Strategies to Mitigate Declines in the Economic Value of Wind and Solar at High Penetration in California

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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.

Keywords: economic valuation, real-time pricing, storage, renewable integration

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

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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 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, Figure 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, 6, 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].

Figure 1: Illustration of investment criteria for variable generation

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, Figure 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 (2013) 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 (2012) [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.

Figure 2: Marginal economic value of wind, PV, and CSP with thermal storage found in the Reference scenario of Mills & Wiser (2012) [10].

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 de-

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

Component (\$/MWh)	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
a - Capacity value is reported in \$/kW-yr terms in parentheses.							
Curtailment (% of Wind)	0.0%	0.0%	0.0%	0.0%	0.0%	0.3%	3.2%

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

Component (\$/MWh)	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
a - Capacity value is reported in \$/kW-yr terms in parentheses.							
Curtailment (% of PV)	0.0%	0.0%	0.0%	0.0%	0.0%	0.1%	2.9%

cline 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].
50 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
55 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
60 literature. Specifically, we examine increased geographic diversity of wind siting [15, 16, 17, 18], technological diversity through combinations of wind and PV [19, 20, 21], lower-cost bulk power storage [22, 23, 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
65 regions [30, 31]) but are not described here. In some cases we did not examine these other strategies due to limitations of the model (e.g., we did not consider transmission between regions in the model), in other cases we did examine them but did not find notable increases in the value of wind or PV (more details regarding those findings are in Mills & Wiser (2014) [32]).

70 The primary contribution of this paper is the quantification of the change in the marginal economic value of wind and PV at various penetration levels when these measures are implemented. The change in value is quantified in a consistent, long-run investment framework that accounts for operational constraints for conventional generation (in contrast to studies that only use short-run production cost models or long-run investment models with limited representation
75 of operational constraints). We use this framework to decompose the economic

value of wind and PV into different components in order to identify the reasons for the change in the value of wind and PV when the mitigation measure is implemented. Finally, we obtain additional insight by conducting the analysis for both wind and PV which allows us to compare and contrast the impacts.

2. Methods

We use the same model and data previously used to examine the changes in the value of variable generation with increasing penetration levels in California by Mills & Wiser (2012). The model is a generation investment and dispatch model of a power system that accounts for detailed operational constraints (such as part-load inefficiencies, commitment decisions based on forecasts, ramping limits, and minimum generation levels for thermal power plants). Particular aspects of the original model are altered to simulate implementation of the mitigation strategy. We then use the results of the modified model to estimate the marginal value of wind and PV with the mitigation strategy.

The model structure is as follows. For a given load profile, wind or solar penetration level, and set of incumbent generation, the model finds a set of new generation investments that earn sufficient revenue to cover their fixed cost of investment, but that no additional generation would find it profitable to enter the market (e.g., a long-run equilibrium). For any set of generation, day-ahead (DA) power prices are based on DA forecasts of wind and PV and real-time (RT) prices are based on the actual generation. Revenues for each generator are based on the DA schedule and the DA price with RT deviations from the day-ahead schedule paid at the RT price. The model also calculates DA and RT ancillary services (AS) prices (for regulation, spinning reserve, and non-spinning reserve). The new investment options include natural gas combined cycle gas turbine (CCGT) and combustion turbine (CT) plants as well as coal, nuclear, and pumped-hydro storage (PHS).

For new generation to fully cover its fixed investment and operations and maintenance (O&M) costs through the power market, wholesale prices must

periodically exceed the marginal fuel cost of generation. In some hours, generation will be at its full capacity and unable to meet all of the AS targets, and eventually load will need to be shed involuntarily. The wholesale prices in those hours rise to predefined, administratively set scarcity prices that reflect the need for additional generation at those times. In other hours, excess generation can lead to curtailment of generation. There are no additional penalties or costs associated with curtailment, so prices periodically fall to zero but do not become negative. In effect, the marginal economic value of wind and PV is found by simulating a competitive, “energy-only” power market [2, 33]. The fixed costs of new generation are recovered during times with price spikes rather than relying on side payments from a capacity market.

2.1. Marginal Economic Value

The marginal value of wind and PV is based on the revenue earned by selling into the simulated power market in long-run equilibrium. The total revenue is calculated as the sum of the revenue earned by selling forecasted generation into the DA market at the DA price and the revenue earned (or lost) by selling any deviations from the DA forecast in the RT market at the RT price. No punitive imbalance penalties are levied on wind or PV for RT generation that differs from the DA forecast. Instead, deviations from the DA forecast are generally sold at an RT price that is lower than the DA price, or shortfalls in RT generation from the DA forecast are purchased at RT prices that exceed the DA price. In addition, wind and PV are allowed to sell the ancillary service of regulation in the downward direction. Wind and solar are also charged for any assumed increase in the hourly AS requirements due to short-term variability and uncertainty. Following the assumptions in the original model, the regulation reserve requirement is assumed to increase by an amount equivalent to 5% of the DA forecast of wind and PV in each hour.

