

## Renewables and Storage – Does Size Matter?

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By

*Judy Chang, Kathleen Spees and Jurgen Weiss<sup>1</sup>*

### Abstract

A number of factors, climate change prominent among them, are driving state and federal policies towards increasing goals for renewable energy in the United States. An issue facing two of the most prominent technologies, wind and solar photovoltaic (PV), is their intermittency and imperfect generation profile when compared to the pattern of demand. Storage is often being proposed as the solution for harnessing renewable energy when the system cannot absorb it so that it can be used when demand is greater. In this paper, we examine the characteristics of a storage system that would be needed to capture *all* the wind or solar PV energy generated from an increasing level of renewable capacity. We use data from two U.S. regions to examine systems powered by wind and solar PV, supported by either storage or natural gas fired generation. We find that there is significant regional and resource-related variation in the mismatch between renewable power output and load and that the renewable energy mix will influence the amount of storage needed. We find that capturing and using all of the wind/PV energy generated would require systems with very high energy storage capability (in terms of MWh) compared to those currently used in storage systems. Given current and projected costs for various storage technologies, we show that under realistic expectations about future carbon prices, the goal of capturing “all of the wind/PV energy generated” is likely an unrealistic and uneconomical one. We do find, however, that some additional storage, with characteristics similar to current storage systems, would likely be beneficial at likely carbon price levels. While our analysis starts with the assumption of an all-renewable energy system, our results are applicable to current and near term energy systems. Several regions experience significant near-term barriers to using all the energy generated by wind due to high minimum-generation levels and high start-up costs associated with coal and nuclear base load power generators, which make up the majority of existing power generation fleet. Minimum generation conditions create frequent periods of excess generation, particularly during off-peak periods, even at relatively modest levels of installed wind capacity. The conclusions of our paper suggest that in such regions some additional storage may be beneficial, but avoiding all excess wind generation may be uneconomical.

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<sup>1</sup> Judy Chang, Principal, *The Brattle Group*; Kathleen Spees, Associate, *The Brattle Group*; Jurgen Weiss, Principal, *The Brattle Group*. The content of this paper does not reflect any position by *The Brattle Group* or its clients. All errors are the responsibility of the authors.

## I. INTRODUCTION

The absence of affordable storage, options has made markets for power different from other commodity markets for a long time. Over the past decades, a substantial literature addressing the various benefits of storage has emerged. Much of the traditional literature on storage focuses on inter-temporal arbitrage, *i.e.* the benefits resulting from buying and storing power during periods of low prices for resale during periods with high prices. The power supply system that forms the backdrop for the arbitrage analyses is characterized by mostly dispatchable fossil fuel generation. In such a system, power prices increase over the course of a typical day as relatively inelastic demand increases, making it necessary to generate power from power plants with increasingly higher variable costs, mostly driven by higher fuel costs and decreasing plant efficiency.

Using this traditional “fossil fuel dispatch model” to derive the value of storage is beginning to less accurately reflect the current power system and we anticipate that this trend will likely accelerate. The change is driven by the increasing penetration of renewable resources at near-zero variable cost and demand side programs that can cut off demand during high-priced periods. In a power system increasingly dominated by non-dispatchable non-fossil resources such as wind and solar, and even nuclear, along demand-side price responsiveness, intra-day price variation may become significantly muted.

In such a market environment, the primary role of storage for arbitraging intra-day price differentials may become less pronounced. Rather, it is suggested that the primary role for storage may be to ease the integration of intermittent wind and solar resources. In this paper, we intentionally steer clear of discussing arbitrage opportunities, and instead focus on the potential benefit of using storage to improve the renewable energy usage under consideration of the associated emissions reductions.

At least two issues have emerged in which storage of some kind could play a role. One is to smooth out the very short-term variations in output from wind or solar PV generation related to unpredictable short-term fluctuations in wind speed or sun shine. The other is to deal with longer term mismatches between the time pattern of output from wind and solar and the time pattern of demand. The former is more related to what is traditionally described as ancillary services, the latter more like long-term storage of the traditional pumped storage, the new compressed air storage under development, or new battery technologies.

In this paper we focus on the latter. In particular, we examine some of the economic issues that arise in a system where the mismatch between substantial wind and PV<sup>2</sup> and demand leads to periods of excess generation from renewable power during some periods, and under-generation during others. To do so, we set up a relatively simple model of demand in two representative

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<sup>2</sup> We limit our analysis to wind and PV because wind and PV are the primary new sources of renewable generation being deployed globally and because both resources’ intermittency creates significant new problems. It is worth mentioning that while it is possible to thermally store energy from concentrated solar power systems, some of the economic considerations explored here are likely to apply in that context as well, since thermal storage in concentrated solar system also requires significant capital expenditures.

regions in the United States. We use simulated wind and solar profiles in those regions to analyze how storage might be used given the mismatch of demand and the generation pattern of renewable resources. Then, we compare a system with storage to one where gas plants are used to back up wind and solar PV generation. By doing so, we can assess the technological progress in storage and the carbon price level needed to make storage competitive with gas-fired generation as a means of backing up renewable power generation.

Some of the questions we answer are: For a given capacity of renewable resources, how much storage would be needed to capture all of the output from such renewable resources? What are the technological characteristics of such a storage device? How does the cost of the storage device relate to the cost of either wind or solar resources and, in that context, should one build more renewable capacity and allow for shedding of some of that output, or should more storage be built to capture a larger share of the output from renewables?

The rest of this paper is organized as follows. In Section II we provide a brief review of the relevant literature; in Section III we describe our modeling approach and the data we use. Section IV shows the results, Section V discusses the relevance of the results in the context of work others have done, and Section VI provides conclusions.

## II. LITERATURE REVIEW

While much of the traditional literature regarding storage has focused on the arbitrage value of storage<sup>3</sup>, there is also an increasing body of research investigating the impact of large amounts of renewable generation on energy systems and the potential role of storage and storage alternatives to capture excess generation from intermittent renewable resources. The majority of studies in this area have examined either relatively small electricity systems with existing high renewable power capacities, such as Denmark or the Netherlands, or insular electricity systems such as the Canary Islands<sup>4</sup>, where renewable energy potential is high but where there is no possibility to export excess renewable generation through an existing transmission system.

Ummels, Pelgrum and Kling (2007) examine the use of three types of storage as well as electric boilers as a means of capturing wind in excess generation situations in the Netherlands. They conclude that the cost savings from storage increase with the level of installed wind capacity. They also conclude that among the alternatives considered, none of the storage options – two pumped hydro technologies and compressed air storage – are economical at their current cost levels, but that electric boilers used as part of a combined heat and power system are.

This result is broadly consistent with Matthiesen and Lund (2008), who compare seven technologies as means of integrating fluctuating renewable energy sources into the Danish electric system. The authors conclude that heat pumps and electric boilers are the most cost-

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<sup>3</sup> See for example “Estimating the value of electricity storage in PJM: Arbitrage and some welfare effects”, Ramteen Sioshansi, Paul Denholm, Thomas Jenkin and Jurgen Weiss, *Energy Economics*, Volume 31, Issue 2, March 2009, Pages 269-277 and the references therein.

<sup>4</sup> See for example Bueno and Carta (2006)

effective ways of absorbing potential excess generation from renewable power. Unlike in the United States, combined heat and power (“CHP”) plants play a major role in both the current and expected future energy portfolio in both the Netherlands and Denmark. Both studies in essence suggest that a partial electrification of heating demand may be the most cost effective way of absorbing excess power generation from intermittent renewable sources.

The study that addresses most closely the issues we address is Greenblatt, Succar, Denkenberger, Williams and Socolow (2007). They model various options to create baseload wind energy using gas turbines (single and combined cycle) and compressed air energy storage (CAES). Using assumed costs of wind resources of \$700/kW, gas prices of \$5/GJ (or approximately \$5.28/mmBtu) and CAES costs of \$1/kWh<sup>5</sup>, the authors conclude that an all gas system is more economical than a system with any wind for carbon prices below roughly \$150/ton. Between carbon prices of \$150-\$250, a wind system with gas turbines is more economical than a wind with CAES system, and only for carbon prices above \$250/ton the wind with CAES system becomes the most economical option. To derive these results, Greenblatt et al. constructed a wind profile without diurnal or seasonal variation. The authors point to this as a potential shortcoming of their study. Our study attempts to address this issue at least partially by explicitly using renewable energy profiles derived from real measurements and incorporating seasonal variation. Another difference between Greenblatt et al. and our study is that Greenblatt et al. assume a constant demand profile throughout their study period.

