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Strategies to mitigate declines in the economic value of wind and solar at high penetration in California

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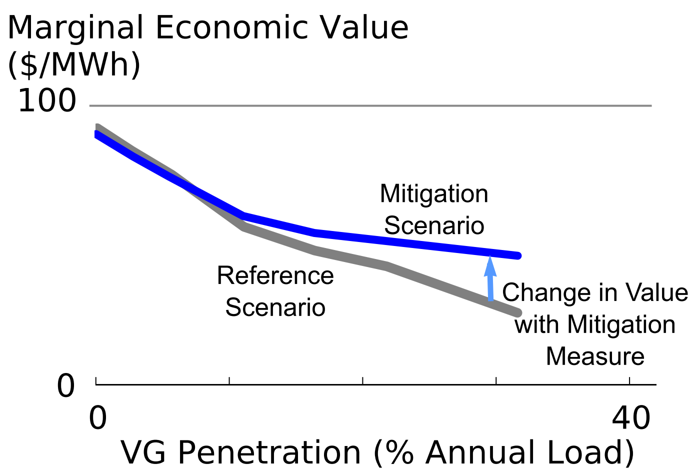
HIGHLIGHTS

- We evaluate several options to stem the decline in the value of wind and PV.
- We use a long-run equilibrium investment and dispatch model.
- Geographic diversity leads to the largest increase in the value of wind.
- Low-cost bulk power storage leads to the largest increase in the value of PV.
- Other attractive options include real-time pricing and technology diversity.

GRAPHICAL ABSTRACT



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ABSTRACT

Previously, we quantified a decline in the marginal economic value of wind and PV with increasing penetration levels based on a long-run equilibrium investment and dispatch model that accounted for operational constraints for conventional generation. We use the same model and data, based loosely on California in 2030, to evaluate several options to stem the decline in value of these technologies. The largest increase in the value of wind at high penetration levels comes from increased geographic diversity. The largest increase in the value of PV at high penetration levels comes from assuming that low-cost bulk power storage is an investment option. Other attractive options, particularly at more modest penetration levels, include real-time pricing and technology diversity.

1. Introduction

Broadly, two approaches are used to determine how much investment to make in generation capacity: centralized planning and decentralized markets. The decisions in the centralized planning approach are often based on cost-minimizing capacity expansion models [1] whereas decisions in the decentralized market approach are based on maximizing profitability with expected wholesale power prices [2]. Based on these two approaches, it is possible to develop criteria for increasing investments in variable renewable generation (VG) like wind and solar photovoltaics (PV). In the centralized approach the addition of VG can contribute to minimizing overall system costs when the marginal value is greater than the cost of VG [3]. In the decentralized approach the addition of VG contributes to maximizing profits when the net

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revenue earned from selling generation exceeds the cost of VG [4]. Though the specifics between these two approaches differ, these criteria have many similarities. At a high level, the comparison of benefits to costs is key to understanding investment decisions in decentralized markets or recommended investments from capacity expansion models.

For a given cost of VG, the optimal investment is up to the point where the marginal value curve intersects with the cost curve, Fig. 1. Increases in the marginal value (i.e., shifting the value curve up), without changing the costs, will increase the optimal quantity of investment, while decreases in the marginal value (i.e., shifting the value curve down) will decrease the optimal quantity. While the costs of wind and PV are well documented e.g., [5–7], the marginal value of wind and PV with increasing penetration levels is less understood, though the body of literature on the subject is growing e.g., [8,9].

The purpose of this paper is to evaluate methods that can help maintain the value of wind and PV with increasing penetration. Previously, we used a case study of increasing penetration of wind and PV in California to quantify a decline in marginal value and to understand drivers of the changes in value [10,11]. We found that the changes in value with increasing penetration, Fig. 2, were primarily driven by decreases in energy value or capacity value. The costs associated with forecastability and short-term variability of wind and PV did not change as much with increasing penetration levels. The quantitative results from that study are summarized in Table 1 and 2. The details of the method used to decompose the marginal value is described in Section 2. Similar conclusions are summarized by Hirth [8] both based on results from other modeling studies and based on empirical analysis of actual market impacts in Germany [8]. Findings from that research support the conclusion by Mills & Wiser [10] that the marginal value of PV is higher than the value of wind at low penetration, but that the marginal value drops at a faster rate for PV with increasing penetration.