To better understand the source of value and the causes of changes in value, we decompose the value into four categories:

- 135 • Capacity Value (\$/MWh): The portion of net revenue earned during hours with scarcity prices (defined to be greater than \$500/MWh).
- Energy Value (\$/MWh): The portion of net revenue earned in hours without scarcity prices, assuming the DA schedule exactly matches the RT generation.
- 140 • Day-ahead Forecast Error (\$/MWh): The net earnings from RT deviations from the DA schedule.
- Ancillary Services (\$/MWh): The net earnings from selling AS in the market from wind or PV and paying for increased AS due to increased short-term variability and uncertainty from wind or PV.

145 The resulting estimate of the marginal economic value is based only on a subset of the benefits of adding VG. The subset of the benefits is primarily based on avoiding the capital investment cost and variable fuel and O&M costs from other (fossil-fuel-based) power plants in the power system. These avoided costs are calculated while accounting for operational constraints on conventional
 150 generators and the increased need for AS when adding VG. The analysis does not consider many other costs and impacts that may be important, including environmental impacts, transmission and distribution costs or benefits, effects related to the “lumpiness” and irreversibility of investment decisions, and uncertainty in future fuel and investment capital costs.

155 2.2. Case Study of California in 2030

The case study loosely matches characteristics of California projected to 2030. These characteristics of California include generation profiles for wind and PV, existing generation capacity, and the hourly load profile. Thermal generation parameters and constraints (e.g., variable O&M costs, the cost of fuel
 160 consumed just to have the plant online, the marginal variable fuel cost associated with producing energy, start-up costs, limits on how much generation can ramp from one hour to the next, and minimum generation limits of generation that is

online) are largely derived from observed operational characteristics of thermal generation in the Western Electricity Coordinating Council (WECC) region, averaged over generators within the same vintage. Aside from fossil-fuel-fired generation, the existing generation modeled in California includes geothermal, hydropower, and pumped-hydro storage (PHS). California load and conventional generation is treated in isolation from any other load or conventional generation in the rest of WECC. In other words, we do not consider existing or future transmission capacity between California and the rest of WECC, except for imports of wind and PV to serve California loads. Fossil-fuel prices are based on the fuel prices in 2030 in the EIA's *Annual Energy Outlook 2011* reference case forecast [34].

2.3. Change in Value with Mitigation Strategy

The primary question in evaluating each mitigation strategy is: If this mitigation strategy were to be implemented, how would it change the value of VG relative to an unmitigated case?

Figure 3: Change in the value of VG after implementation of a mitigation strategy is defined in relation to the value in the unmitigated Reference scenario in Mills & Wiser (2012) [10].

We calculate the impact of the mitigation strategy on the value of wind or PV by finding the difference between the marginal value of wind or PV after implementing the mitigation strategy relative to the marginal value of wind or PV at the same penetration level without the mitigation strategy, as

illustrated in Figure 3. We refer to the case without the implementation of the mitigation strategy as the Reference scenario. To make this comparison, we use new scenarios in which a mitigation strategy is implemented, find new long-run equilibrium investments and wholesale prices with that mitigation strategy, and then recalculate the value of wind or PV in that new long-run equilibrium. An increase in the value of wind or PV with the mitigation strategy relative to the case without the mitigation strategy signals that the mitigation strategy can help moderate the decline in the value of wind or PV with increasing penetration found in earlier studies.

3. Results and Discussion

For each of the mitigation methods we first provide more detail on how the strategy was implemented in the model, we then present the estimated change in the value of wind or PV with the implementation of the strategy, explore the reasoning for the observed changes, and any additional considerations that help understand the potential effectiveness of the mitigation strategy.

3.1. Geographic Diversity

The geographic diversity mitigation strategy is based on siting wind plants in locations that minimize the variance of the aggregate wind production. This leads to wind sites being much more geographically distant from one another relative to the wind sites in the Reference scenario.¹

Wind sites in the Reference scenario were selected from resource hubs identified in the Western Renewable Energy Zone (WREZ) Initiative [35]. These resource hubs are assumed to have a finite capacity available for building wind plants. As the penetration of wind was increased in the Reference scenario, wind sites from additional WREZ hubs were included in the wind portfolio. As

¹Geographic diversity of PV is not considered since variability from clouds has little to do with the decline in the value of PV with increasing penetration.

a consequence, a certain amount of geographic diversity is already reflected in the Reference scenario.