The ability of storage to economically increase the effective capacity factor of intermittent renewable resources depends critically on the cost of storage. Cost estimates are changing as technology improves and/or experience with actual storage projects is gathered. Much of the existing studies on the cost of storage assume that storage devices will have typical pond:pipe characteristics<sup>6</sup>. As the purpose of storage moves away from the concept of relatively short-term storage, a more differentiated assessment of the various components making up a storage system with different pond:pipe ratios may be necessary. In particular, a better understanding of the costs of the energy (rather than capacity) storage is critical in assessing the ability of longer term storage to support renewables<sup>7</sup>. Denholm (2006) cites several studies estimating the cost of a wind/CAES baseload system to be 5-7¢/kWh<sup>8</sup>.

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<sup>5</sup> Our capital cost assumptions differ significantly, in particular with respect to the capital costs of renewable generation. However, since our study does not attempt to derive the optimal level of renewable generation, this difference is unlikely to make the two studies less comparable. The assumption of a very low capital cost of energy storage through CAES does make storage significantly more attractive than our range of capital cost assumptions.

<sup>6</sup> See for example SAND2008-4247 (2008), available at [www.electricitystorage.org/site/technologies/](http://www.electricitystorage.org/site/technologies/)

<sup>7</sup> SAND2001-0765 (2001), page 12 (Table 3), which breaks down the total capital cost of storage systems into a cost per unit of energy (kWh), per unit of capacity (kW) and for balance of plant (kWh)

<sup>8</sup> Denholm (2006), p. 1365. To our knowledge this very low estimate is not confirmed by any actual CAES project at this time.

### III. THE MODEL

We developed a simplified energy model of two regions of the United States, the Midwest ISO and Southwest Power Pool (SPP), both of which have significant amount of wind potential.<sup>9</sup> For each region, we created a hypothetical system where wind and PV resources will be the dominant supply resource to serve load. Such a model also represents a system where demand is met to a significant degree by non-dispatchable base load resources such as nuclear and large fossil fuel fired power plants. Based on this model, we estimate the likely storage size necessary to store renewable energy to meet demand at all times of the year under different storage and CO<sub>2</sub> price scenarios.

#### A. MODEL DESCRIPTION

In estimating the size of storage needed to supplement wind and PV generation to achieve an all-renewable system, we compared the hourly wind and solar generation profiles with hourly load for the selected regions. It is well-known that wind generation is typically stronger during off-peak hours and winters and it is typically weaker during the summer peak days. Solar production has a different profile, generally stronger during summer days and weaker during other periods (and zero at night), but with significant regional variation. To determine the potential storage size necessary for an all-wind, all-solar PV, or a blended system, we performed the following analysis:

First, we estimated the amount of wind/PV capacity that would be needed to meet a full-year's load. For example, if in a given region the average capacity factor of a renewable resource was 25%, we assumed that renewable capacity equal to four times ( $1/0.25$ ) the average demand needs to be installed as a minimum to meet all load, assuming that all the output from the renewable resource can be used.

Second, we used simulated hourly generation profiles from the National Renewable Energy Laboratory (NREL) for the regions<sup>10</sup> in question and hourly demand profiles from the regional transmission organizations (RTOs) to estimate the mismatch between renewable generation and load in each hour of the year.

Finally, based on the mismatch between hourly renewable generation and demand, we estimate the amount of storage necessary to capture and use all excess renewable generation supply. We performed the analysis for wind, solar PV and a 50/50 blend of wind and solar PV. In each case, the installed renewable capacity is sized so that the energy output from renewables over the year is the same as the total load over the year (although much of the energy is lost without storage and even with storage, some would still be lost due to the efficiency loss of the storage technology). Table 1 below shows the resulting capacity in each case. The blended case represents a system where half the total annual energy is generated by wind and the other half by

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<sup>9</sup> 20% Wind Energy by 2030, U.S. Department of Energy, July 2008, Section 2.2.1, page 24.

<sup>10</sup> Blended wind and solar PV generation are used such that the diversity of resources within a region is accounted for in the use of the generation profiles.

PV, with resulting higher than 50% share of PV capacity, due to PV’s lower average capacity factor.

**Table 1: Installed Renewable Capacity Assumptions**

Case	Renewable ICAP, % of Average Load	
	Midwest ISO	SPP
Wind	265%	281%
PV	676%	567%
50-50 Blend	320%	338%

We did not consider the different cost of wind and solar PV and hence do not intend to suggest that solar PV might be an economical way of meeting 100% of electrical demand. Rather, by performing this analysis, we can compare the amount of storage an all-wind, all-PV, or blended-wind-PV systems for a range of assumptions related to the amount of renewable generation installed, cost of storage and the price of carbon. To the extent solar PV costs continue to decrease, it is possible that in the not so distant future solar PV and wind can compete with other generation resources without subsidies, at which point a significant amount of future generation would come from wind and solar.

Finally, we developed a simple model to estimate to what extent combinations of storage and natural gas may result in lower total costs than using either one or the other exclusively. To do so, we used the renewable profiles described above, i.e. sized to generate an amount of energy in a year exactly equal to total demand, and calculated the cost of supplementing renewable energy in a system with increasing amount of storage. We estimate this supplemental cost for an increasing amount of storage level by adding up the capital cost of storage and the cost of energy produced by natural gas fired combustion turbines to meet demand in every hour of the year.

**B. THE DATA**

We used NREL wind and solar profile data to construct hourly generation profiles for an all wind and an all solar PV scenario for both MISO and New England. We used load forecast data from the RTOs and information from the 2005 FERC Form 714 to construct theoretical load shapes.

Except where otherwise noted in the sensitivity analyses, the results in this paper use the cost and other assumptions shown in Table 2.

**Table 2: Model Parameters**

<b>Capital Costs</b>	<b>Overnight</b>	<b>Per Year</b>
Wind Capital Costs, \$/kW	\$2,200	\$241.00
Solar PV Capital Costs, \$/kW	\$6,000	\$657.28
Gas Capital Costs, \$/kW	\$900	\$98.59
Storage Capital Cost, \$/kWh	\$50	\$5.48
Equipment Lifetime, Years	20	
Cost of Capital	9%	
<b>Gas Parameters</b>	<b>\$/MWh</b>	
Fuel Cost, \$/mmBTU	\$6.00	\$66.00
Carbon Cost, \$/ton_CO <sub>2</sub>	\$50.00	\$32.20
Heat Rate, BTU/kWh	11,000	
<b>Storage Parameters</b>		
Charge Efficiency	90%	
Discharge Efficiency	90%	

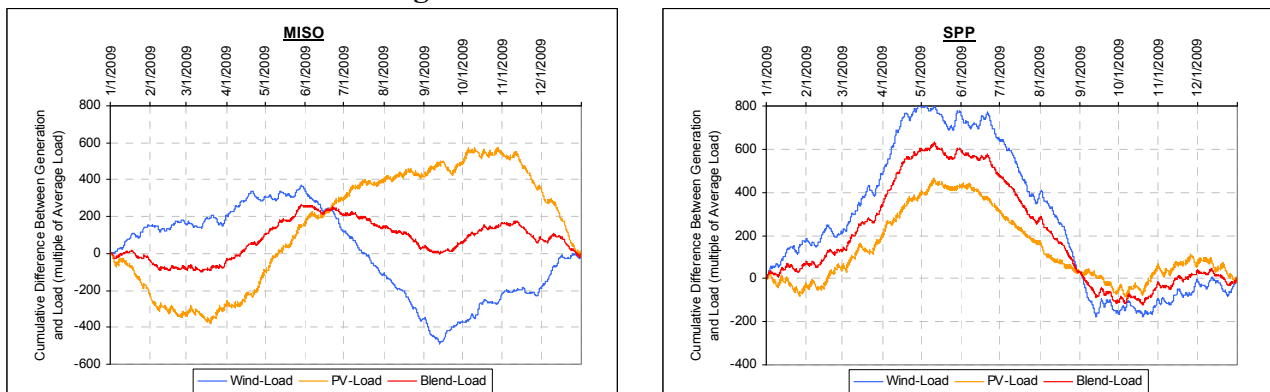
#### IV. RESULTS

This section presents our analytical results.

