource adequacy and the missing money problem¹ ([1]-[5]). The *fundamental* goal of FCM is to attract the right amount of capacity at the right locations (so that the appropriate level of system reliability is maintained) through proper price signals, while the “rightness” should be defined through the balance between reliability and cost. Most capacity markets employ fixed capacity requirements for the system or zones. These fixed requirements are determined prior to the capacity auction based on a prescribed reliability level, e.g., Loss of Load Expectation (LOLE) of 1 day in 10 years. The use of fixed capacity requirements, or, equivalently, vertical or price-inelastic demand curves in FCM, undermines the above fundamental FCM goal in three aspects: *First*, by fixing the capacity requirements, the market does not have the option to choose the proper level of system reliability. As a result, the reliability level implied by these requirements could be suboptimal, e.g., the cost for the required capacity levels could outweigh the value of the implied reliability. *Second*, when capacity zones are modeled in FCM to address the capacity deliverability issue, the fixed capacity requirements do not allow the market to trade off capacity among different zones. As a result, the capacity distribution may not be optimal, e.g., FCM may procure expensive capacity in a zone to meet its fixed zonal requirement while potentially ignoring a more efficient solution of procuring less capacity in that zone but more in another zone. *Lastly*, vertical demand curves lead to significant price volatility, e.g., the market clearing price tends to skyrocket when there is *any* capacity shortage from the fixed requirement, and the market price plummets when there is a capacity surplus. Such price volatility increases the risk for capacity investment and load payment, and impedes the formation of adequate price signals for long-term investment. Furthermore, the market may be prone to the market power.

In light of the above shortcomings of fixed capacity requirements, sloped or price-elastic capacity demand curves have been discussed or implemented in different regions. Particularly in 2013, Federal Energy Regulatory Commission (FERC) issued a report on centralized capacity market design that identifies demand curves as a major design element [6]. ISO-NE has implemented a 3-segment linear system capacity demand curve since 2015 to replace the fixed Installed Capacity Requirement (ICR), and was required by FERC (Docket No. EL16-15-000) to develop zonal capacity demand curves. Despite being an important improvement to the fixed ICR, the parameters of the 3-segment system demand curve are determined by market simulations that use presumed market bids, and the transition points of the curve are selected administratively, largely based on

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¹The missing money problem arises when a resource could not recover its investment and operational costs due to the presence of administrative price caps in energy markets. While the problem takes a more prominent form of revenue inadequacy for those units that run only in peak hours, it applies to all units. The problem likely leads to the resource inadequacy problem in the long run. Therefore, the two problems are two sides of the same coin.

stakeholder consensus. Furthermore, the *linear* shape and the *number* of segments are more a convenient choice than the rigorous analysis. As a result, the approach was found difficult to extend to zonal demand curves. PJM implements 4-segment linear Variable Resource Requirement (VRR) curves (i.e., capacity demand curves) for both system and Locational Deliverability Areas (LDAs) in its FCM [7]. The approach suffers similar drawbacks as the ISO-NE's existing 3-segment system demand curve. Furthermore, the approach uses separate system and local reliability objectives, i.e., 1-in-10 LOLE for the system and 1-in-25 for LDAs, to produce the system and local VRRs, thus disregarding the correlation between system and local loss of load events. NYISO uses 3-segment linear demand curves for its Installed Capacity (ICAP) *spot* market [8]. The transition points on the demand curve are prescribed as certain percentages of the forecasted peak load plus a reserve margin. The parameters of the curve, including the transition points, are subject to recurring reviews. MISO runs a 1-year ahead Planning Resource Auction (PRA) to procure capacities that cover the forecasted peak load plus the reserve margin [9]. Vertical or fixed demand is currently implemented in the PRA. However, there is an increasing interest in MISO to introduce a new 3-year ahead Forward Resource Auction (FRA) with sloped demand curves. Demand curves in the above capacity markets have been analyzed in [10]-[12], but none has produced rigorous justifications for the existing demand curves.

All demand curves implemented in the existing capacity markets share the following common weaknesses: lack of a *rigorous and complete economic framework* that supports the development of demand curves; and lack of clear recognition of the *interactions between system and local demand curves*. As a result, the demand curves often involve assumptions that are hard to justify, while the meaning of demand curves is often obscure and does not connect with the demand's willingness to pay for reliability (especially in the presence of both system and local demand curves).

Demand curve is not a new concept in economics literature. Efforts were made to derive demand curves. Hogan [13] proposed an operating reserve demand curve (ORDC) based on the product of VOLL and Loss of Load Probability (LOLP) for short-term reserve markets. In the presence of local reserve zones, the approach implies zonal ORDCs based on the prescribed zonal "configuration of lost load" and may not lead to explicit two-dimensional curves. Furthermore, the paper did not instruct how to estimate the VOLL, an important parameter for ORDC. The Brattle Group reviewed the PJM's capacity market design and recommended "defining local reliability objectives in terms of normalized unserved energy" and "exploring this alternative standard based on a multi-area reliability model that simultaneously estimates the location-specific EUE among different PJM system and sub-regions" [14]. The Brattle report did not provide a systematic framework or details of "local reliability objectives." Rudkevich et al. [15] proposed a stochastic optimization framework to derive locational resource adequacy indicators as price indicators for general transmission constrained systems. While the paper did not address demand curves, it provides useful insights about how the marginal capacity cost is related to the cost of unserved energy.

In the absence of demand bids for capacity, the **major theoretical challenge** for designing meaningful demand curves is to appropriately reflect their economic essence, i.e., the value of reliability, *without* direct expression from the consumers. Also, in the presence of zonal interface limits, capacities in different zones have different reliability implications, while they are all counted as part of the system capacity. How to design zonal and system demand curves that appropriately capture the interaction between zonal and system capacities while keeping the curves in a simple form (e.g., 2-dimensional) becomes the **major technical challenge**.

In this paper, we present a rigorous economic framework based on *social-surplus maximization* that incorporates both the cost of capacity and the **value of reliability**. The reliability value is measured by consumers' avoided Cost of Unserved Energy (CUE), i.e., the product of Value of Lost Load (VOLL) and Expected Unserved Energy (EUE). Then the marginal value of reliability, based on the derivative of CUE, is used to represent the *load's willingness to pay for capacity*, i.e., **the demand curve**². Since capacities in different locations have different impact on reliability, EUE is not only affected by the total capacity in the system, but by the allocation of the system capacity as well. As a result, EUE and CUE are multi-variate functions of the total system capacity and its distribution among zones. The marginal value of reliability is also a multi-variate function of the system and zonal capacities. To obtain a simple 2-dimensional form for demand curves, we first decompose EUE into a *system capacity related component* that is caused by the system capacity shortage, and an *additional component* that is caused by interface limits. Note that the decomposition here is different from the zonal LOLP configuration in [13], which needs to be prescribed and amounts to unconventional locational reliability criteria. Our approach counts the total system EUE for each decomposed component, consistent with the widely adopted system reliability criteria in practice. With the independence assumption for reliability impact of different interfaces, the additional component is further split into individual zonal capacity related components. As a result, the EUE function is decomposed into system and zonal capacity related components that are used to derive the corresponding demand curves. Since power system reliability is treated as a public good, a uniform VOLL is considered for all locations. Estimating VOLL is notoriously difficult and a wide range of values from several thousand to tens of thousands of U.S. dollars per MWh have been reported [16]-[19]. Based on the property of the long-term market equilibrium, this paper derives VOLL from the marginal cost of capacity, i.e., Net Cost of New Entry (Net-CONE) that has been established in all existing capacity markets. With decomposed EUE, system and zonal demand curves are derived from the derivatives of

² The demand curve is the inverse demand function in economics terms.

corresponding EUE components scaled by the VOLL. The economic **interpretation of demand curves** is obtained from the Karush-Kuhn-Tucker (KKT) optimality conditions of the social surplus maximization problem.