In this mitigation analysis, we develop an alternative wind portfolio in which
210 wind sites are selected using only the criteria that the sites are geographically
diverse (based on the approach outlined by Palmintier et al. (2008) [36]). We use
increasing wind penetration at these high-diversity sites to find new investment
and dispatch decisions and long-run equilibrium power prices. We then compare
the marginal value of wind in this Diverse scenario to the marginal value of wind
215 in the Reference scenario. For illustration purposes, we similarly find the change
in the marginal value of wind in a scenario that concentrates all of the wind
sites in one region. In this Concentrated scenario, the wind sites are located at
WREZ hubs in and around Southern California.²

3.1.1. *Change in Value*

220 Using the Diverse scenario’s wind portfolios instead of the Reference sce-
nario’s portfolios increases the marginal value of additional wind by about
\$5/MWh at moderate penetration (10%) and high penetration (30%). At very
high penetration, the Diverse scenario’s portfolio increases the marginal value of
additional wind by more than \$10/MWh, Figure 4 (27% increase in the marginal
225 value of wind relative to the value in the unmitigated scenario with 40% wind
penetration). At 40% wind, increased geographic diversity leads to the largest
increase in the value of wind when compared to the other mitigation strategies
examined in this analysis.

In contrast, concentrating the wind sites in one geographic region decreases
230 the value of wind relative to the Reference scenario. Concentrating wind sites
decreases the value of additional wind by around \$6/MWh, with wind penetra-
tion up to 40%, as also shown in Figure 4.

² In the Concentrated scenario, we ignore constraints identified in the WREZ Initiative in terms of how much wind could be sited in a particular region.

Figure 4: Change in the marginal economic value of wind with geographically concentrated or diverse wind sites relative to the Reference scenario.

3.1.2. Reasons for Change

Detailed analysis of the Diverse scenario’s wind portfolios indicates that the increase in value relative to the Reference scenario is primarily based on an increase in the capacity value for penetrations below 30%. At 40% penetration, the increase in the value of wind for the Diverse scenario’s portfolio is due to an increase in energy value followed by a smaller increase in the capacity value and a small decrease in the DA forecast error cost. The increase in energy value is in part due to a reduction in curtailment in the Diverse scenario. Over 3% of the annual wind is curtailed at 40% wind penetration in the Reference scenario, but less than 0.1% is curtailed in the Diverse scenario.

A portfolio with high geographic diversity leads to a higher value of wind due to a reduction in extremes: fewer hours have significant amounts of wind from all wind sites in the portfolio (reducing over-generation and curtailment), and more hours have at least a small amount of wind generation from some sites. The benefit of increased geographic diversity is more pronounced with high wind penetration levels since wind is more likely to affect wholesale prices at high penetration levels.

Concentrating wind in one region tends to increase the frequency of extremes, where all wind is generating or no wind is generating. Increases in wind generation tend to occur simultaneously in areas where wind speeds are already

high and thus while wholesale prices are already low (due to the surplus wind generation). Similarly, wind forecast errors tend to be correlated when wind sites are concentrated. The lower value in the Concentrated scenario is driven primarily by an increase in the DA forecast error cost. Since large forecast errors can be technically challenging to manage, concentrated wind also raises concerns about secure system operations.

3.1.3. Further Considerations

With increasing penetration, wind at geographically diverse sites could earn higher revenue than wind sited closer to existing wind. This increase in the value of wind will need to be weighed against any increased costs due to additional transmission or lower wind quality associated with these alternative sites.

Given the potential wide variation in wind quality and access to transmission capacity, considerations about geographic diversity are not likely to dominate siting decisions at present. Wind resource quality and transmission availability are likely to be more important factors. In regions with more correlated wind or less flexible generation, however, the importance of geographic diversity may be greater than observed in California (e.g. [14]).

3.2. Technological Diversity

The value of wind can depend on the amount of PV included in a scenario, and vice versa. In the Reference scenario, only wind or PV was added at a time while the other was kept at zero penetration whereas the technological diversity strategy explores combinations of wind and PV. First, we estimate the change in the value of wind when the system has 10% PV penetration ³ relative to the

³The choice of 10% penetration of the second technology is somewhat arbitrary. For the purpose of this analysis the penetration needs to be substantial enough to produce changes in the timing of high and low prices (meaning it needs to be greater than 0%) while not being too high to lead to overcrowding (i.e. not as high as 30-40% penetration). We would expect to see somewhat similar results for any choice of 5-20% penetration of the second technology, though we did not test these other choices.

value of wind without PV. Second, we look at the change in the value of PV with 10% wind penetration.