##### A. WIND AND SOLAR PV GENERATION PROFILES AND THEIR IMPLICATIONS FOR AN ALL-RENEWABLE SYSTEM

We first analyzed the relationship between power generated from either wind or PV and load in two representative regions: MISO and SPP. Figure 1 below shows the difference of load and renewable energy accumulated hour by hour in a typical year.

**Figure 1: Load-Generation Mismatch**



Notes: Difference between cumulative generation from either wind, PV or a 50/50 blend of wind and PV and load. PV and Wind capacity is sufficient to generate power exactly equal to total annual load.

The two graphs in Figure 1 show the cumulative hourly load minus renewable generation, expressed in multiples of average load. In other words, we estimate the “excess renewable

generation” from every hour and accumulate the excess generation chronologically across a year. The y-axis on each graph represents the multiple of average load in each system. The larger of the maximum and the minimum of any of the lines on Figure 1 shows the storage size (in terms of energy) that would be needed to capture all generation from any of the three hypothetical systems. Accordingly, Figure 1 shows that the storage capacity required to capture *all output* from an all wind portfolio in MISO would be roughly 500 hours of storing average demand, as compared to roughly 800 hours in SPP. A PV system would require almost 600 hours of average load storage in MISO and about 400 hours in SPP. Figure 1 also shows that by blending wind and PV generation, the energy storage needed to capture all renewable energy could be reduced to approximately 200 hours of average demand in MISO whereas in SPP, there is no benefit from blending in terms of creating a renewable generation profile that would require less storage capability.

Several interesting observations emerge from this analysis. The correlation between load and renewable generation differs significantly across regions as well as renewable technology. For example, in MISO, wind and PV generation profiles both vary greatly from load. In MISO, cumulative wind and PV generation are inversely correlated. As a result, a 50/50 blend of power generation from wind and PV results in a much better match to load than a system dominated by one or the other technology. By contrast, in SPP, the annual generation profiles from wind and PV are positively correlated with each other, resulting in an all PV system to be better matched against load than either a wind or a blended system. To get a better sense for the degree of regional variation, we performed the same analysis for all major electric regions in the United States. Table 3 below shows the results of this analysis.

**Table 3: Renewables Mix and Storage Requirements**

NERC Region	Average Load GWh	Peak Load GWh	Discharge Hours			Min Storage Renewables Profile	Discharge Hours # of hours
			All Wind	All PV	50/50 Wind/PV		
ECAR	108	179	647	552	373	Blend	373
ERCOT	34	60	937	400	648	PV	400
MAAC	108	179	943	415	566	PV	415
MAIN	108	179	544	563	430	Blend	430
MAPP	25	39	475	573	451	Blend	451
NPCC_NY	19	32	777	422	510	PV	422
NPCC_NE	16	27	749	430	476	PV	430
FRCC	26	46	1131	620	862	PV	620
SERC	117	195	938	332	624	PV	332
SPP	23	39	808	464	632	PV	464
WECC_NWPA	26	39	605	280	310	PV	280
WECC_SW	21	39	956	626	722	PV	626
WECC_CA	32	54	972	287	618	PV	287
MISO	71	107	487	572	263	Blend	263

One interesting observation emerges from Table 3. Ignoring the capital cost difference between wind and PV, in most regions PV is better matched with load for storage purposes, and in no region is the wind output better matched with load than a blend of wind and PV. Therefore, if solar PV experiences a technological breakthrough such that its costs become comparable to that of wind, blended solar PV and wind generation can reduce the amount of storage needed on certain systems and thereby further reduce the cost of using primarily renewable energy to serve load. In addition, the weekly or daily charge and discharge cycles for which current storage technologies are used would be better suited for a combined solar PV and wind system.



## B. ANALYSIS OF STORAGE REQUIREMENT FOR AN ALL-RENEWABLE SYSTEM

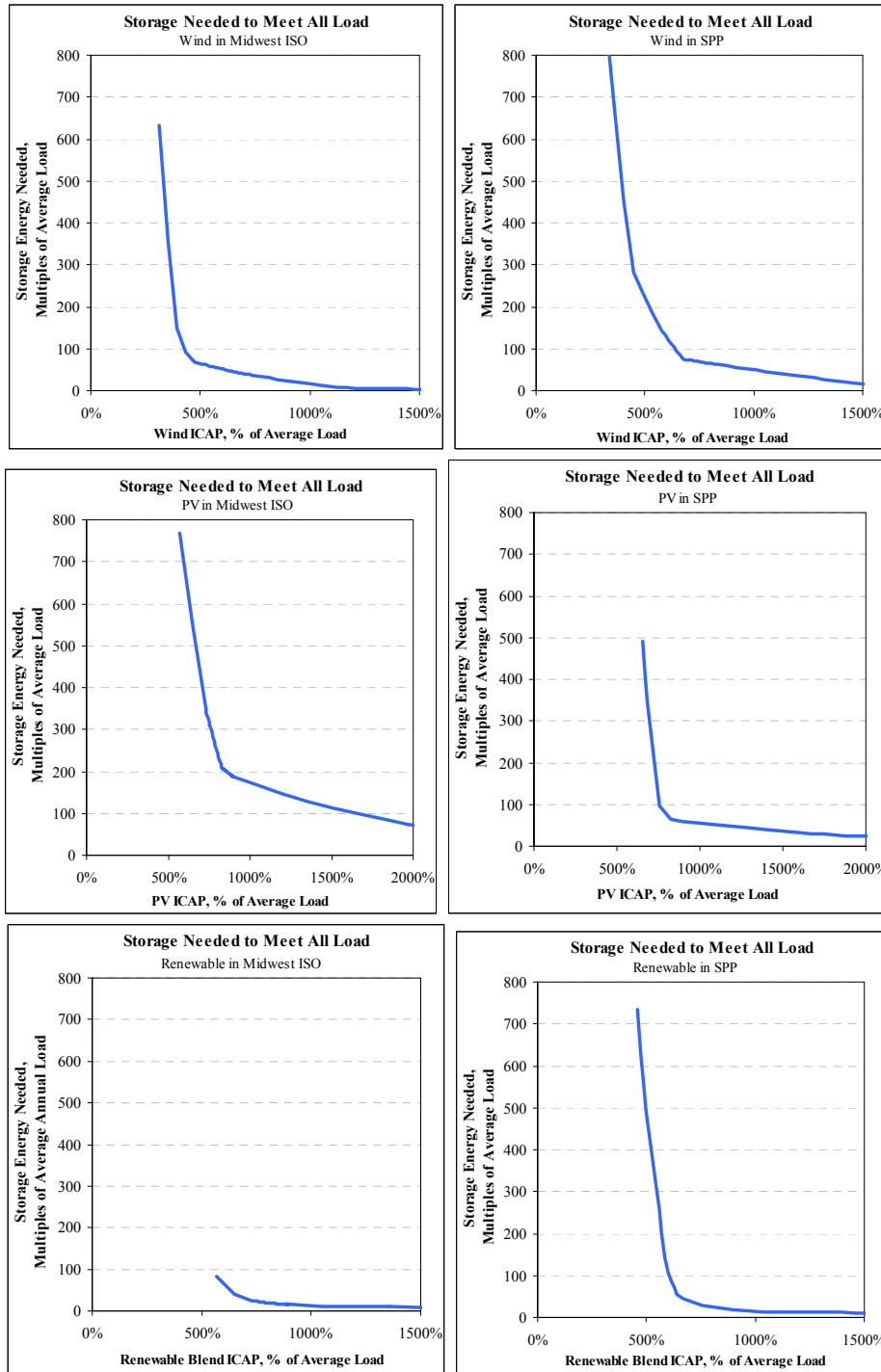
Independent of region or renewable technology, because wind and solar generation is variable, it would require substantial amount of energy storage (in MWh terms) to smooth out the generation and meet load. That amount far exceeds the storage capacity in place today. The flip side is also important to consider. Without any storage, a system using solely wind and solar generation would need to be vastly over-built to meet load, particularly during peak (with significant amounts of the renewable generation being lost). By adding *some limited* amount of storage, the renewable capacity required to meet load drops substantially.

