The Integration of Variable Generation and Storage into Electricity Capacity Markets

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Many electricity systems throughout the world now operate capacity markets. While such markets have been largely designed with conventional generation in mind, it is increasingly necessary to incorporate both variable generation and storage within them.

The present paper shows how to value both variable generation and storage so as to enable them to be optimally integrated into such markets. We develop a theory based on balancing expected energy unserved against costs of capacity procurement, and in which the optimal procurement may be expressed as that necessary to meet an appropriate reliability standard. In the absence of variable generation and storage the theory reduces to that already in common use, both in the definition of a standard and in its economic justification. Further the valuation of both variable generation and storage in the proposed approach coincides with the traditional risk-based approach leading to the concept of an equivalent firm capacity.

We show that the contribution of any given amount of variable generation or storage is crucially dependent on the characteristics of the remainder of the system to which it is being added. The determination of the contribution of storage requires particular care. This is partly due to the time-limited nature of storage and the flexibility with which its addition to an existing system may be scheduled, and partly due to the fact that, when *any* capacity-providing resource is added to an existing system, storage *already within that system* may be flexibly rescheduled. This leads ultimately to substantial *subadditivity* of the equivalent firm capacities of storage resources.

A further conclusion of our analysis is that the contribution of storage to capacity adequacy is not well measured by the reduction it achieves in the traditional *loss-of-load* risk metric employed in GB and in many other countries. Rather it is necessary to consider directly the contribution of storage to reduction in *expected energy unserved*, something which has now been accepted in the design and running of the GB capacity market.

Finally, we study also the operation of a capacity market in an example system which closely mimics that of GB, except only that substantially more storage than at present participates within the capacity market.

The results of the paper should enable also the correct evaluation of the contributions of variable generation and storage resources elsewhere, together with the correct design of the markets required to optimally utilise these resources.

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