The major contributions of this paper are: First, it provides a *complete and rigorous economic framework* for the development of FCM demand curves. To the authors' best knowledge, no existing design has achieved the level of completeness and rigor of this paper. Second, it provides a *sensible decomposition of reliability* (i.e., EUE in this paper) that leads to a simple yet meaningful 2-dimensional representation of demand curves. Lastly, the proposed demand curve design is highly practical. A filing based on this paper's approach has been approved recently by FERC (Docket No. ER16-1434-000, Issued June 28th, 2016), and we demonstrated our approach with a real-size New England system in this paper. The rest of the paper is organized as follows. Section II presents the economic framework and the derivation of demand curves. Section III describes a practical process of generating the demand curves. Section IV studies the demand curves for the ISO-NE system. Section V concludes the paper.

II. ECONOMIC FRAMEWORK

In this section, we present an economic framework for producing and applying capacity demand curves. We start with analyzing the reliability value of the capacity for loads (*Subsection II.A*). The demand curves are derivatives of the reliability value function. In view of the multi-variate reliability function of zonal capacities and the desired single-variable capacity demand functions, decomposition and approximation of the multi-variate reliability function are introduced to obtain system and zonal components of reliability (*Subsection II.B*). The corresponding system and zonal capacity demand curves are then derived from these components (*Subsection II.C*). The demand curves are used in the capacity market clearing (*Subsection II.D*), resulting in desired cascading capacity clearing prices (*Subsection II.E*). Then, VOLL as the scaling factor of the demand curves is implied from the Net capacity Cost of New Entry (Net-CONE) based on long-term market equilibrium (*Subsection II.F*). Finally, we discuss the extensibility and limitation of our framework (*Subsection II.G*).

For simplicity, we use a stylized capacity market with one Import Constrained Zone (ICZ), one Export Constrained Zone (ECZ) and the Rest of System (ROS) zone³. The system configuration is depicted in Fig. 1.



Fig.1. System configuration

A. The value of reliability

Capacity demand curves are supposed to reflect *consumers' willingness to pay* for capacity. In the absence of direct capacity demand bids from consumers, we rely on the economic essence of capacity product to derive the demand curves. As discussed in [20], *capacity* product indeed is a surrogate for *reliability*. Therefore, the **value of reliability** is essential for deriving capacity demand curves.

Conventional reliability theory [21] establishes various reliability indices. The mostly adopted reliability index in North America is Loss of Load Expectation (LOLE) with the typical criterion of 1 day in 10 years [22]. While LOLE captures the frequency of loss of load events, it does not reflect the severity of service interruptions, e.g., the size of loss of load. EUE captures both frequency and size that affect the value of reliability. Therefore, we adopt EUE as the reliability index in the following derivation.

For a multi-zone system such as the one depicted in Fig. 1, unserved energy can be caused by the deficiency in the system capacity or limitation of transfer capability between zones. Therefore, system reliability is impacted by both the total system capacity and the allocation of system capacity among zones. Let's denote the capacities in the system, ICZ and ECZ by Q_{SYS} , Q_{ICZ} , Q_{ECZ} , respectively. Then, the reliability, measured by EUE in *MWh/Year*, is a **multivariate function** of all three capacity levels, i.e., $EUE(Q_{SYS}, Q_{ICZ}, Q_{ECZ})$. The multivariate surface with one ICZ and no ECZ is illustrated in Fig. 2 where the dots on the surface represent EUEs corresponding to the sampled system and ICZ capacity levels.

³ The example can be easily extended to more complicated configurations.

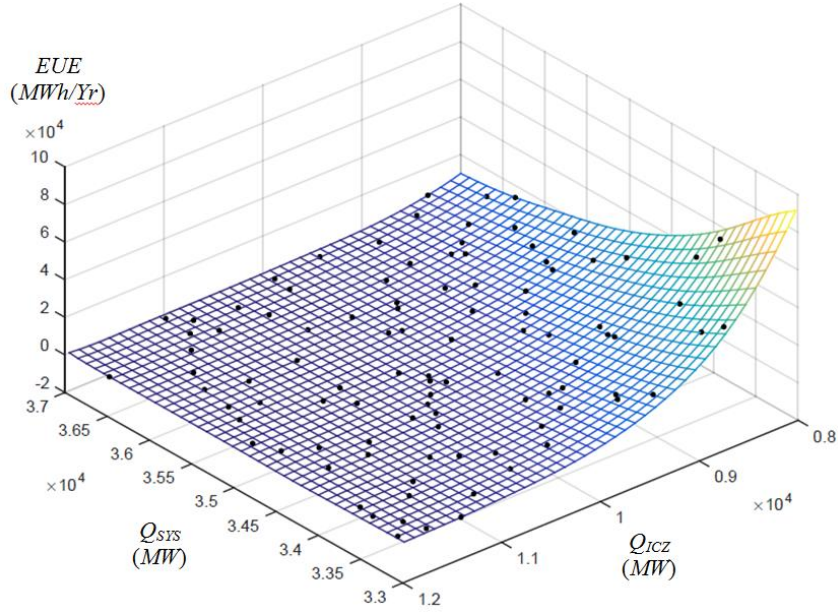


Fig.2. Multivariate EUE function

To measure the value of reliability, we introduce VOLL in $\$/MWh$. Since reliability is treated as a public good, the same VOLL shall apply to every MW of lost load, irrespective of its location. Therefore, the **value of reliability**, which is based on the *Cost of Unserved Energy* (CUE), can be represented as:

$$CUE(Q_{SYS}, Q_{ICZ}, Q_{ECZ}) = VOLL \cdot EUE(Q_{SYS}, Q_{ICZ}, Q_{ECZ}) \quad (1)$$

B. Decomposition of EUE/CUE

The **marginal value of reliability**, or the derivative of CUE, represents consumers' willingness to pay for reliability, or, the demand curve. Since CUE is a multi-variate function, its derivatives, are also multi-variate functions. Multi-variate demand functions imply coupling among capacity levels of different zones, i.e., one zone's willingness to pay would not only depend on the demand level of that zone, but demand levels of all other zones as well. Evaluation of the multi-variate CUE function based on the multi-area reliability theory is much more complex than the single area reliability [23]-[26]. Furthermore, the coupling among different capacity zones makes the demand functions difficult to interpret, and poses significant challenges to numerical approximation of the demand functions and the market clearing process.

To address the above challenges, our approach is to decompose the EUE function (and hence CUE) into single-variable components such that each would lead to a demand curve relating only to the capacity level of a particular zone. Approximation may need to be involved in the decomposition as shown later in this subsection. Also, there exists multiple ways of decomposition. The **key challenge** is to find an appropriate decomposition formula that yields meaningful and easy-to-interpret demand curves. Below is our decomposition.