Figure 2 shows the relationship between the amount of wind, solar PV and a blended system and the amount of storage that would have to be available in order to meet all load with renewables in the Midwest ISO and SPP. Renewable installed capacity (ICAP) is shown on the x-axis, normalized by average system load; the y-axis shows the energy storage capability required in the system, expressed as a multiple of average load in MWh. In each graph, we can see the minimum amount of renewable (installed) capacity required, below which an all renewable system would be impossible because there would not be enough energy produced over the year to meet all load.

Minimizing the amount of renewable capacity would require a vast amount of storage capability, amounting to a storage resource that could store average load for approximately a month. Increasing renewable capacity somewhat beyond the minimum would mean that some renewable energy would be lost, but the required quantity of storage drops dramatically – reaching a level reasonable for current trend of storage usage.

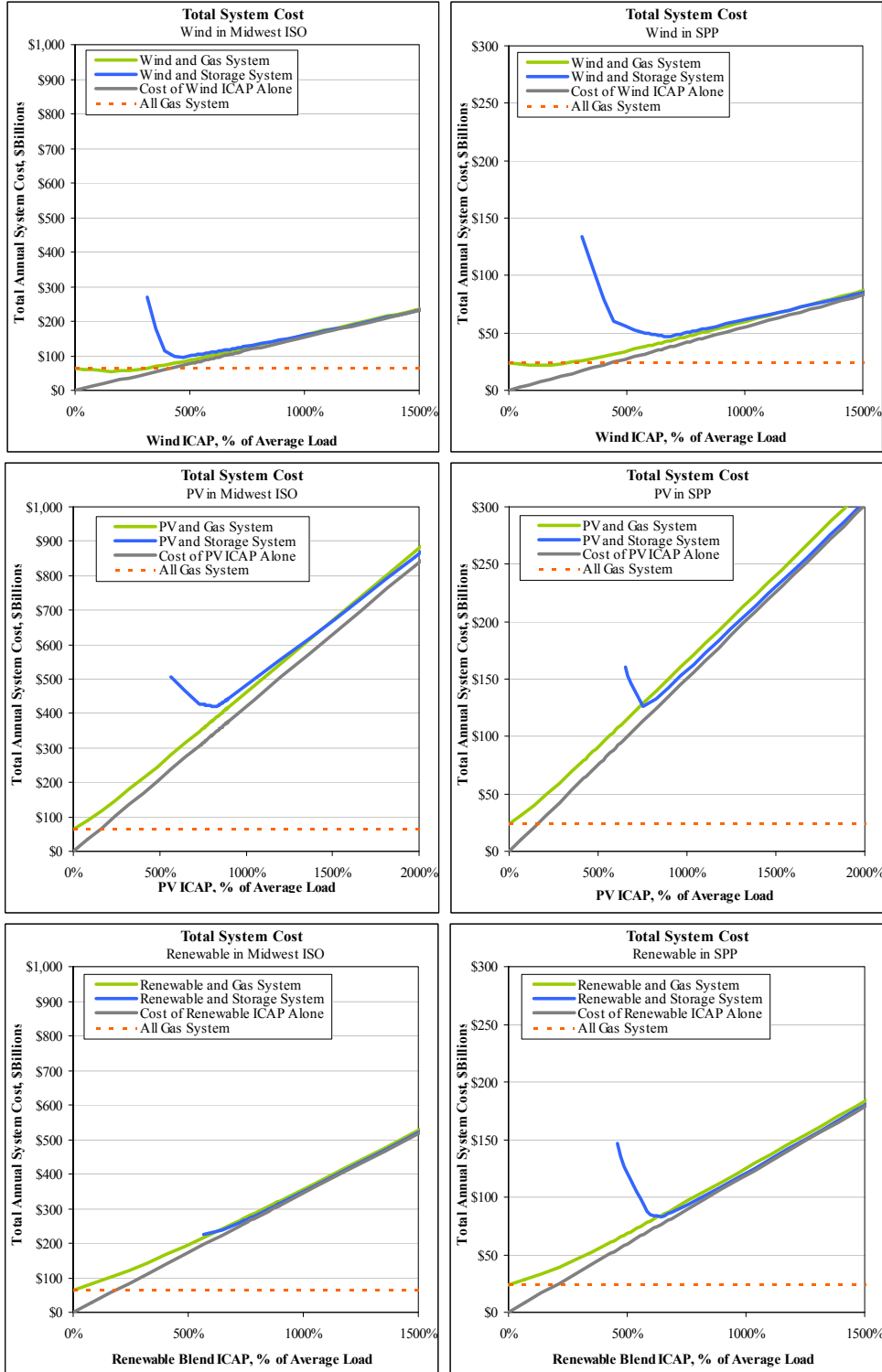
The graphs in Figure 2 show the relationship between energy storage and renewable capacity needed to meet a system's annual load. They show that increasing renewable capacity slightly above the minimum amount needed to meet load would significantly reduce the size of the accompanying storage needed. However, the sizing analysis shown in Figure 2 ignores the relative cost of storage and renewables, which would clearly influence the optimal choice of the relative size of each. Thus, we analyze the economics of such combinations next and the graphs in Figure 3 show the result of the analysis.

**Figure 2: Storage Needed to Meet All Load**



## C. ANALYSIS OF BACK-UP GENERATION FROM GAS PLANTS VERSUS FROM STORAGE

**Figure 3: Total System Costs: Using Gas versus Storage**  
**Assuming \$50/kWh Storage Cost and \$50/ton of CO<sub>2</sub> Emissions Cost**



Note: Assumes capital cost \$50 per kWh of energy storage and \$50/ton of CO<sub>2</sub>

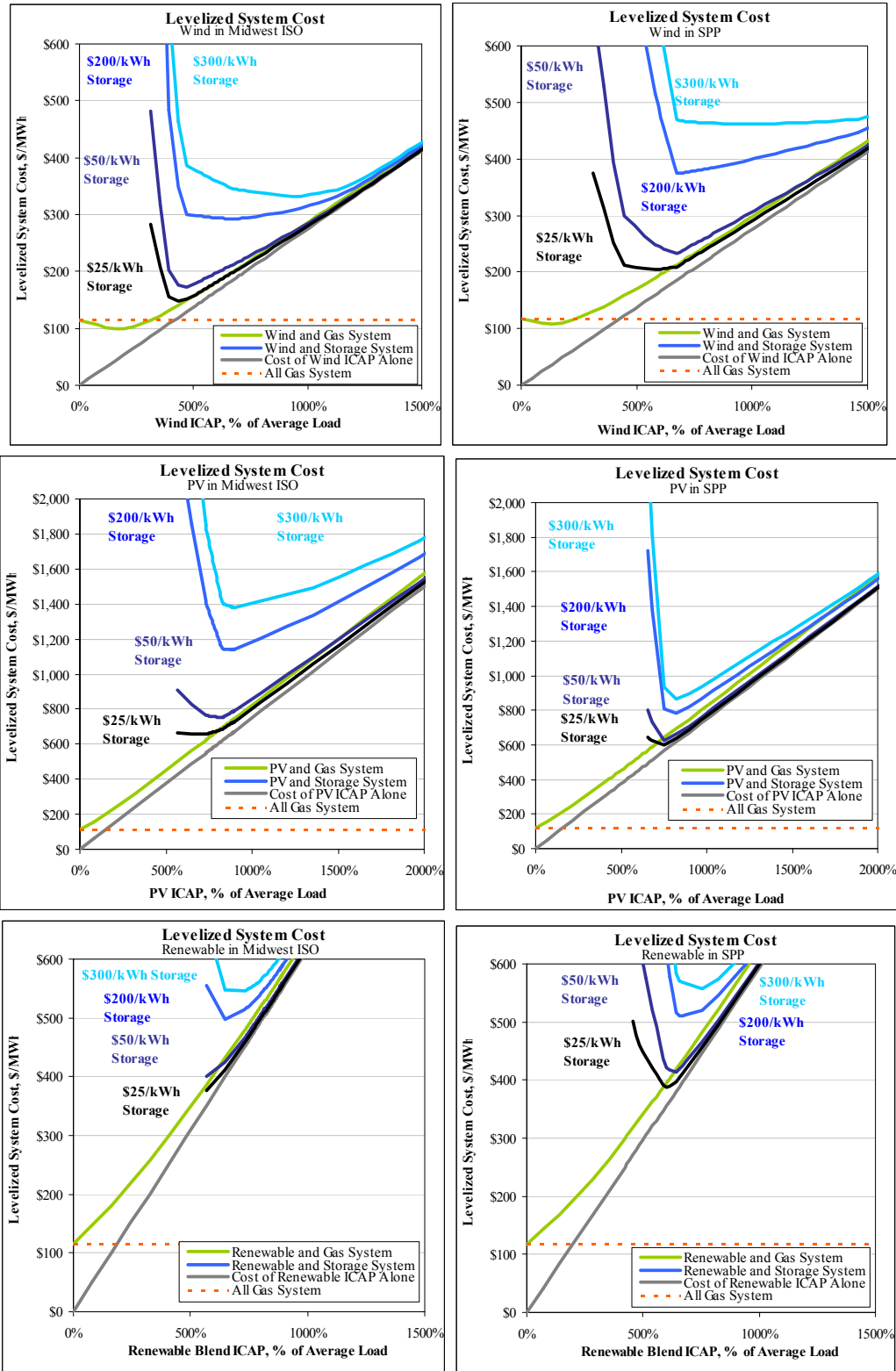
The gray lines in each graph show the cost of the renewable capacity alone and the blue lines show the cost of a renewable with storage system. For comparison, we also show the costs of an all-gas system (with no renewables) in the orange dotted lines and the costs of a renewable system with compensation for intermittency provided with gas instead of storage in the green lines.