3.2.1. Change in Value

The marginal value of additional wind when 10% of the energy is served by PV is greater than without 10% PV for wind penetration levels between 0% and 20%, Figure 5. At 0% wind penetration,⁴ the marginal value of wind is just over \$7/MWh greater with 10% PV than without it; this positive value steadily decreases until it is only slightly greater at 20% wind penetration. Beyond 20% wind penetration, the value of additional wind with 10% PV begins to decrease relative to its value without 10% PV. For wind penetrations above 20%, adding 10% PV is not an effective mitigation strategy and instead can reduce the value of additional wind.

Figure 5: Change in the marginal economic value of wind with 10% penetration of PV relative to the Reference scenario.

To what degree can adding 10% penetration of wind mitigate the decline in the value of PV found in the Reference scenario? As shown in Figure 6, at very low PV penetration ($\sim 0\%$) the value with or without 10% wind is similar. However, as PV penetrations increase, adding 10% wind increases the marginal

⁴Every case, even the “No wind/PV” cases, include at least a small amount of wind and PV so that the marginal value at near 0% penetration can be estimated.

value of PV substantially relative to the Reference scenario, reaching roughly \$7/MWh higher at 10% PV penetration.

Figure 6: Change in the marginal economic value of PV with 10% penetration of wind relative to the Reference scenario.

Above about 10% penetration of PV, the value of PV with 10% wind starts declining toward the value of PV without wind. At 20% PV penetration, the value of PV is again similar with or without 10% wind. At 30% penetration of PV, the marginal value of PV with 10% wind is \$6/MWh lower than the value of PV without wind. Wind can, therefore, reduce the decline in the value of PV at moderate PV-penetration levels, but not at 20% or greater PV-penetration levels.

3.2.2. Reasons for Change

The increase in the value of 10% wind with 10% PV is largely due to an increase in the capacity value of wind and a slight increase in the energy value of wind. Since the system is in long-run equilibrium with or without the 10% PV, the average wholesale power prices over the whole year remain at around \$70/MWh (sufficient to cover the investment cost of new CCGT generation). The main difference in the wholesale prices between scenarios with or without 10% PV is instead the timing of high or low prices. The increase in the capacity value of wind with 10% PV is due to PV shifting the timing of the peak prices into the early evening, when wind generation is somewhat stronger. While wind

is not operating at its full capacity during the early evening, it is generating more during that time, on average, thus the value of wind increases with 10% PV. In contrast, the cost of DA forecast errors for 10% wind does not change with or without 10% PV and curtailment remains at 0%.

315 The high value of PV at low penetration is due to the coincidence of PV generation and scarcity prices in the late afternoon on peak-load days. Wind does not generate much power in the late afternoon, so adding 10% wind does not substantially affect the timing of scarcity prices and the marginal value of PV at low penetration. Hence, the value of PV at 0% penetration does not vary
320 with the decision to include some wind.

At 10% PV penetration, however, the increase in the marginal value of PV with 10% wind penetration is due to an increase in the capacity value of PV relative to the Reference scenario. The increase in the capacity value is tied in part to wind generation occurring in early evening. The wind generation
325 in early evening slows the shift of high-price hours into the early evening with increasing PV. In turn, the PV generation continues to occur during times with high prices, increasing its value. The cost of DA forecast errors for 10% PV decreases by less than \$1/MWh with 10% wind and curtailment remains at 0%.

The decline in the value with technological diversity at very high penetration
330 levels is due to a “crowding-out” effect. When the penetration of one technology is very high, net demand and wholesale prices are frequently very low, lessening the value of additional generation. Increasing overall variable generation further exacerbates this decline in value in hours where both technologies are generating power. This crowding leads to the reduction in value with technological diversity
335 at penetrations above 30% penetration for wind and above 20% penetration of PV.