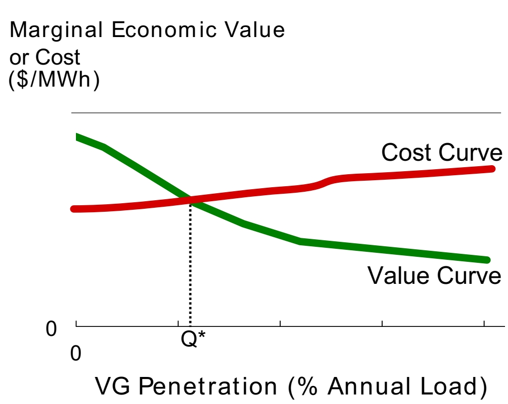

Fig. 1. Illustration of investment criteria for variable generation.

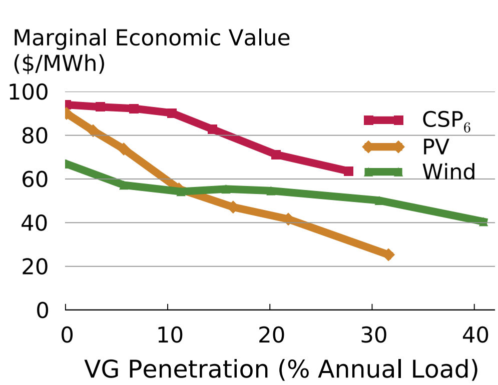

Fig. 2. Marginal economic value of wind, PV, and CSP with thermal storage found in the Reference scenario of Mills & Wiser [10].

Table 1
Decomposition of the marginal economic value of Wind in 2030 with increasing penetration.

Component ($/MW h)	Penetration of wind						
	0%	5%	10%	15%	20%	30%	40%
+ Capacity value[a]	(69) 17	(37) 12	(30) 10	(30) 10	(28) 9	(25) 8	(25) 8
+ Energy value	50	49	48	48	48	46	39
+ DA forecast error	−0.4	−3	−4	−2	−2	−3	−6
+ Ancillary services	−0.4	−0.2	−0.2	−0.2	−0.2	−0.2	−0.2
= Marginal economic value	67	57	54	55	54	50	40
Curtailment (% of Wind)	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	3.2%

[a] Capacity value is reported in $/kW-yr terms in parentheses.

Table 2
Decomposition of the marginal economic value of PV in 2030 with increasing penetration.

Component ($/MW h)	Penetration of PV						
	0%	2.5%	5%	10%	15%	20%	30%
+ Capacity value[a]	(120) 37	(110) 34	(82) 27	(39) 13	(24) 8	(11) 4	(4) 1
+ Energy value	54	53	52	49	45	41	27
+ DA forecast error	−0.2	−5	−4	−6	−5	−4	−3
+ Ancillary services	−0.9	−0.8	−0.7	−0.4	−0.2	−0.1	−0.0
= Marginal economic value	89	81	73	55	47	41	25
Curtailment (% of PV)	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	2.9%

[a] Capacity value is reported in $/kW-yr terms in parentheses.

The relatively rapid drop in the value of PV is largely due to decreases in capacity value with increasing penetration. As PV penetration increases, the period of system need shifts into hours with low solar generation, decreasing the marginal contribution of solar to resource adequacy. Similar rates of decline of the capacity contribution of PV with increasing penetration have been documented in other studies [3].

The more modest costs of forecast errors and increased ancillary services have similarly been corroborated with additional research on solar PV forecasting [12], integration studies of solar PV [13], and integration studies of wind [6]. Regions with highly concentrated wind and relatively inflexible generation may see larger costs associated with uncertainty and variability [14].

In this paper, we use the same model and methods as used to estimate the change in the value of wind and PV with increasing penetration in California to examine the degree to which the value of wind or PV increases at different penetration levels when a mitigation strategy is implemented. Changes in the value of wind and PV with implementation of mitigation strategies can change the optimal investment quantities for wind and PV.

We examine several strategies that have been discussed elsewhere in the literature. Specifically, we examine increased geographic diversity of wind siting [15–18], technological diversity through combinations of wind and PV [19–21], lower-cost bulk power storage [22–24,8,25,26], and price-elastic demand subject to real-time pricing (RTP) [27,28,23,29]. Several other strategies are possible (e.g., increased interconnection capacity between regions [30,31]) but are not described here. In some cases we did