Loss of load can be caused either by the inadequate system capacity or the insufficient transfer capability between zones. Therefore, a natural way of decomposing the multi-variate EUE function is to separate the two causes, i.e.,

$$EUE(Q_{SYS}, Q_{ICZ}, Q_{ECZ}) = EUE_{SYS}(Q_{SYS}) + EUE_{A/SYS}(Q_{ICZ}, Q_{ECZ} | Q_{SYS}) \quad (2)$$

where $EUE_{SYS}(Q_{SYS})$ is the expected unserved energy resulting from the system capacity deficiency (i.e., treating the entire system as a single zone without considering zonal interface limits); and $EUE_{A/SYS}(Q_{ICZ}, Q_{ECZ} | Q_{SYS})$ is the “**additional**” expected unserved energy resulting from the distribution of system capacity Q_{SYS} in the presence of interface constraints. It can be seen that $EUE_{SYS}(\cdot)$ is a single-variable function since it only depends on the total system capacity. However, $EUE_{A/SYS}(\cdot)$ is still a multivariate function as it depends on the total system capacity and its distribution in ICZ and ECZ. Further decomposition of $EUE_{A/SYS}(\cdot)$ is needed.

In practice, the fixed zonal capacity requirements are calculated one zone at a time [27], i.e., one zone's capacity requirement is not affected by other zones' capacity allocation. The underlying assumption is that the reliability impact of one zone's capacity is independent of other zones'. Under the same assumption, the $EUE_{A/SYS}$ resulting from the distribution of system capacity can be decomposed into individual zones, i.e.,

$$EUE_{A|SYS}(Q_{ICZ}, Q_{ECZ} | Q_{SYS}) = EUE_{ICZ|SYS}(Q_{ICZ} | Q_{SYS}) + EUE_{ECZ|SYS}(Q_{ECZ} | Q_{SYS}) \quad (3)$$

where $EUE_{ICZ|SYS}(Q_{ICZ} | Q_{SYS})$ is the additional expected unserved energy caused by the ICZ import limit when allocating Q_{ICZ} of system capacity Q_{SYS} into the ICZ; and $EUE_{ECZ|SYS}(Q_{ECZ} | Q_{SYS})$ is the additional expected unserved energy caused by the ECZ export limit when allocating Q_{ECZ} of system capacity Q_{SYS} into the ECZ. Note that $EUE_{ICZ|SYS}(\cdot)$ and $EUE_{ECZ|SYS}(\cdot)$ depend not only on the capacity in the corresponding zone, but the total system capacity as well. Therefore, these two functions are still multi-variate. However, in our testing of the NE system, we found that these EUE values are not sensitive to the system capacity Q_{SYS} around the *nominal* system capacity level of ICR, which corresponds to the desired “1-in-10” LOLE criterion. As a result, $EUE_{ICZ|SYS}(\cdot)$ and $EUE_{ECZ|SYS}(\cdot)$ in (3) are approximated as

$$EUE_{ICZ|SYS}(Q_{ICZ} | Q_{SYS}) \approx EUE_{ICZ|SYS}(Q_{ICZ} | ICR) \quad (4)$$

$$EUE_{ECZ|SYS}(Q_{ECZ} | Q_{SYS}) \approx EUE_{ECZ|SYS}(Q_{ECZ} | ICR) \quad (5)$$

Ideally, the system capacity Q_{SYS} in the above approximations should be the optimal level of the system capacity from the capacity market clearing, e.g., Q_{SYS}^* , instead of ICR. Therefore the approximation error can be measured by the difference between $EUE_{Z|SYS}(E_Z | Q_{SYS}^*)$ and $EUE_{Z|SYS}(E_Z | ICR)$ where $Z = ICZ$ or ECZ . In the lack of knowing Q_{SYS}^* prior to the market clearing, we can specify a range $[Q_{min}, Q_{max}]$ surrounding ICR for estimating Q_{SYS}^* , with Q_{min} and Q_{max} denoting the bounds for possible cleared system capacity⁴. Then the approximation error in (4)-(5) can be capped by the deviation from $EUE_{Z|SYS}(E_Z | ICR)$ to $EUE_{Z|SYS}(E_Z | Q_{min})$ or $EUE_{Z|SYS}(E_Z | Q_{max})$. Our testing of the NE system found the error to be quite small.

Substituting (3)-(5) into (2), we have:

$$EUE(Q_{SYS}, Q_{ICZ}, Q_{ECZ}) \approx EUE_{SYS}(Q_{SYS}) + EUE_{ICZ|SYS}(Q_{ICZ} | ICR) + EUE_{ECZ|SYS}(Q_{ECZ} | ICR) \quad (6)$$

The right-hand side components in (6) are single-variable functions with respect to the system total capacity Q_{SYS} , ICZ capacity Q_{ICZ} and ECZ capacity Q_{ECZ} , respectively. Consequently, the **value of reliability**, or the *Cost of Unserved Energy* (CUE) in (1), can be decomposed as:

$$CUE(Q_{SYS}, Q_{ICZ}, Q_{ECZ}) = VOLL \times EUE_{SYS}(Q_{SYS}) + VOLL \times EUE_{ICZ|SYS}(Q_{ICZ} | ICR) + VOLL \times EUE_{ECZ|SYS}(Q_{ECZ} | ICR) \quad (7)$$

where the right-hand-side components represent the CUE associated with Q_{SYS} , Q_{ICZ} and Q_{ECZ} , respectively.

System reliability improves (i.e., less unserved load) when there is more capacity in the system. Therefore, $EUE_{SYS}(\cdot)$ in (6) is a *monotonically decreasing* function of Q_{SYS} . Also, the capacity in ICZ has more value than that of the rest of system due to the zone’s import limit. Therefore, system reliability improves when more capacity is allocated in ICZ, i.e., $EUE_{ICZ|SYS}(\cdot)$ in (6) is a *monotonically decreasing* function of Q_{ICZ} . On the other hand, system reliability deteriorates when more capacity is allocated in ECZ where the capacity is constrained by the export limit. Namely, $EUE_{ECZ|SYS}(\cdot)$ in (6) is a *monotonically increasing* function of Q_{ECZ} .

C. Capacity demand curves

With the above decomposition of the value of reliability in (7), **demand curve**, as the *marginal value of reliability* for corresponding system or zonal capacity, can be represented by the *negative* derivative of the corresponding CUE components in (7) (with the negative sign to convert cost into value), i.e.,

$$D_{SYS}(Q_{SYS}) = -VOLL \times \frac{dEUE_{SYS}(Q_{SYS})}{dQ_{SYS}} \quad (8)$$

$$D_{ICZ}(Q_{ICZ}) = -VOLL \times \frac{dEUE_{ICZ|SYS}(Q_{ICZ} | ICR)}{dQ_{ICZ}} \quad (9)$$

$$D_{ECZ}(Q_{ECZ}) = -VOLL \times \frac{dEUE_{ECZ|SYS}(Q_{ECZ} | ICR)}{dQ_{ECZ}} \quad (10)$$

where $D_{SYS}(\cdot)$, $D_{ICZ}(\cdot)$ and $D_{ECZ}(\cdot)$, respectively, are the system and zonal demand curves representing the annualized marginal value of capacity in \$/mw-year.