3.2.3. Further Considerations

For moderate penetration levels, technological diversity can increase the value of wind or PV relative to a scenario with just one VG technology (though
340 these particular results depend on the correlation of load, wind, and PV in Cal-

ifornia, which may be different in other regions). Just as importantly, we find a range of penetration levels where wind and solar technologies do not interfere with each other. The value of additional wind at 20% penetration and 10% PV (a total VG penetration of 30%) is similar to the value of additional wind at 20% penetration of wind alone. In other words, there is no reduction in economic value of wind at 20% wind penetration with or without 10% penetration of PV. At 30% wind penetration, wind is only slightly less valuable with 10% PV (a total VG penetration of 40%) than without it. Similarly, the value of additional PV at 20% PV penetration and 10% wind (a total VG penetration of 30%) is almost equal to the value of additional PV at 20% PV penetration alone. This suggests that analysts can evaluate the value of wind or PV at up to 20% penetration with only one technology at a time, knowing that the value of that technology will not decrease if up to a 10% penetration of the other variable technology is added.

Taken together, these scenarios indicate that relatively high penetrations of total VG can be achieved using combinations of wind and solar technologies while maintaining or even enhancing the value of the wind/solar generation compared with the value of using single wind and solar technologies in isolation. However, determining whether to pursue technological diversity as a mitigation strategy would require comparing the anticipated increase in value against the potential higher cost of building combinations of technologies to achieve the target penetration level. For example, even though the value of 20% wind may be lower than the value of 10% wind and 10% PV, PV might be more expensive than wind, leading to an overall higher cost. The value changes illustrated in here are an important part of this full consideration. We posited 10% penetration of the other technology, but the right combination to maximize the benefit of technological diversity is also an important question. Similar analysis where the quantity of variable generation is an endogenous decision could be used to find the combination that leads to long-run equilibrium or that minimizes cost (e.g., [37]).

3.3. Low-Cost Storage

In this section we quantify how much more valuable wind and PV are when low-cost storage is added to the system. Bulk power storage in this section refers specifically to any storage resource that charges using power from the grid and discharges when providing power to the grid. Storage is modeled as PHS that has a round-trip efficiency of 81%. Storage dispatch is optimized concurrently with the dispatch from all other generation options (including conventional generation and hydro). Storage can be charged or discharged and can also provide AS, specifically, regulation (up or down), spinning reserve, and non-spinning reserve. Additional details on the dispatch of storage are provided in Mills & Wisner (2012) [10]. The size of the assumed storage reservoir is sufficient to provide power for 10 hours at full nameplate capacity.

The Low-Cost Storage scenario assumes a lower annualized investment cost and fixed O&M cost equivalent to \$140/kW-yr, approximately 20% of the cost used in the Reference scenario. This low investment cost is based on the cost estimate for a proposed PHS facility that uses two existing mine pits for the upper and lower reservoirs [38]. Since the cost of storage in the Low-Cost Storage scenario is even lower than the annualized fixed cost of a CCGT or CT and new capacity is needed, low-cost storage automatically becomes one of the investment options selected in the model.

With the assumption of low storage-investment costs, 4.4 GW of new storage capacity are built even in the no wind and PV cases. The amount of new storage capacity grows by 57% with 40% wind, to the point that the total new and existing storage capacity is 25% of the nameplate capacity of wind. The amount of new storage grows by 122% with 30% PV, to the point that new and existing storage capacity is 38% of the nameplate capacity of PV.

3.3.1. Change in Value

The investments in new storage change the value of wind relative to the Reference scenario with no new storage. Although additional storage increases the value of wind at nearly all penetration levels, the increase is negligible until

40% wind penetration, Figure 7. With 40% wind, the availability of low-cost bulk power storage leads to an 11% increase in the value of wind relative to the Reference scenario.

Figure 7: Change in the marginal economic value of wind with low-cost PHS.

At low PV penetration, the value of PV declines modestly with low-cost stor-
 405 age relative to the value of PV in the Reference scenario, Figure 8. The results
 are different at higher PV penetrations, where low-cost storage substantially
 increases the value of PV. Low-cost storage begins to increase PV value relative
 to the value without low-cost storage at greater than 5% PV penetration. By
 30% PV penetration, the marginal value of additional PV is \$20/MWh greater
 410 with low-cost storage than without (an 80% increase in the marginal value of
 PV relative to the value in the Reference scenario with 30% PV penetration).

3.3.2. Reasons for Change

The introduction of low-cost storage results in two somewhat competing
 effects. First, the assumed low cost of storage capacity slightly reduces the
 415 capacity value of wind and PV at low penetration levels. Since storage is now
 the option with the lowest investment cost, it becomes the new capacity resource.
 Fewer hours with scarcity prices are required to cover the fixed cost of investment
 in storage compared to the number of hours required to cover the cost of a
 CCGT. This in turn lowers the capacity value of wind and PV, since those
 420 resources now generate less power during periods with scarcity prices. Second,

Figure 8: Change in the marginal economic value of PV with low-cost PHS relative to the Reference scenario.

the increase in storage capacity tends to increase the energy value of wind and PV. Storage, particularly with high penetrations of wind or PV, tends to be charging when wind or PV is generating, and storage tends to be generating when the wind is not blowing or the sun is down, although this relationship
425 does not always hold for a particular day. The increased demand from charging storage during times with wind and PV generation reduces curtailment and increases energy prices during those times.