Figure 3 suggests that given the current costs of wind and solar PV, an all-gas system is cheaper than using wind, solar PV or a blended system of wind and solar PV, even at the relatively high CO<sub>2</sub> price of \$50/ton, which we use as a basis for this analysis. Second, compensating for wind and solar generation variations with gas is generally cheaper than compensating with storage, except that blending solar PV generation with that from wind significantly reduces the size of storage to achieve the same renewable usage. As a consequence, we find that with our assumptions of \$50/kWh energy storage costs and \$50/ton carbon prices, a system with storage accompanying solar PV in SPP and a 50/50 wind-solar blend in both region can be competitive with using gas to supplemental renewable generation.

#### **D. LEVELIZED COST OF STORAGE AND RENEWABLE RESOURCES ACROSS VARIOUS STORAGE AND CO<sub>2</sub> COST ASSUMPTIONS**

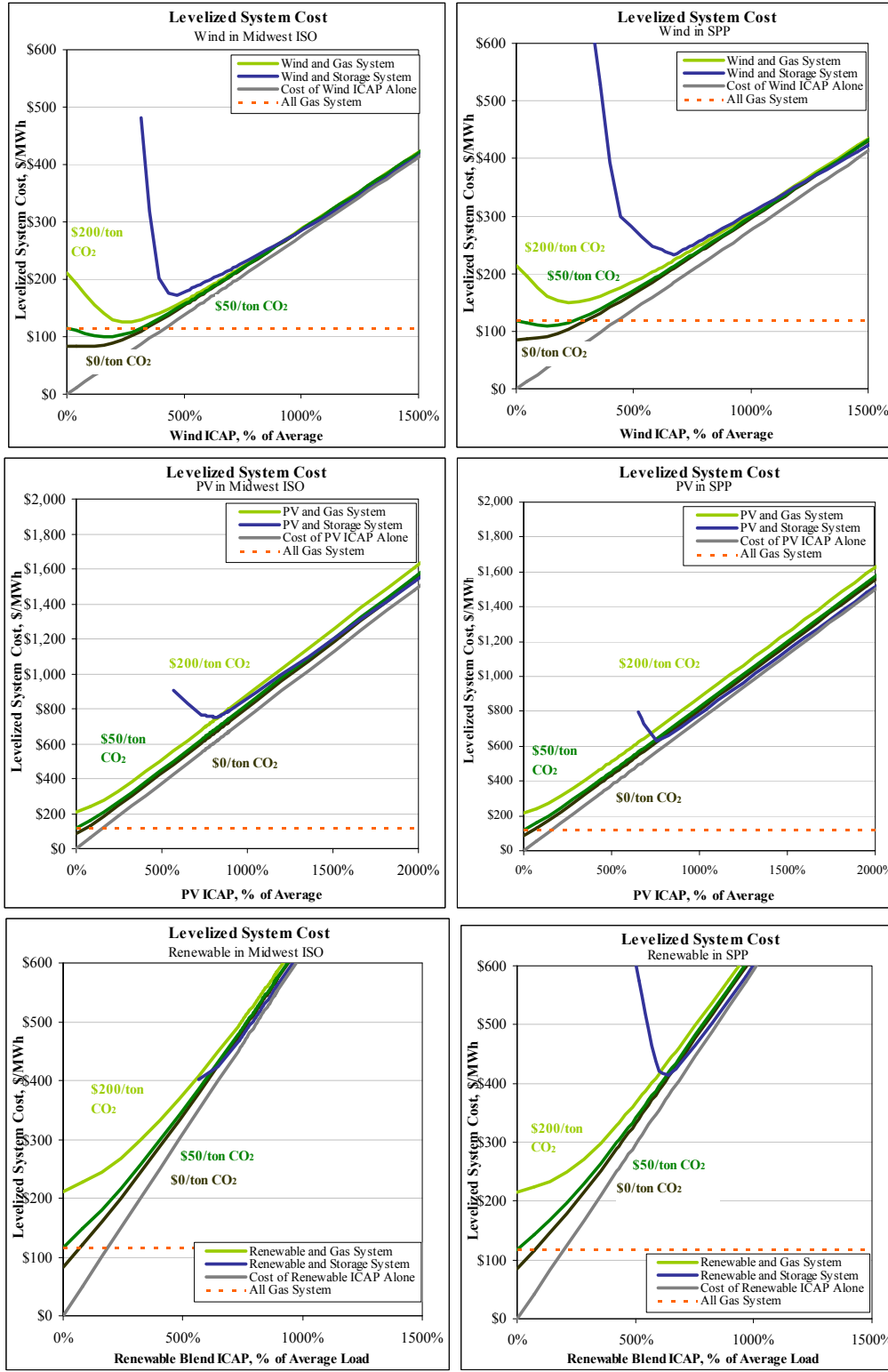
As a next step, we evaluate the system's levelized costs that are consistent with the total costs shown in Figure 3. The graphs in Figure 4 compare the costs of a high-renewable system in MISO and SPP at various storage cost levels, ranging from \$25/kWh to \$300/kWh installed cost, while keeping the assumed CO<sub>2</sub> price at \$50/ton. The graphs in Figure 5 show similar graphs with an assumed storage cost of \$50/kWh with varying CO<sub>2</sub> prices. As expected, the costs in an all-solar system are many times higher than the costs in an all-wind system, driven largely by the higher capital costs and lower capacity factors of PV. The economics of solar PV also vary substantially by region, with the associated energy cost almost twice as expensive in Midwest ISO as it is in SPP due to a lower capacity factor and a greater seasonality (and consequently greater need for storage) in MISO than in SPP.

**Figure 4: Levelized System Cost for Carbon Price of \$50/ton**



Note: Y-axis range different for PV systems.

**Figure 5: Levelized System Cost at Storage Cost of \$50/kWh**



Note: Y-axis range different for PV systems.

Over a wide range of CO<sub>2</sub> prices and storage cost assumptions, we observe that it's less costly to compensate for wind and PV with gas rather than storage. However, Figures 4 and 5 also show that for relatively high carbon prices and for storage for levelized storage costs below \$50/kWh, using storage versus gas to backup renewable generation could become relatively comparable. We have chosen a range of carbon prices between \$0 and \$200/ton to show more or less the full range of carbon prices that are typically suggested to be necessary and/or sufficient to lead to reductions in greenhouse gas emissions consistent with the scientific recommendation to limit long-term warming to less than 2 degrees Celsius. The choice of the appropriate range for the cost of energy storage is more complex, given that the cost of storage is determined by a number of factors, some related to the trajectory of technological change and related declines in cost, and many related to site-specific circumstances. Most existing long-term storage is provided by pumped-storage systems designed more or less for one-day storage, (*i.e.* with energy storage capacity sufficient to charge during off-peak hours and discharge during on-peak hours). As a result, available cost data reflects the typical ratio of energy storage volume to discharge capacity characteristic of such daily cycling. As we have discussed, capturing a higher share of renewable power with storage would required larger energy storage capability than a daily cycle. Depending on both technology and storage site, it is possible that creating more energy storage capability would not increase the costs proportionally relative to the average cost of existing systems. Using estimates for the cost of storage by component (energy, capacity, balance of plant) from Sandia Laboratory<sup>11</sup> suggests that it might be possible to build storage systems, either pumped-hydro or compressed air ("CAES"), with a large energy storage relative to discharge capacity at combined costs of between \$25 and \$50/kWh of energy storage capacity.