⁴ As we design the VOLL parameter to achieve the “1-in-10” criterion under the long-term market equilibrium (discussed in Section II.F), the optimal system capacity Q_{SYS}^* is considered to converge to the ICR in the long run. Under the convergence, the range is bounded and would be narrower along the convergence path, implying smaller approximation error in (4)-(5).

The EUE components associated with system and ICZ capacities in (6) are monotonically decreasing functions. As a result, their derivatives are negative, and the corresponding system and ICZ demand curves in (8)-(9) have positive values. Furthermore, as we will derive in the next Section, the derivative of EUE (with the negative sign) is in general proportional to the Loss of Load Hours (LOLH)⁵. The LOLH, as a reliability index, decreases when the capacity increases. Therefore the system and ICZ demand curves are monotonically decreasing. Likewise, the ECZ demand curve in (10) has negative values and is monotonically decreasing.

It should be noted that zonal demand curves are derived from the EUE components that reflect the additional unserved energy caused by the interface limits. Therefore, zonal demand curves reflect the load's *additional willingness to pay* for capacity in the corresponding zones besides the marginal value of the total system capacity. The *total willingness to pay* for capacity in an ICZ or ECZ zone is then a combination of the system and zonal demand curve values, i.e.,

$$D_{SYS}(Q_{SYS}) + D_Z(Q_Z), \quad Z = ICZ \text{ or } ECZ. \quad (11)$$

Note that the above total willingness to pay in (11) depends on both the system capacity Q_{SYS} and its allocation Q_Z in the zone.

With the demand curves (8)-(10), the CUE in (7) can be represented as

$$CUE(Q_{SYS}, Q_{ICZ}, Q_{ECZ}) = -\int_0^{Q_{SYS}} D_{SYS}(Q) \cdot dQ - \int_0^{Q_{ICZ}} D_{ICZ}(Q) \cdot dQ - \int_0^{Q_{ECZ}} D_{ECZ}(Q) \cdot dQ \quad (12)$$

D. Social-surplus maximization

The objective of the Forward Capacity Market (FCM) is to maximize the total surplus of capacity supply and demand, or equivalently, to **minimize the total costs of capacity offers and CUE**, i.e.,

$$\begin{aligned} \text{Minimize} \quad & \sum_{i \in Z_{ICZ}} C_i(q_i) + \sum_{j \in Z_{ECZ}} C_j(q_j) + \sum_{k \in Z_{ROS}} C_k(q_k) \\ & - \int_0^{Q_{SYS}} D_{SYS}(Q) \cdot dQ - \int_0^{Q_{ICZ}} D_{ICZ}(Q) \cdot dQ - \int_0^{Q_{ECZ}} D_{ECZ}(Q) \cdot dQ \end{aligned} \quad (13)$$

where Z_{ICZ} , Z_{ECZ} and Z_{ROS} , respectively, are the sets of capacity offers in ICZ, ECZ and ROS; q_i , q_j , and q_k are the cleared quantities of capacity offers in the corresponding zones; Q_{ICZ} , Q_{ECZ} and Q_{ROS} are cleared demand in corresponding zones; and $C_i(\cdot)$, $C_j(\cdot)$, and $C_k(\cdot)$ are the costs associated with corresponding capacity offers.

The total cleared system capacity should meet the total system demand, i.e.,

$$\sum_{i \in Z_{ICZ}} q_i + \sum_{j \in Z_{ECZ}} q_j + \sum_{k \in Z_{ROS}} q_k \geq Q_{SYS} \quad (14)$$

Similarly, the cleared capacity in ICZ should meet the ICZ demand, i.e.,

$$\sum_{i \in Z_{ICZ}} q_i \geq Q_{ICZ} \quad (15)$$

For the export zone, the zonal demand serves as a “*limit*” instead of *requirement* in order to limit the capacity allocated in the interface-constrained export zone, i.e.,

$$\sum_{j \in Z_{ECZ}} q_j \leq Q_{ECZ} \quad (16)$$

Each capacity offer has its own constraints, e.g., capacity size. The constraints for an offer i is denoted by Ω_i . Thus we have

$$q_i \in \Omega_i, \quad \forall i \in Z_{ICZ} \cup Z_{ECZ} \cup Z_{ROS} \quad (17)$$

The FCM clearing problem is then (13)-(17). It can be seen that with demand curves, the FCM problem allows tradeoffs between costs and values of capacity, and tradeoffs between capacities in different zones. These features are unavailable under the fixed capacity requirements.

E. Capacity Clearing Prices

In this subsection, we define the capacity clearing prices and link them to the demand curves based on the KKT optimality conditions [28] of the social-surplus maximization problem (13)-(17). We denote the Lagrange multiples associated with the capacity constraints (14)-(16) by λ_{SYS} , λ_{ICZ} and λ_{ECZ} , respectively. The Lagrangian of the social-surplus maximization problem is then

⁵ The exact relation form between EUE and LOLH depends on the reliability evaluation process that is adopted.

$$L = \sum_{i \in Z_{ICZ}} C_i(q_i) + \sum_{j \in Z_{ECZ}} C_j(q_j) + \sum_{k \in Z_{ROS}} C_k(q_k) - \int_0^{Q_{SYS}} D_{SYS}(Q) \cdot dQ - \int_0^{Q_{ICZ}} D_{ICZ}(Q) \cdot dQ - \int_0^{Q_{ECZ}} D_{ECZ}(Q) \cdot dQ$$

$$+ \lambda_{SYS} \cdot \left(Q_{SYS} - \sum_{i \in Z_{ICZ}} q_i - \sum_{j \in Z_{ECZ}} q_j - \sum_{k \in Z_{ROS}} q_k \right) + \lambda_{ICZ} \cdot \left(Q_{ICZ} - \sum_{i \in Z_{ICZ}} q_i \right) + \lambda_{ECZ} \cdot \left(\sum_{j \in Z_{ECZ}} q_j - Q_{ECZ} \right) \quad (18)$$

Suppose that the problem (13)-(17) is convex, e.g., capacity offer costs are convex functions and demand curves are monotonically decreasing. Then the KKT optimality conditions for the problem hold and yield the following:

$$\lambda_{SYS}^* = D_{SYS}(Q_{SYS}^*) \quad (19)$$

$$\lambda_{ICZ}^* = D_{ICZ}(Q_{ICZ}^*) \quad (20)$$

$$\lambda_{ECZ}^* = -D_{ECZ}(Q_{ECZ}^*) \quad (21)$$

where Q_{SYS}^* , Q_{ICZ}^* and Q_{ECZ}^* , respectively, are cleared demand in system and zones; and $\lambda_{SYS}^* (\geq 0)$, $\lambda_{ICZ}^* (\geq 0)$ and $\lambda_{ECZ}^* (\geq 0)$ respectively, are the shadow prices associated with the system and zonal capacity constraints.