At most wind penetration levels, the reduction in capacity value is similar to the increase in energy value, leading to only minor changes in the marginal
430 value of wind. At 40% wind penetration, the increases in wholesale prices when storage is charging and wind is generating leads to an increase in the energy value of wind. Additionally, the energy value of wind increases in part due to a reduction in wind curtailment from 3.2% with 40% wind in the Reference scenario to 0.2% in the Low-cost Storage scenario. The increase in the energy
435 value with storage is distinctly larger than the reduction in the capacity value. As a result, the marginal value of wind increases by about \$4/MWh with storage relative to the Reference scenario.

Since the capacity value is a large source of PV value at low penetration levels, a decrease in the number of hours with scarcity prices, as seen with the
440 introduction of low-cost storage, has a negative impact on the value of PV at

low penetration. Furthermore, at low PV penetration, storage and PV tend to generate power at similar times, resulting in lower wholesale prices at these times and potentially lower energy value.

With high PV penetration, storage is charging during times with PV generation, which increases prices during these times relative to their level absent
445 any new storage. A strong negative correlation between PV generation and generation from storage at high PV penetrations indicates storage is consistently charging when PV is generating and discharging otherwise. The increase in the value of PV above 5% penetration with low-cost storage is almost entirely due
450 to the increase in the energy value of PV relative to the Reference scenario. The only other contributor to the increase in PV value is a decrease in the cost of DA forecast errors of less than \$2/MWh. The energy value of PV increases in part due to a reduction in PV curtailment from 2.9% with 30% PV in the Reference scenario to less than 0.1% in the Low-cost Storage scenario.

455 3.3.3. Further Considerations

This analysis only considered one type of storage: PHS with 10 hours of reservoir capacity. The amount of energy that can be stored in the bulk power storage reservoir becomes increasingly important with higher penetrations of wind. Whereas the storage reservoir capacity is only a binding constraint 22
460 times during the year with 0% wind penetration, the reservoir capacity is a binding constraint 64 times with 30% wind. Since we only allow storage reservoir capacity to increase in proportion to storage generating capacity, the increase in the number of times that the storage reservoir is a binding constraint indicates that wind might benefit more from proportionally larger storage reservoirs. The
465 relatively small increase in the value of wind with low-cost storage may also be due to the limited storage reservoir capacity.

In contrast to wind, the amount of energy that can be stored in the bulk power storage becomes less important with higher penetrations of PV. The reservoir capacity is only a binding constraint 13 times during the year with
470 30% PV (compared to 22 times at 0% PV). This suggests that PV requires

proportionally smaller reservoirs than the 10 hours of storage capacity assumed here and smaller reservoirs than would be ideal for wind. This is likely due to the diurnal profile of solar where storage would need to be charging for at most half of the day with high solar penetrations. In contrast wind is more variable
475 over longer periods: high wind periods can last for multiple days, leading to a larger benefit from more storage reservoir capacity.

To achieve the benefits to wind and PV of bulk power storage, the cost of storage needs to be low. No additional pumped-hydro storage was built in the Reference scenario when storage costs were based on EIA cost estimates.
480 Only by lowering the assumed investment cost for PHS did the model invest in new PHS. If an external policy measure (e.g., a storage subsidy or a utility requirement to invest in a certain amount of storage) were used to lower the market cost of storage, then this analysis would similarly be ignoring the cost of that subsidy or investment mandate.

485 Finally, the increase in the value of wind and PV with storage and the amount of storage added depend in part on the generation mix. The benefits of storage would likely be greater in regions with greater heterogeneity in variable costs of thermal generation plants than found for California where natural-gas fired power plants are usually on the margin.

490 3.4. Real-Time Pricing

In the Reference scenario, all electricity demand is assumed to be indifferent to the DA and RT wholesale market price. This is the situation in much of the United States, where customers pay retail rates that do not vary depending on actual conditions in the DA and RT markets. Increasingly, however, retail
495 rates are including pricing signals to retail customers to indicate periods when electricity consumption is particularly expensive. Large industrial and commercial customers already participate in programs that subject them to prices in wholesale markets in some parts of the United States. Furthermore, the roll-out of smart meters that record demand at 15-minute intervals will enable small
500 commercial and residential customers to transition to retail prices reflecting

conditions in the wholesale market. The Real-Time Pricing (RTP) mitigation strategy assumes that load changes in response to wholesale power prices in both the day-ahead and real-time market.