#### **E. MINIMIZE SYSTEM COST BY USING BOTH STORAGE AND GAS GENERATION TO SUPPORT WIND**

So far in Sections III-A through III-D, our analysis has focused on simulating systems that *mutually exclude* the use of either natural gas or storage to supplement renewable generation to meet demand. As a next and final step, we also analyze a situation that more closely resembles the conditions that could emerge in at least some parts of the United States over the next couple of decades. In particular, we analyze a system with very significant renewable penetration, but allow for some of load to be met with gas-fired generation and dump some excess renewable generation that might not be economical to store.

We do not attempt to derive the optimal mix of storage and gas in each simulation, but rather use a simple algorithm to estimate the appropriate level of gas combined cycle capacity *given* a particular level of wind or solar PV capacity. In particular, we assume that enough renewable capacity would be built to generate total annual energy that exactly equals total annual demand, as illustrated in Table 1 above (though some of the energy will be lost due to the absence of sufficient storage, less than 100% storage efficiency, or a combination of both). The system we modeled here is not very dissimilar to a system where a fixed portion of total load is met from relatively large and inflexible base load power plants, such as nuclear or large coal-fired units, and where the renewable generation effectively meets the residual demand.

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<sup>11</sup> See Sandia (2001), Table 3, page 12.

In our simulation, we calculate the total cost of supplementing renewables (without taking into account the capital cost of the renewable resources) across a wide range of storage capacities. For each level of storage, we estimate the magnitude of natural-gas fired capacity and energy needed to meet load. By doing so, we can estimate the mix of storage and gas-fired generation that minimizes the cost of supplementing renewables. Figures 6-8 below show the results of our analysis.

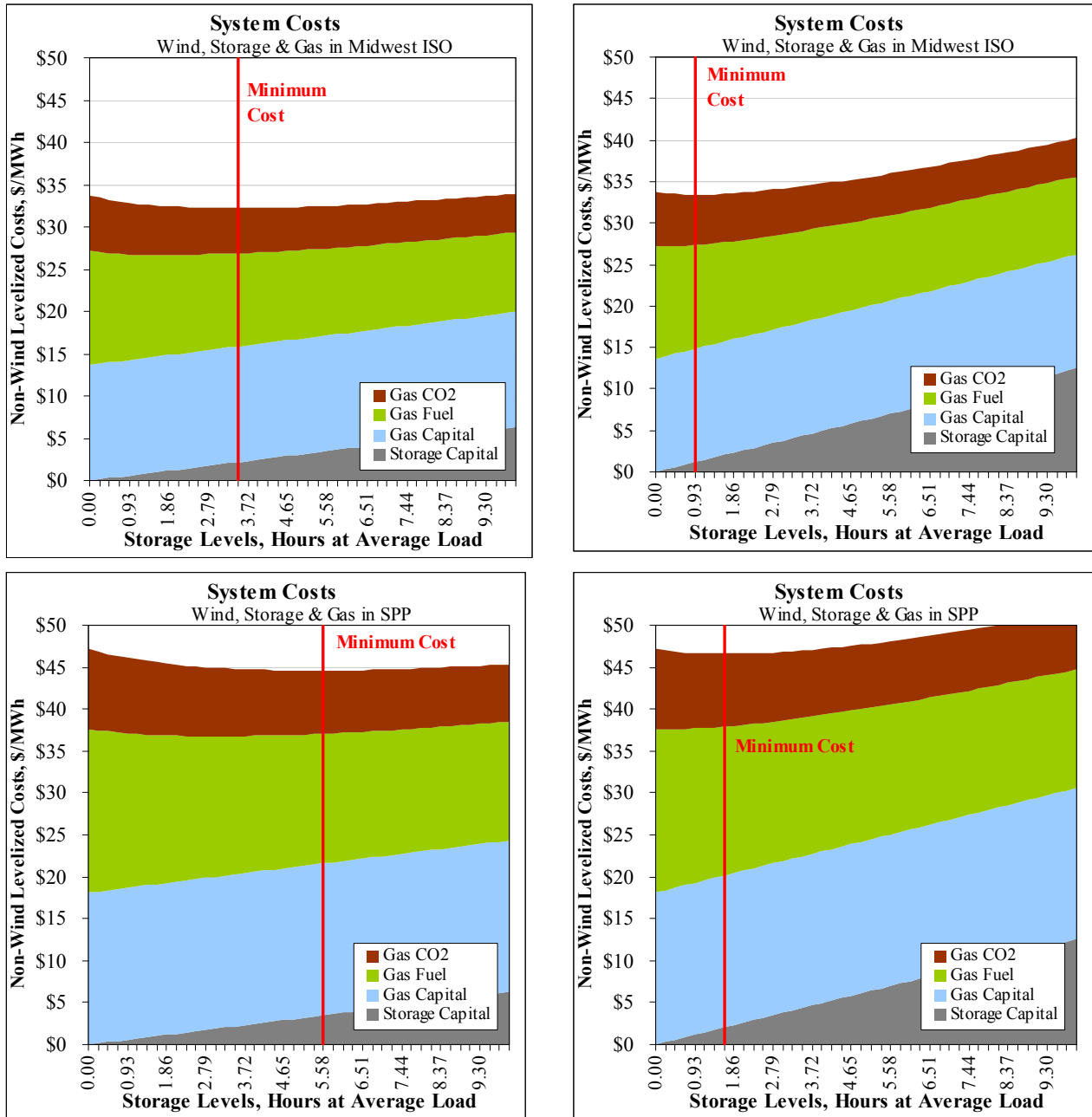
The x-axis in Figures 6-8 is the ratio of storage in MWh over average load. For example, if the average load of the system is 40,000 MW, a 5.0 in the x-axis corresponds to the cost estimate for a 200,000 MWh size storage. The 5.0 multiple is also the storage size in terms of number of hours the storage facilities can store the amount of power equal to the average system load.

Figures 6-8 suggest that in systems with large renewable capacity, some amount of storage is economical even if in general gas-fired generation seems to be cheaper than storage. Intuitively, these graphs show that some amount of storage allows for a decrease in the all-in cost of energy generated from gas plants (distributed across the overall load MWh). More storage means that less energy generated from renewable resources is dumped or curtailed and thus less supplemental gas generation is needed. The economics of an incremental MWh of storage relative to using gas depends significantly on the utilization of that incremental unit of energy storage – if an incremental MWh of energy storage is used often, the capital cost of the extra storage can be spread over more storage cycles and hence may be lower than the fuel and emissions cost of meeting the same MWh of energy with natural gas.

The levelized cost of supplementing renewable generation differs somewhat by region and by renewable energy mix, with solar PV systems requiring a more expensive and storage-intensive storage/gas combination than wind or blended systems. Many factors play into the tradeoff between using storage versus gas to supplement wind and solar PV generation. Figures 6-8 show that the economic energy storage capacity for solar PV systems is larger than that for wind or blended systems. This is partially due to the fact that PV systems will have a stronger daily pattern of over-generation, while wind, by comparison, will have a more dominant seasonal pattern. A system with sufficient PV capacity to serve a full-year's load would over-generate significantly during each day with excess to be stored and used at nights. If storage were not used to supplement PV in such a system, gas plants would need to supply all the electricity needed at night. For this reason, incremental storage would be used very frequently and consequently building *some* incremental storage helps reduce the overall system cost associated with running the gas plants. With wind, the overgeneration pattern is more related to wind's seasonal mismatch with load than to the daily mismatch (even though a daily mismatch is also present, with wind tending to be stronger during off-peak than peak hours). As a consequence, even without storage there is less daily excess generation and therefore less daily supplemental gas generation will be needed than it is the case of solar PV. Consequently, as the graphs in Figures 6 and 7 show, less storage is economical for wind or blended systems, but the total levelized cost of a system with the storage and gas needed to support PV is substantially higher than a similar system for wind.