The Capacity Clearing Price (CCP) for the ROS zone can be defined as the marginal value of increasing by 1MW of capacity in ROS (or equivalently, system capacity), i.e., $D_{SYS}(Q_{SYS}^*)$. Based on (19), we have

$$CCP_{ROS} \equiv D_{SYS}(Q_{SYS}^*) = \lambda_{SYS}^* \quad (22)$$

Similarly, the capacity clearing price for the ICZ zone can be defined as the marginal value of increasing by 1 MW of capacity in ICZ. Together with (11), we have

$$CCP_{ICZ} \equiv D_{SYS}(Q_{SYS}^*) + D_{ICZ}(Q_{ICZ}^*) = \lambda_{SYS}^* + \lambda_{ICZ}^* \quad (23)$$

For ECZ, we have

$$CCP_{ECZ} \equiv D_{SYS}(Q_{SYS}^*) + D_{ECZ}(Q_{ECZ}^*) = \lambda_{SYS}^* - \lambda_{ECZ}^* \quad (24)$$

Based on (23)-(24), it can be seen that shadow prices λ_{ICZ}^* and λ_{ECZ}^* can be interpreted as “congestion components” of the corresponding capacity zone clearing prices, e.g., if the ICZ constraint (15) or the ECZ constraint (16) is not binding, then the corresponding shadow price becomes zero, and the ICZ or ECZ clearing price would be the same as the ROS clearing price. This interpretation is also consistent with the EUE decomposition in (6) where the zonal EUE components that lead to the corresponding demand curves reflect the unserved energy due to interface limits. Furthermore, since the shadow prices are non-negative, we have the following price cascading relationship:

$$CCP_{ICZ} \geq CCP_{ROS} \geq CCP_{ECZ}, \quad (25)$$

which is consistent with the intuition that the capacity of an import zone is the most valuable and the capacity of an export zone is the least valuable.

F. Implied VOLL

Power system reliability in many ways represents a classic *public good* [29]-[31]. Despite the market liberalization, there’s still a lack of a mechanism for consumers to express their reliability preferences. With the centralized capacity markets, capacity is still purchased to achieve the uniform system reliability criterion (e.g., 1-in-10) enforced by regulatory institutions such as North America Electric Reliability Corporation (NERC). Consequently, we consider the uniform VOLL for the entire system in the centralized capacity market, i.e., the same value of reliability is considered for all consumers throughout the electric network. Estimating VOLL is notoriously difficult and a wide range of values from several thousand to tens of thousands of U.S. dollars per MWh have been reported [16]-[19]. The popular estimation methods include customer survey [32], macroeconomic analysis [33], and case study [34]. Each of them has strengths and weaknesses. In this paper, we imply the VOLL value from **Net Cost of New Entry** (Net-CONE) based on the long-term equilibrium property of the economic framework established in the previous subsections.

Many capacity markets use the Net-CONE for market power mitigation and administrative price setting. The Net-CONE value, calculated as the annualized capital costs for the new resource, less its expected margin from energy and reserve markets, essentially reflects the “missing-money” or the *marginal cost* of the new resource. Depending on the assumptions made for the

new resource, different markets may have different Net-CONE values. ISO-NE calculated the Net-CONE value of \$11.64/kw-month for the capacity commitment period of 2019-2020 [35]. PJM used a Net-CONE value of \$102,315/MW-year for the same period of 2019-2020 [36]. Nevertheless, the Net-CONE value is calculated prior to the FCM clearing, and we therefore can use it to derive the implied VOLL in the following.

Based on (22)-(24) and the *marginal cost* meaning of Net-CONE, we have the following relations between the demand curves and Net-CONEs:

$$\begin{cases} D_{SYS}(Q_{SYS}^*) = Net_CONE_{SYS} \\ D_{SYS}(Q_{SYS}^*) + D_{ICZ}(Q_{ICZ}^*) = Net_CONE_{ICZ} \\ D_{SYS}(Q_{SYS}^*) + D_{ICZ}(Q_{ECZ}^*) = Net_CONE_{ECZ} \end{cases} \quad (26)$$

The above (26) represents the well-known result in microeconomics theory that the marginal benefit of demand equals the marginal cost of new entry at the market equilibrium. Substituting (8)-(10) into (26) and denoting the *negative* derivative of EUE as Marginal EUE (*MEUE*), we have

$$\begin{cases} MEUE_{SYS}(Q_{SYS}^*) = Net_CONE_{SYS}/VOLL \\ MEUE_{SYS}(Q_{SYS}^*) + MEUE_{ICZ|SYS}(Q_{ICZ}^* | ICR) = Net_CONE_{ICZ}/VOLL \\ MEUE_{SYS}(Q_{SYS}^*) + MEUE_{ECZ|SYS}(Q_{ECZ}^* | ICR) = Net_CONE_{ECZ}/VOLL \end{cases} \quad (27)$$

With (27), one can calculate $MEUE_{SYS}$, $MEUE_{ICZ|SYS}$ and $MEUE_{ECZ|SYS}$ for a given VOLL. As shown in the later Section III, the *MEUE* functions are monotonically decreasing and can be numerically evaluated with existing reliability assessment tools. Therefore, one can look up the *MEUE* curves to obtain the system capacity and its distribution with respect to the given VOLL, i.e., $Q_{SYS}^*(VOLL)$, $Q_{ICZ}^*(VOLL)$ and $Q_{ECZ}^*(VOLL)$. With the monotonically decreasing *MEUE* functions and (27), Q_{SYS}^* , Q_{ICZ}^* and Q_{ECZ}^* are *monotonically increasing* with respect to *VOLL*. This is intuitive since a higher evaluation of reliability, i.e., higher *VOLL*, would lead to more installed capacity and higher reliability level.

Furthermore, with the LOLE of 0.1 days/year as the reliability criterion, it should be achieved at the market equilibrium. Similar to EUE, the system LOLE is affected by both the total system capacity and its allocation among zones, i.e., $LOLE(Q_{SYS}^*, Q_{ICZ}^*, Q_{ECZ}^*)$. The existing reliability assessment software can calculate the LOLE for a given set of capacities (Q_{SYS}^* , Q_{ICZ}^* , Q_{ECZ}^*) associated with a multi-zone model. As a result, for a given *VOLL*, one can first calculate the capacities based on (27) and then run the reliability assessment software to obtain the corresponding $LOLE(Q_{SYS}^*(VOLL), Q_{ICZ}^*(VOLL), Q_{ECZ}^*(VOLL))$.

LOLE is monotonically decreasing when Q_{SYS} , Q_{ICZ} or Q_{ECZ} increases. This is obvious since adding capacity anywhere in the system could only improve, not worsen, the system reliability. Combined with the fact that Q_{SYS}^* , Q_{ICZ}^* and Q_{ECZ}^* are monotonically increasing functions of *VOLL*, the compound function LOLE is **monotonically decreasing** with respect to *VOLL*. Based on this monotonicity property, we can obtain the VOLL value that leads to the system LOLE of 0.1 days/year by a simple bisection algorithm.

In the case that a uniform Net-CONE is used across the system, implying no limiting interfaces at the equilibrium, the calculation of VOLL diminishes to the following simple equation:

$$VOLL = - \frac{Net_CONE_{SYS}}{dEUE_{SYS}(Q_{SYS})/dQ_{SYS} \Big|_{Q_{SYS}=ICR}} \quad (28)$$

Note that the above VOLL is endogenously calculated through the proposed framework, in contrast to most other demand curve designs (e.g., [13]) that treat the VOLL as an exogenous parameter.