Studies of customer demand when retail prices shift from static to dynamic
505 indicate a wide range of estimates of the price elasticity of customer demand [e.g., 39, 40, 41, 42, 43]. In the RTP scenario, electricity demand is assumed to have a constant own-price elasticity of -0.1,⁵ such that a 10% increase in wholesale prices leads to a 1% reduction in demand relative to the historical demand in the same hour of the year.

510 The RTP program is implemented in the model by making demand price elastic and then finding new investment decisions, generation dispatch, and wholesale power prices with price-responsive demand. In the model, both DA and RT demand are price responsive. To be clear, active participation of the demand side in wholesale power markets through RTP, as modeled in this paper,
515 per, does not match tariffs or programs used in practice. The first program to expose residential customers to RTP in the U.S., for instance, uses the DA market price to set the RTP price for customers prior to the operating day, but does not update that price based on real-time conditions [43]. The demand response offered by RTP as modeled in this report is a simplified representation of
520 the “idealized” demand-side participation that might be achieved through new designs of RTP programs or combinations of other existing demand-response programs.

3.4.1. *Change in Value*

Implementing the RTP program increases the value of wind at all pene-
525 tration levels, Figure 9. The largest increase in the value of wind relative to the Reference scenario is \$7–8/MWh, which occurs both at 5% wind and 40% wind. Implementation of RTP leads to 20% increase in the value of wind at

⁵A constant elasticity of -0.1 is within the range of assumptions used in other studies on the impact of RTP [e.g., 44, 27, 28].

40% penetration relative to the Reference scenario.

Figure 9: Change in the marginal economic value of wind with RTP and price-responsive demand relative to Reference scenario.

As with wind, implementing the RTP program increases the value of PV
 530 at high penetration levels; in contrast to wind, the RTP program decreases the
 value of PV at low penetration levels ($<5\%$), Figure 10. At 10% PV penetration,
 however, implementing RTP increases the value of PV by up to \$10/MWh. At
 even higher penetration levels, the increase in PV value from RTP is closer to
 \$7–8/MWh (a 29% increase in the value of PV at 30% penetration relative to
 535 the Reference scenario).

Figure 10: Change in the marginal economic value of PV with RTP and price-responsive demand relative to the Reference scenario.

3.4.2. *Reasons for Change*

One of the most prominent changes observed in the long-run equilibrium with RTP is the change from infrequent but high price spikes with inelastic demand to more frequent but lower price spikes with elastic demand. With inelastic demand, the prices jump to the administratively-set scarcity price when generation is unable to meet demand. Because these price spikes are so high they do not need to occur very frequently in order to justify the cost of building new generation capacity. With elastic demand, on the other hand, a rise in prices triggers some reduction in demand (therefore helping to maintain balance between the remaining demand and generation). Since the prices do not spike to as high of levels, the price spikes must occur more frequently to cover the cost of new generation investments.

The increase in value of wind with RTP is primarily due to an increase in the sum of the capacity and energy value of wind with increased penetration. The marginal value of wind increases because RTP tends to increase the load during times when wind power is available. The capacity value of wind increases because the increase in the number of hours with prices above \$500/MWh happens to cover more hours with some wind generation. The energy value increases because price-responsive demand increases relative to historical levels during times with increased wind generation (due to wind's impact on depressing wholesale prices at these times leading to higher load with RTP and therefore and increase in wholesale prices relative to a case without RTP). In addition, wind curtailment is no longer needed, even at 40% wind penetration, with RTP which increases the energy value of wind. Less than \$2/MWh of the increase in the marginal value of wind with RTP is due to a decrease in the cost of day-ahead forecast errors.

The reason for the decrease in PV value with RTP at low penetration is similar to the reason for the decrease in PV value with low-cost storage. Implementing RTP reduces the cost of capacity and the duration of very high price spikes. At low PV penetration, PV and the demand response from RTP are

positively correlated, indicating that RTP decreases demand at the same time that PV is generating power. Lower demand leads to lower wholesale prices and therefore lowers the marginal value of PV at low penetration.