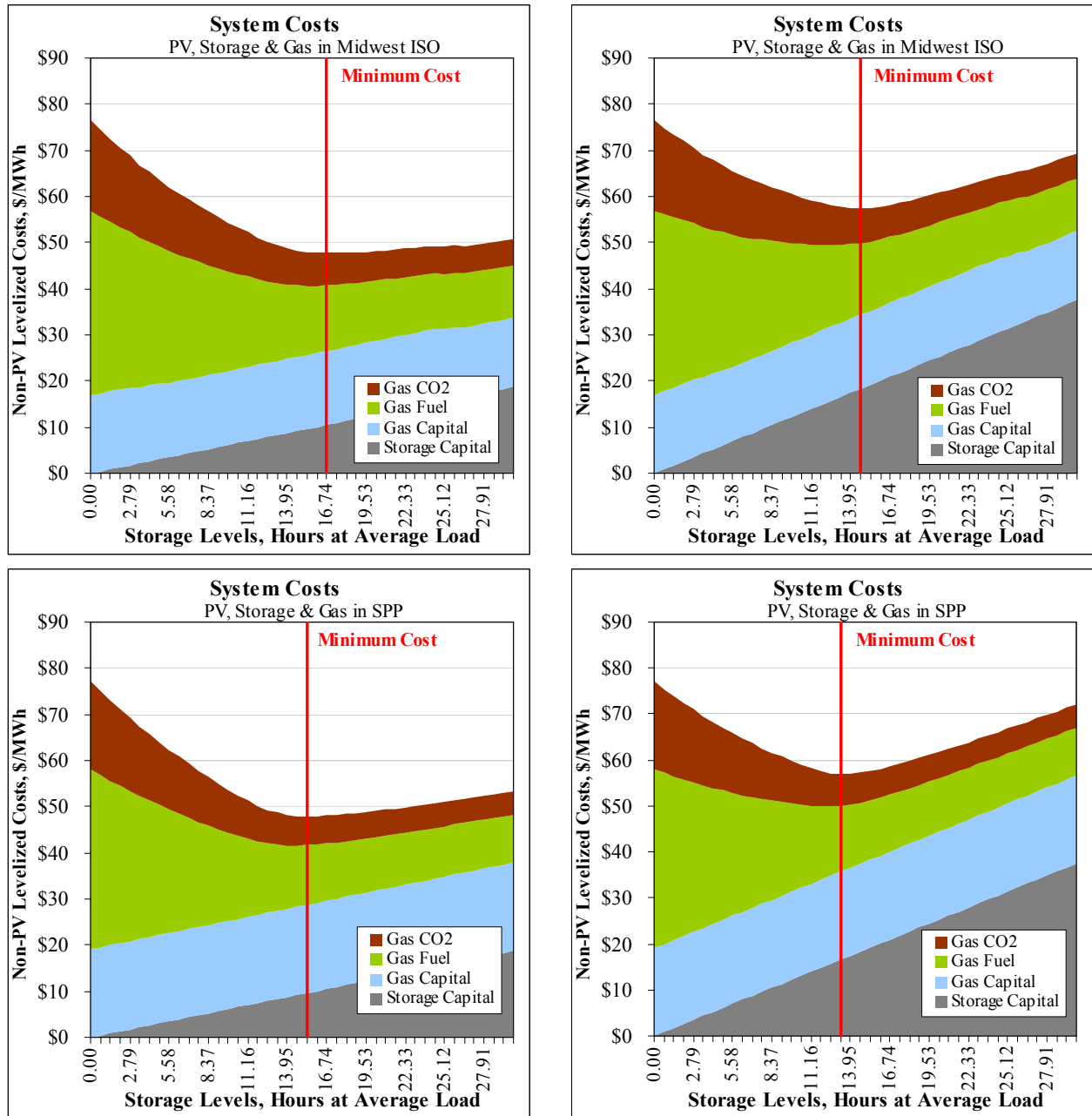


**Figure 6: A system with wind, storage and gas capacity in the Midwest ISO and SPP**  
 Energy Storage Capital Cost \$50/KWh Energy Storage Capital Cost \$100/KWh



Note: Renewable capacity sized to meet total load ignoring storage losses and lost renewable generation due to non-storage mismatch between load and generation. Carbon price assumed to be \$50/ton.

**Figure 7: A system with solar PV, storage and gas capacity in the Midwest ISO and SPP**  
 Energy Storage Capital Cost \$50/KWh      Energy Storage Capital Cost \$100/KWh

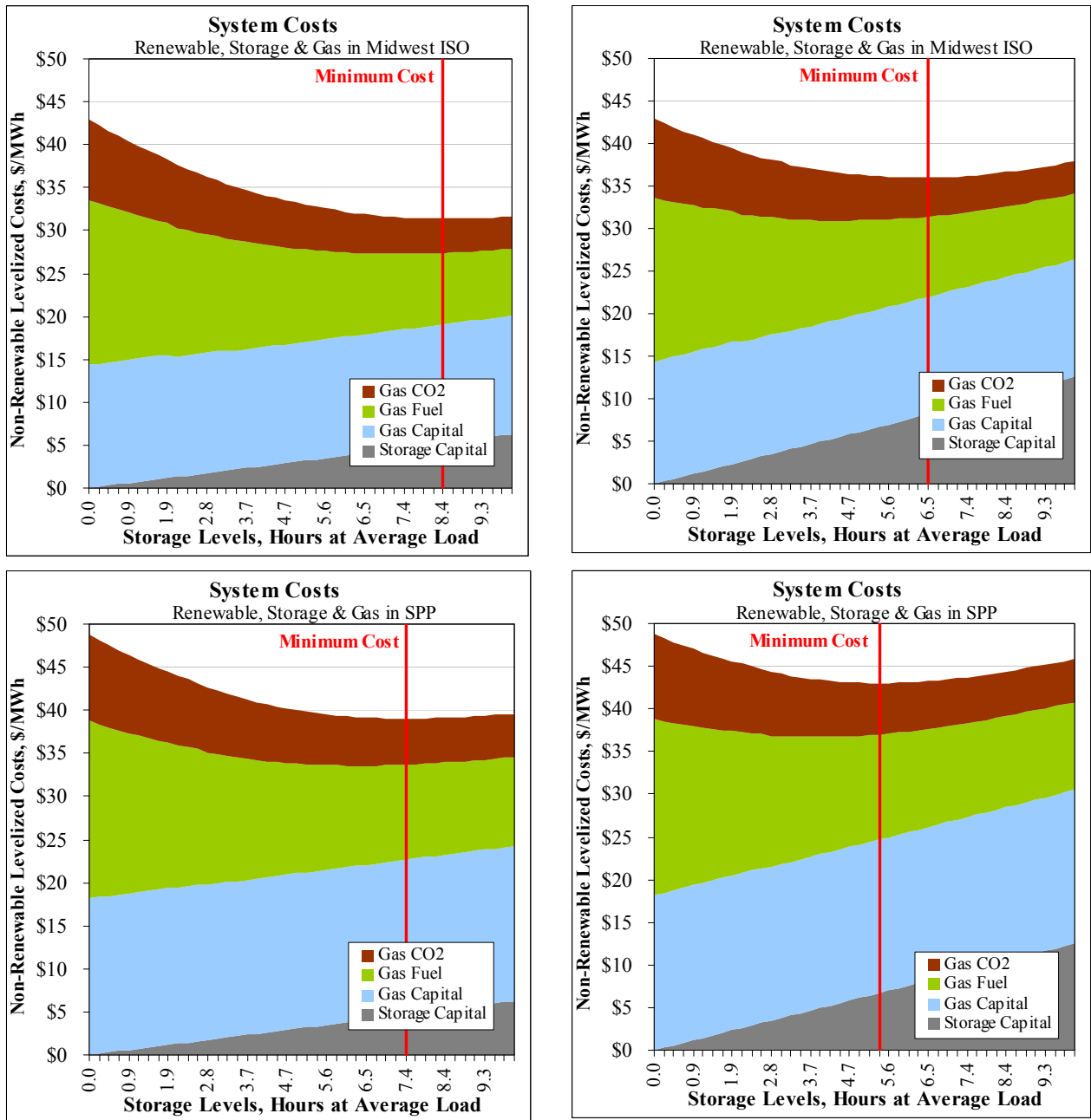


Note: Renewable capacity sized to meet total load ignoring storage losses and lost renewable generation due to non-storage mismatch between load and generation. Carbon price assumed to be \$50/ton.