G. Extension of the Framework

The economic framework presented in this section is based on the ISO-NE's capacity market that models import, export and ROP zones. Some capacity markets, e.g., NYISO, do not model export zones but have nested import zones, e.g., one import zone is enclosed in another import zone. The proposed method can be adapted to the nested zones by treating the outer import zone as a subsystem and further decomposing the subsystem reliability function into the components associated with the inner import zone and the rest of the subsystem. Also, some markets may need demand curves for inter-zonal transfer capability instead of the zone's capacity. Then the multi-variate reliability function, also a function of the transfer capability, will be decomposed into components that include one single-variable function for the transfer capability. In essence, the decomposition of the reliability

function relies on the configuration of the capacity market model, and different decompositions may involve different approximations to the multi-variate reliability function. As a result, the applicability of the proposed method will be determined by how good the approximation is.

The VOLL as the important scaling factor for the proposed demand curves is implied based on the 1-in-10 criterion. Different ISOs may have different reliability criteria. Similar derivation using equilibrium conditions and the Net-CONE can be used to imply the VOLL parameter.

III. CALCULATING DEMAND CURVES

In this section, we present a practical process of producing capacity demand curves based on the proposed theoretical framework. EUEs and their derivatives are evaluated at different capacity levels by existing reliability assessment tools. The implied VOLL value is also calculated. With VOLL as a scalar factor, demand curves are produced based on linear interpolation of the EUE derivative points.

A. Reliability Evaluation

The EUEs serve as the fundamental reliability measure for deriving capacity demand curves (8)-(10). Existing reliability assessment tools such as GE's Multi-Area Reliability Simulation (MARS) can evaluate various reliability indices, including EUE, LOLH and LOLE, for a multi-area system by chronological simulation of the system [37]. Details of the generator outage, maintenance schedule, renewable resource treatment, and tie-benefit assumptions can be modeled in the reliability assessment tool, following the ISO's reliability assessment procedure. To produce capacity demand curves for the system and zones, the corresponding EUE components in (6) are evaluated separately as described below.

To evaluate the EUE_{SYS} component in (6), i.e., the unserved energy resulting from the system capacity deficiency, the entire system is modeled as one area. One can predetermine the range of system capacity levels to be evaluated, and pick the capacity level points within the range for evaluation. The range should be chosen to cover the possible cleared system capacity level and the number of points should be sufficient enough to characterize the shape of the demand curve. For a given system capacity level, the reliability assessment software calculates the reliability indices through simulations. The evaluation process for each capacity level is independent of the evaluations of other capacity levels. Therefore, the evaluation for different system capacity levels can be carried out in parallel to improve the computational efficiency.

To evaluate zonal EUE components in (6), i.e., the *additional* unserved energy resulting from allocating certain capacity out of the system ICR into the corresponding zone, the system is modeled as two areas: the ICZ or ECZ zone under consideration; and the rest of the system. Note that zonal EUE components are considered independent of each other as described in Section II. Therefore, the evaluation for each ICZ or ECZ is independent of each other and can be performed in parallel. For each ICZ or ECZ zone, we select a range of capacity levels in that zone and sufficient number of sample points within the range. For each selected capacity level, e.g., Q_Z ($Z=ICZ$ or ECZ), we evaluate the reliability indices by performing the 2-area simulations with the total system capacity held at ICR and the zonal interface limit imposed. The resulting reliability measure reflects the reliability impact of both system capacity at ICR and its allocation of Q_Z in the zone. Denote the EUE measure of the 2-area system by $EUE_2(Q_{SYS}^*, Q_Z)$ where $Q_{SYS}^* = ICR$. Then the zonal EUE component in (6) is obtained as

$$EUE_{Z|SYS}(Q_Z | ICR) = EUE_2(ICR, Q_Z) - EUE_{SYS}(ICR) \quad (29)$$

where $EUE_{SYS}(ICR)$ is a constant and can be calculated during the evaluation of system EUE component. The evaluation of different zonal capacity levels can be carried out in parallel to improve the computational efficiency.

The above description applies also to other reliability indices such as LOLH; and the reliability assessment software produces all reliability indices simultaneously. Thus the LOLH components can be obtained along with the EUE components.

B. EUE derivatives

Capacity demand curves (8)-(10) are the derivatives of EUE components. With EUE components for various capacity levels obtained from subsection III.A, a simple numerical approximation⁶ of the EUE derivative at each capacity level is the average slope of the two linear segments adjacent to the capacity point as illustrated in Fig. 3.

⁶ More sophisticated numerical approximations are out of the scope of this paper.

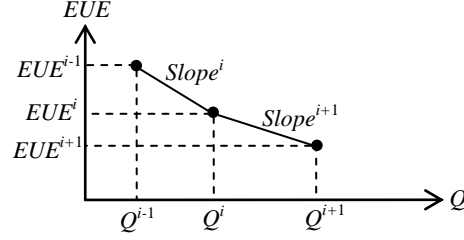


Fig.3. Approximate EUE derivative.

The EUE derivative at capacity level Q_i is then calculated as:

$$\left. \frac{dEUE(Q)}{dQ} \right|_{Q=Q_i} = \left\{ \frac{EUE^i - EUE^{i-1}}{Q^i - Q^{i-1}} + \frac{EUE^{i+1} - EUE^i}{Q^{i+1} - Q^i} \right\} / 2 \quad (30)$$

Alternatively, the EUE derivatives can be obtained from the LOLH values, thus avoiding the numerical approximation of EUE derivatives. This is achieved by using the relationship between EUE derivative and LOLH as demonstrated below.

Each EUE component (system or zonal) in (6) is a single-variable function of the corresponding capacity Q . The $EUE(Q)$ is basically the average hourly Loss of Load (LOL) across simulated years, i.e.,

$$EUE(Q) = \sum_{n=1}^N \sum_h LOL_{n,h}(Q) / N \quad (31)$$

where n and h , respectively, are the indices of the simulated years and hours, N is the total number of the simulated years, and $LOL_{n,h}(Q)$ is the loss of load in MWs for Hour h of Year n under Q . Now consider a small firm load change dL . The change of EUE caused by dL can be represented as

$$dEUE(Q) = \sum_{n=1}^N \sum_h \{dL \cdot I(LOL_{n,h}(Q) > 0)\} / N \quad (32)$$

where $I(LOL_{n,h}(Q) > 0)$ is the indicator variable indicating non-zero LOL . Based on the definition of LOLH, i.e.,

$$LOLH(Q) = \sum_{n=1}^N \sum_h I(LOL_{n,h}(Q) > 0) / N, \quad (33)$$

we have

$$dEUE(Q)/dL = LOLH(Q) \quad (34)$$

The firm load change can be translated to the capacity change. For instance, one can convert dQ to dL by the average Equivalent Forced Outage Rate – in Demand ($EFORD$), i.e.,

$$dL = -dQ \times (1 - \overline{EFORD}). \quad (35)$$

From (35)-(36), we have

$$dEUE/dQ = -LOLH(Q) \times (1 - \overline{EFORD}). \quad (36)$$

C. Producing demand curves

With the derivatives of EUE components for selected capacity levels calculated in Subsection III.B, we create continuous demand curves based on these evaluated capacity levels. Demand curves should be monotonically decreasing. Due to the statistical nature of reliability simulation and the possible numerical approximation error introduced by (30), the calculated EUE derivative values at the selected capacity levels may not be monotonic. Therefore, we first ensure monotonicity of the points. A simple filter that checks all points and removes the non-monotonic ones can be applied. These points can be simply connected to form a piece-wise linear curve. Then the system EUE derivative that corresponds to ICR^7 can be found to calculate the VOLL based on (28). The piece-wise linear curve of EUE derivatives is then scaled with VOLL to produce the corresponding system or

⁷ The system Installed Capacity Requirement (ICR) is the capacity level where the 1-in-10 $LOLE$ is met, i.e., $LOLE(ICR) = 0.1$. ICR can be obtained by linear search since $LOLE(Q)$ is a monotonically decreasing function of Q .

zonal capacity demand curve based on (8)-(10). The above process to generate demand curves is summarized in the diagram below.