At 10% PV penetration and above, PV and demand response are negatively
570 correlated, indicating an increase in demand when PV is generating. At 30% penetration, the correlation between PV and demand response is substantially more negatively correlated than wind and demand response at 30% penetration. On average over the entire year, RTP increases the total demand by only 0.1% at 10% PV penetration but by 3.2% at 30% PV penetration. Nearly all of the
575 increase in demand occurs during daytime hours when PV is producing power, particularly in spring months. The increase in demand while PV is generating increases the energy value of PV and obviates the need to curtail PV. A decrease in the cost of day-ahead forecast errors contributes less than \$1/MWh to the increase in the marginal value of PV with RTP.

580 3.4.3. Further Considerations

The trends currently leading to the roll-out of smart meters and RTP programs are largely based on efforts to reduce peak demand, independent of mitigating changes in the economic value of wind and PV. This analysis indicates that, at low penetrations, wind and demand response occur at different times
585 and PV and demand response occur at the same time (e.g., provide similar services). But with increasing wind or PV penetration, price-responsive demand increases during times with high wind or high PV generation. Contrary to most demand-response programs that have historically been designed to decrease demand, these results indicate that the value of wind or PV is increased
590 by shifting demand to, or even increasing demand during, times when wind or PV are generating power. This conclusion is expected to apply to regions outside of California, though the particular generation patterns from wind and PV (and their correlation with load) may be different. Many other factors go into the design of demand-response and retail-pricing programs, but this analysis
595 suggests that expectations for future wind or PV penetration levels might be

an important consideration.

Demand-response strategies for peak-load days, such as pre-cooling, which shifts cooling loads away from the peak to earlier in the day, may need to be adjusted in scenarios with high PV penetration. At 0% PV penetration, a pre-cooling strategy would aim to reduce demand before around 6 pm on peak-load days. With high PV penetration, the pre-cooling would need to reduce demand between about 6 pm and 9 pm. High PV penetrations may also shift the focus from one customer class to another, depending on the load profiles of different customer classes. In some regions, commercial loads tend to peak earlier in the day while residential loads peak later in the evening. In that case, demand-response programs could target commercial customers at low PV penetration but shift to residential customers at high PV penetrations. Such changes in consumption patterns may require end-use control technologies or customer behaviors that differ from those in traditional demand-response programs, which primarily reduce demand during summer afternoons. Midday electric vehicle charging might be well suited to increasing customer demand during times with high PV production.

4. Conclusions

Implementation of mitigation strategies has different impacts on marginal value depending both on the type of renewable technology (wind or PV) and the penetration level of that technology. A conclusion from this analysis is that one cannot assume that the effect of a mitigation strategy found for one technology at one penetration level will result in the same effect for a different technology or penetration level. A comprehensive analysis of the impact of several mitigation measures on both wind and PV, as presented in this paper, strengthens such a conclusion.

Another important finding is that although many of the mitigation strategies did increase the value of wind or PV relative to the unmitigated Reference scenario, none of them were able to fully maintain the value of wind or PV

625 estimated at very low penetration levels.

The most effective combinations of mitigation strategies and renewable technologies at high penetration levels are as follows. The largest increases in the value of wind relative to the unmitigated Reference scenario at penetration levels above 20% occur with increased geographic diversity in wind sites, implementation of RTP for retail sales, and the availability of low-cost bulk power storage. 630 The largest increases in the value of PV above 10% penetration occur with the availability of low-cost bulk power storage and RTP.

We also find interesting interactions between wind and PV in the technological diversity cases. In particular, various combinations of wind and PV do not 635 decrease the value of wind or PV relative to the Reference scenario, even though the aggregate proportion of annual demand met by VG technologies is higher. Specifically, combinations of 10–20% wind and 10% PV have no lower value than wind alone. Similarly, combinations of 10–20% PV with 10% wind have no lower value than PV alone. These results suggest that if 10–20% wind or PV 640 penetrations can be economically justified on their own, then 30% penetration from combinations of wind and solar technologies would be similarly justified.

Throughout this analysis, only one mitigation measure is implemented at a time. In some cases, the benefits of different mitigation measures are caused by similar factors (e.g., increases in the value of wind at high penetration with 645 RTP and storage are both linked to an increase in demand during times when wind is generating). As such, the change in the value of wind or PV from simultaneously implementing multiple mitigation measures is not expected to be the same as the sum of the change in value from each mitigation measure implemented in isolation. Interactions between mitigation measures is an area 650 for future research.

The results presented here depend on many factors (correlation of load, wind, and PV; mix of incumbent generators; etc.), some of which may be unique to California. The general framework used in this analysis can be applied elsewhere, though the particular results may differ.

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Graphical Abstract

Marginal Economic Value
(\$/MWh)

100

0

0

40

VG Penetration (% Annual Load)

Reference
Scenario

Mitigation
Scenario

Change in Value
with Mitigation
Measure