**Figure 8: A system with a blend of wind and solar PV, storage and gas capacity in the Midwest ISO and SPP**

Energy Storage Capital Cost \$50/KWh

Energy Storage Capital Cost \$100/KWh



Note: Renewable capacity sized to meet total load ignoring storage losses and lost renewable generation due to non-storage mismatch between load and generation. Carbon price assumed to be \$50/ton.

Figure 8 shows that blending a PV and wind system would lower the levelized cost of supplementing renewable generation with storage and gas to near the cost of supplementing a primarily wind-driven system. By combining solar and wind, we diversify the overall renewable generation pattern and reduce the amount of supplemental gas generation needed. Thus when

compared to the gas generation costs, less storage is cost-effective than in a solar-only system. The combination of smaller storage and less gas generation required yields a lower overall system cost to supplement the renewable energy. The economics of storage would further improve if carbon prices exceeded \$50/ton, but would decline for carbon prices below \$50, a prospect that seems more likely over the next ten to twenty years.

In summary, in the extreme case of a system where using gas as a back-up fuel is not an option, solar PV or 50/50 PV and wind blends would require a lower amount of energy storage than wind-only systems due to wind's seasonal pattern of generation. However, when considering a more realistic system where gas plants are also used to supplement renewable generation, a blended solar PV and wind system could reduce the need for supplemental energy and increase the magnitude of cost-effective storage compared to a wind-alone system.

## V. DISCUSSION

Our finding that over a reasonable range of storage cost and carbon price estimates it is uneconomical to use storage to capture all seasonal renewable over-generation relative to load is consistent with both the current use of storage and with the conclusions of others who have studied seasonal energy storage.

To use all of the renewable generation, storage would have to cycle seasonally, rather than daily or weekly, and consequently would require very high energy storage capacities – much more similar to how natural gas storage is operated than how current electric storage technologies are designed. This suggests that if storage is to play the role of seasonal storage in the future, there have to be significant advances in technology or proof of concept of some of the proposed technologies to address seasonality. In particular, cost estimates for CAES suggest that CAES may allow economical seasonal storage, but CAES is still largely unproven<sup>12</sup>.

While the United States is still far from being a renewable power-dominant system, our results are nonetheless relevant. For one, our results apply equally to systems with increasing renewable power capacities and substantial amounts of must-run base load generation. Such systems are quickly emerging in the United States. For example, both the Midwest ISO and ERCOT now experience negative wholesale prices with increasing frequency. These are generally caused by exactly the kind of situation we describe, i.e. by renewable power sources generating more energy than can be absorbed by the demand that remains unmet by already committed base load generation. Second, other parts of the world are moving more quickly in that direction. As a consequence, a substantial amount of research on renewable power-dominant systems has already emerged from places like Denmark and the Netherlands, where renewable power already represents a significant portion of the overall power mix and is likely to approach a renewable-dominant world in the foreseeable future. Therefore, the results of this research may point to useful alternatives for the United States as well.

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<sup>12</sup> The questions addressed in this paper are generation proposals for CAES projects and technologies capable of seasonal energy storage. See for example [www.generalcompression.com/gcaes.html](http://www.generalcompression.com/gcaes.html).

The existing literature from Denmark and the Netherlands generally concludes that storage is not the least cost option to balance the mismatch between renewable power generation and load. Rather, this literature suggests that it may be most useful to consider joint optimization of both electricity and heating demand and supply systems. Both countries have a relatively high share of combined heat and power (CHP) systems, which has forced a look at the combination of electricity and heating for quite a while. Studies of all renewable energy systems in the presence of CHP (and considering heating as well as electricity demand) generally conclude that the cheapest way to harness excess renewable generation is in essence the electrification of heating supply when renewable electricity generation exceeds base electricity demand. This electrification takes place either through electric heat pumps (centralized or distributed, air or ground source) or through electric boilers.

The conclusions emerging from the European research are likely applicable to the United States, both in the short run to address existing over-generation issues and in the long run as the United States moves to higher renewable electricity generation shares in response to aggressive long-term greenhouse gas emissions reductions goals. In particular, changing the profile of demand to more closely match the natural profile of available renewable energy sources may be a more promising strategy than trying to develop and build seasonal storage capabilities. Partial electrification of heating is one avenue to do so. Heating demand is higher in winter than in summer and in several parts of the United States, wind generation is also higher in winter than in summer. A move toward an electrified heating system may be facilitated by the economics of certain heating systems such as heat pumps, which already emerge as economic alternatives to current heating systems even without carbon price signals. A second avenue may be the electrification of transportation. It is possible that the charging habits of future owners of electric vehicles may lead to more incremental demand for electricity during the off-peak periods, when wind generation is higher than during day hours.

Gas-fired generation are also a potentially low cost alternative to storage and can be used to meet load when wind or solar is not available, reducing the need for storage, particularly as long as the all-in cost (including the cost of carbon emissions) is significantly lower for gas-fired back-up generation than for storage, which is likely to be the case for the foreseeable future.

In combination, these findings suggest that using storage to capture all of the excess wind and use it when needed is an expensive way to maximize renewable energy usage. This result also suggests that it may not be practical to attempt to use all the renewable resources when those resources are most abundant during non-peak periods. Our analysis suggests that some additional storage may prove economical in some parts of the country, but that it is unlikely that it will be optimal to build enough supplemental storage to capture all such excess generation. It is more likely that using natural gas to meet residual demand when not enough renewable generation is available on-peak is more economical, and that demand-side measures such as shifting heating demand (or eventually some transportation related demand) from natural gas or oil to electricity during times with excess generation is more economical than building additional energy storage capacity.

## VI. CONCLUSIONS

In this paper, we construct a number of scenarios to examine the role storage might play in using increasing renewable power capacities in the United States more effectively. We find that over a wide range of reasonable estimates of storage costs and carbon prices, storage is not generally the cheapest option to overcome the seasonal mismatches between in particular wind power, which is currently the cheapest renewable power source, and load, but largely also solar PV and load. We find that in some parts of the country at least theoretically renewable resources can be blended to create generation profiles that match load much better than generation from just wind or solar PV. Such blended renewable portfolios reduce the amount of seasonal energy storage needed to capture all renewable energy generated from a given renewable capacity. However, unless storage becomes significantly less expensive, seasonal storage will likely remain less economical than either the use of gas or demand side measures. We do find that allowing the dumping or curtailing of *some* renewable generation and the supplemental use of gas-fired generation capacity, it is optimal to build *some additional* storage rather than lose all renewable power generation in excess of load and make up the difference by gas generation. We find that the optimal amount of storage reflects the typical daily mismatch between renewable generation and load rather than the seasonal mismatch. Given the daily mismatch patterns, more storage is optimal for renewable profiles dominated by solar PV. Given the different regional preferences as well as opportunities, we therefore expect that different amount of storage will be optimal in different parts of the United States. Large transmission investments also may be necessary to create overall generation profiles more in line with load.

The research in Europe indicates that combining heating and electric demand and supply may offer some cheaper ways of creating a closer match between supply and demand, for example by shifting heating supply from fossil fuel based to electric when renewable power generation is high but existing power demand low. Of course, a cheap and dispatchable renewable generation technology as a substitute for natural gas-fired power generation would also make it possible to have an all-renewable power mix with some storage, very much along the lines of the results we show for combined renewable, gas and storage systems.

We have not attempted to analyze the optimal choice between various renewable technologies, gas-fired generation and storage once all relevant costs are taken into account. Since there is significant technological progress with respect to some renewable technologies (and potentially storage), determining the optimal capacity expansion path with an increasing share of renewable generation and the potential role of storage in such a system is important, but needs to be left for future research.

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