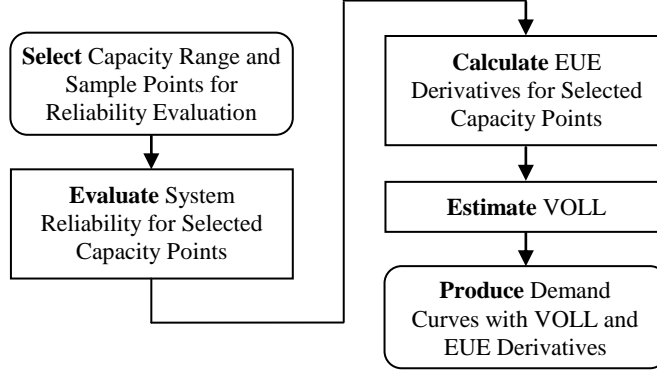


Fig.4. Demand curve process

IV. CASE STUDY

In this section, we first present a 2-zone analytical example to demonstrate the demand curve derivation and the FCM clearing. Then, we apply the process in Section III to a multi-zone ISO-NE system, and analyze the resulting demand curves.

Case 1. Analytical Example

Consider a 2-zone system with one ICZ and the ROS. Assume that the multivariate EUE function has an analytical form of $EUE(Q_{SYS}, Q_{ICZ}) = 10^6/Q_{SYS} + 8000/Q_{ICZ}$. The *Net-CONE* value is \$10/kw-month. The block capacity offers in ICZ and ROS are summarized in Table 1.

Table 1. Capacity offers

Zone		Block 1	Block 2	Block 3
ROS	Capacity (MW)	200	150	150
	Price (\$/kw-month)	\$6	\$9	\$10.5
ICZ	Capacity (MW)	300	200	200
	Price (\$/kw-month)	\$5	\$8	\$10

Since the assumed multivariate EUE function is *separable* in Q_{SYS} and Q_{ICZ} (an assumption used for the simplicity of analysis and does *not* hold for actual systems), the EUE components for the system and ICZ are naturally obtained as

$$EUE_{SYS}(Q_{SYS}) = 10^6/Q_{SYS} \quad \text{and} \quad EUE_{ICZ|SYS}(Q_{ICZ}) = 8000/Q_{ICZ} \quad (37)$$

Note that the zonal EUE component $EUE_{ICZ|SYS}$ does not rely on the system capacity Q_{SYS} due to the above assumption. The derivatives of the corresponding EUE components, respectively, are:

$$dEUE_{SYS}(Q_{SYS})/dQ_{SYS} = -10^6/Q_{SYS}^2 \quad \text{and} \quad dEUE_{ICZ|SYS}(Q_{ICZ})/dQ_{ICZ} = -8000/Q_{ICZ}^2 \quad (38)$$

As analyzed in Section III.2, the derivative of EUE has certain relations to the corresponding LOLH, depending on how firm load is translated into the installed capacity. For the simplicity of analysis, we assume that LOLH is the negative EUE derivative, i.e.,

$$LOLH_{SYS}(Q_{SYS}) = 10^6/Q_{SYS}^2 \quad \text{and} \quad LOLH_{ICZ|SYS}(Q_{ICZ}) = 8000/Q_{ICZ}^2 \quad (39)$$

Furthermore, we assume that 1 hour of LOLH translates into 0.1 day of LOLE. Then,

$$LOLE_{SYS}(Q_{SYS}) = 10^5/Q_{SYS}^2 \quad \text{and} \quad LOLE_{ICZ|SYS}(Q_{ICZ}) = 800/Q_{ICZ}^2 \quad (40)$$

Based on the system LOLE function in (40), one can calculate the ICR that corresponds to 0.1 day/year LOLE, i.e., $ICR = (10^5/0.1)^{0.5} = 1000$ MW. Then based on (38), the system EUE derivative at the ICR is calculated as $dEUE_{SYS}/dQ_{SYS} = -1$. Therefore the VOLL is calculated with (28), i.e.,

$$VOLL = -10 / (-1) = \$10 / kw \cdot month = \$120,000 / mwh \tag{41}$$

The system and zonal demand curves are derived from the EUE derivatives in (38) scaled by the VOLL, i.e.,

$$D_{SYS} (Q_{SYS}) = 10^7 / Q_{SYS}^2 \quad \text{and} \quad D_{ICZ} (Q_{ICZ}) = 8 \times 10^4 / Q_{ICZ}^2 \tag{42}$$

These curves are illustrated in Fig. 5.

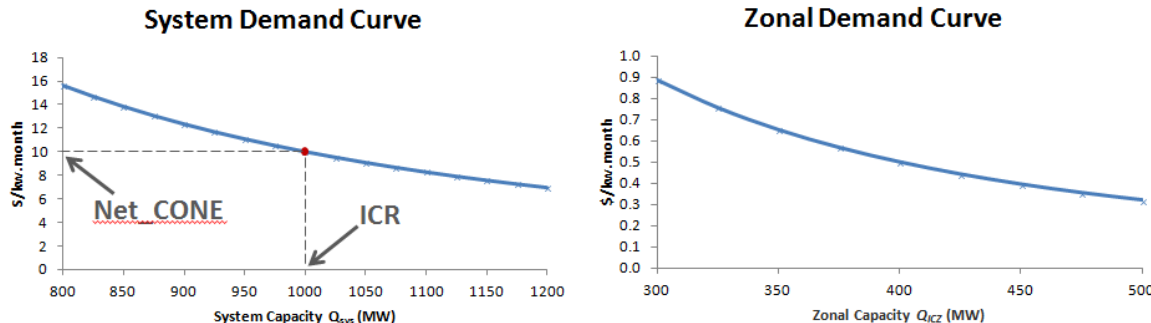


Fig.5. Demand curves for the 2-zone example

With the demand curves in (42) and the capacity offers in Table 1, the FCM clearing problem (13)-(17) can be solved and yield the following solution:

Table 2. Clearing result for the 2-zone example

	Cleared Capacity q^* (MW)	Cleared Demand Q^* (MW)	Clearing Price (\$/kw-month)
ICZ	600	600	10.5
ROS	400	1000 (Q_{SYS}^*)	10

In the following, we interpret the above clearing result based on the meaning of demand curves.

As discussed in Section II.3, the load’s willingness to pay for capacity in ICZ, or the incremental reliability value in ICZ, is reflected by the combination of system and zonal demand curve values. At the system capacity $Q_{SYS}^* = 1000\text{MW}$, the system demand value is \$10/kw-month. Therefore, the total willingness to pay in ICZ can be viewed as the zonal demand curve in Fig.5 shifted upward by \$10. The clearing of the ICZ can then be illustrated by the intersection of the raised demand curve and the aggregated supply offer curve in ICZ (see Fig. 6). It can be seen that the two curves intersect at $q_{ICZ}^* = Q_{ICZ}^* = 400\text{MW}$ and \$10.5/kw-month. These are consistent with the cleared quantity and clearing price in Table 2.

Next we consider the entire system. According to Section II.3, the load’s willingness to pay for the system capacity (absent zonal interface limits) is reflected by the system demand curve in Fig.5. The system supply curve should combine both the capacity offers in ROS and ICZ. With the cleared 400MW in ICZ, the system supply curve is the aggregated supply offer curve in ROS shifted to the right by 400MW. The clearing of the system can then be illustrated by the intersection of the shifted supply curve and the system demand curve (see Fig. 6). It can be seen that the two curves intersect at $q_{SYS}^* = Q_{SYS}^* = 1000\text{MW}$ (including the 400MW cleared ICZ capacity) and \$10/kw-month. These are consistent with the cleared quantity and clearing price in Table 2.

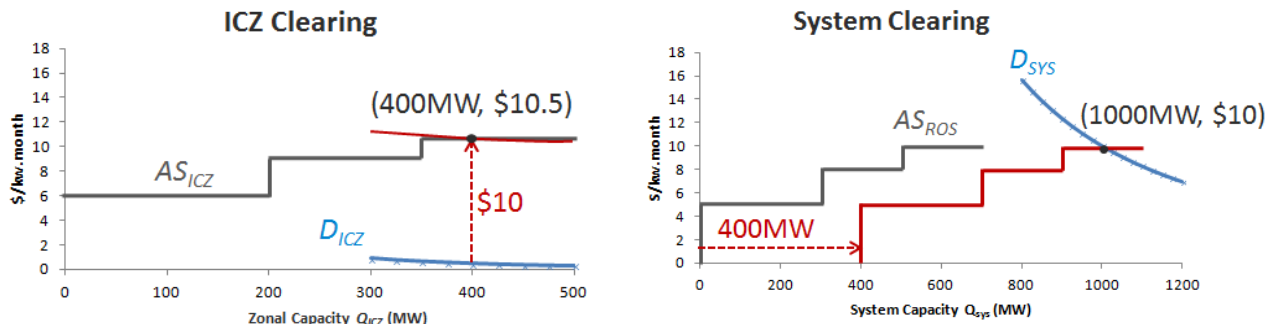


Fig.6. FCM clearing for the 2-zone example

Case 2. ISO-NE System

ISO-NE's 11th FCM for the 2020-2021 commitment period is used for the study. The auction base cases including network configuration can be found in [38]. The system has 1 import zone (SENE), 1 export zone (NNE), and the Rest of System zone. GE-MARS is used for reliability simulations, which were run on Amazon Cloud. All the numerical results can be found in [39].

System demand curve

The system EUE component EUE_{SYS} is evaluated on sample capacity levels within the range of [32.02GW, 37.44GW] at 10MW sample interval. To derive the system demand curve, we took the numerical approximation⁸ of EUE_{SYS} at the sampled capacity levels. The EUE derivatives at these capacity levels are depicted in Fig. 7.

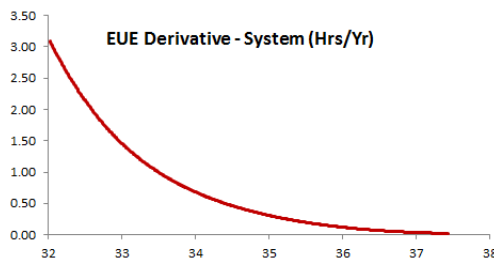


Fig.7. System EUE component and derivative.

It can be seen that the EUE derivative is monotonically decreasing. Since EUE derivative reflects LOLH, a reliability index, this can be explained by the fact that reliability improves when more capacity is added into the system.

The system ICR that corresponds to 1-in-10 LOLE has been calculated by the ISO at 34,070 MW [39]. Based on the EUE derivatives in Fig.7, we obtain the derivative of EUE_{SYS} at the ICR as -0.6465 hours/year. Also, NET_CONE for the FCM has been predetermined by the ISO at \$11.64/kw-month. Therefore, VOLL can be determined as follows based on (29):

$$VOLL = 11.64 / 0.6465 \times 12000 = \$216,048 / MWh \quad (43)$$

The above VOLL implied from NET_CONE can be compared to the values obtained through other methods such as customer survey, which opens the door for research on different VOLL estimation methods. The system demand curve is obtained as the linear interpolation of EUE_{SYS} points scaled by VOLL and is shown in Fig. 8.

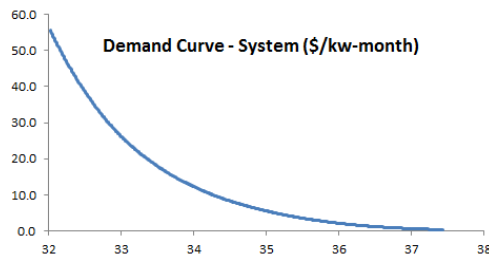


Fig.8. System demand curve.

Zonal demand curves

Zonal demand curves are derived from the derivatives of the corresponding zonal EUE components. Based on (36), we use LOLH for zonal demand curves to avoid numerical approximation of EUE derivative. Zonal LOLH values are functions of the corresponding zonal capacity levels. We evaluate LOLH for selected zonal capacity levels within the selected range for each zone individually while holding the system capacity at ICR. The zonal demand curves are obtained as the linear interpolation of the LOLH points scaled by the VOLL. These zonal demand curves are depicted in Fig.9.

⁸ Note that the EUE derivative can also be obtained through LOLH as mentioned in Section III. However, for the system EUE, the relationship between LOLH and EUE derivative is more complex than (36) due to the specific reliability evaluation procedure. Therefore, we adopt the numerical approximation for the system EUE derivative.

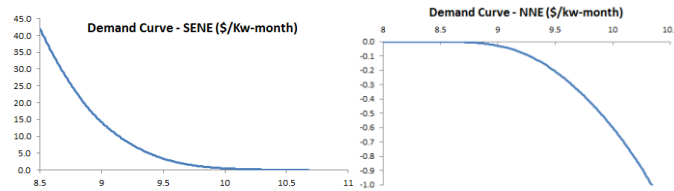


Fig.9. Demand curves for the import SENE and export NNE zones.

It can be seen that the SENE (import zone) demand curve approaches zero when the capacity allocated in the zone increases, and the NNE (export zone) demand curve starts with zero where the capacity allocated in the zone is small. This is because the interface tends not to be constrained when more capacity is allocated in the import zone or less capacity is allocated in the export zone. This is consistent with our analysis in Section II that the zonal demand curves act as congestion components in FCM pricing.

V. CONCLUSION

This paper presents an economic framework for deriving demand curves in Forward Capacity Markets (FCM). Unlike the *ad hoc* demand curves implemented in the existing capacity markets, our approach is built on a rigorous economic and mathematical foundation. Also, an innovative decomposition of EUE is developed to obtain the single-variable demand curves. The resulting demand curves have a clear economic meaning that reflects the reliability impact of capacity in corresponding zones. Our approach may also be used to derive demand curves for other products such as reserves, and the result of our approach has broader impacts on other interesting research topics such as VOLL estimation.

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