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The Cost to Achieve 100% Renewable Energy:
A Comparative Analysis of Texas and California

In this research report, we compare the cost to transition the power grids of California and Texas to 80%, 90% and 100% renewable energy, while preserving a standard of reliability comparable to that of these grids today. We reach several conclusions. First, transitioning to an all-renewable energy system (100% renewable penetration) requires the supply of highly reliable power with intermittent wind and solar resources, and is thus inherently wasteful and prohibitively expensive. Therefore, even in states with ample renewable resources such as Texas and California, we believe it unlikely to be achieved for the foreseeable. Second, to achieve renewable penetration of up to 80% is far less costly, and may be feasible for certain states, such as California, that have access to abundant hydroelectric power. Third, even in these cases, the scale of the renewable resources required will be vast, and their output will far exceed power demand during many hours of the year – creating an economic impetus to connect high renewable energy regions with population centers whose longitude and latitude create complementary patterns of renewable generation and electricity demand. Fourth, renewable penetration of 80% or less is materially cheaper because its allows continued use of conventional, dispatchable power plants that can backstop the supply of energy to the grid at any time, including during hours of low wind and solar generation. However, given the scale of renewable generation, the capacity factors of these backstop power plants will likely fall to very low levels. Keeping these plants on line will require capacity payments, while adding to the backstop generation fleet over time will likely be contingent upon the use of power purchase agreements or the inclusion of these assets in a regulated rate base. Fifth, the high cost of transitioning to renewable penetration above 80% defeats the purpose of these programs, which is to capitalize on low cost renewable energy to reduce the CO2 emissions of the generation fleet. The cost of achieving renewable penetration above 80% exceeds the current price of emissions allowances in the United States and Europe, most estimates of the social cost of CO2 emissions, and the cost of available alternatives, such as the electrification of the vehicle fleet.

- Transitioning to an all-renewable energy system requires the addition of sufficient renewable generation and storage capacity to meet demand during every hour of the year. To achieve this goal with intermittent wind and solar resources is inherently wasteful and excessively expensive. At 100% renewable penetration, we calculate that the levelized cost of energy[1] would rise to $147/MWh on ERCOT and $213/MWh on CAISO, three and four times, respectively, the cost of full requirements power in 2018. We doubt, therefore, that 100% renewable penetration will be achieved.

[1] The levelized cost of energy is expressed in $/MWh and equals (i) the annual cash cost to build and operate a power plant, discounted back to the present, divided by (ii) the annual energy output of the plant over its useful life, also discounted back to the present. The LCOE can be regarded as the minimum fixed price at which a project's electricity must be sold in order to recover the total cost of the project, including construction cost, operation and maintenance expense, taxes and the target return on invested capital, over the lifetime of the project.

- By contrast, 80% renewable penetration is far less costly, particularly for states, such as California, with access to abundant hydroelectric power. (See **Exhibits 7** and **8**).
  - To achieve 80% renewable penetration would increase CAISO's levelized cost of energy to just $54/MWh, versus the 2018 cost of full requirements power on CAISO of ~$53/MWh.
  - For ERCOT, a system with very little legacy hydroelectric or geothermal generation, the cost to achieve 80% renewable penetration would increase the levelized cost of energy on the system to an estimated $71/MWh. Compared to the 2018 cost of full requirements power on ERCOT of ~$47/MWh, this represents an increase of over 50%.
- The rapidly rising cost of increasing levels of renewable penetration reflects the enormous wind, solar and storage resources required to bridge the gap between system demand and renewable generation during days when wind and solar energy are at their lowest (**Exhibits 1, 2** and **9**).
- The construction of a renewable generation fleet adequate to meet demand during deficit days of extremely low wind and solar energy necessarily implies much higher levels of renewable generation during those days of the year when wind and solar energy are abundant (**Exhibit 10**).
- Achieving higher and higher levels of renewable penetration thus drives a rising tide of excess energy. Even at 80% penetration, this excess energy could exceed 50 million MWh annually in ERCOT and 30 million MWh in CAISO (**Exhibit 11**).
  - While excess generation rises with the level of renewable penetration, the efficiency of the utilization of renewable generation can vary greatly between regions, reflecting the coincidence of prevailing demand with the availability of renewable energy. At 100% renewable penetration, the excess of renewable generation on ERCOT is equivalent to 41% of renewable supply, whereas on CAISO it is 57% of renewable supply.
  - This creates an economic impetus to connect high renewable energy regions with ever more distant population centers whose longitude and latitude create complementary patterns of renewable generation and electricity demand.
- The high cost of achieving extremely high levels of renewable penetration points to the economic advantage of the alternative: relying on renewable generation to provide the bulk of the energy, but depending upon the dispatchable capacity of existing power plants to backstop intermittent wind and solar resources and ensure a reliable supply of power to the grid.
- Even at 80% renewable penetration, the scale of the backstop capacity required is huge: to overcome predictable deficits in renewable generation relative to demand, we calculate that ERCOT will require 85% of the existing capacity of its non-renewable fleet, and CAISO 92%.
- With 80% of energy coming from renewable generation in this scenario, the capacity factors of these backstop, conventional power plants will necessarily fall to very low levels. Keeping these plants on line will require capacity payments or periods of extremely high energy prices, while adding to the backstop generation fleet over time will likely be contingent upon the use of power purchase agreements or the inclusion of these assets in a regulated rate base.
- Finally, we find that the high cost of transitioning to renewable penetration above 80% undermines of the effectiveness of these programs by diverting resources away from other programs that could reduce emissions more efficiently. The incremental cost of increasing renewable penetration from 80% to 90% exceeds the current price of emissions allowances in the United States and Europe, most estimates of the social cost of CO_2 emissions, and the cost of available alternatives, such as the electrification of the vehicle fleet. (See **Exhibits 12** and **13**.)

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Details

The Objectives, Constraints and Methodology of Our Analysis

In this research report, we compare the cost to transition the power grids of California and Texas to 80%, 90% and 100% renewable energy, while preserving a standard of reliability comparable to that of these grids today. Of these two states, only California is targeting higher levels of renewable generation, having set a goal of supplying 100% of retail electricity sales from zero-carbon resources by 2045. Our purpose is not contrast policy in the two states, but rather to explore how the transition to higher levels of renewable generation is influenced by differing renewable resource endowments, the degree to which the availability of these resources coincides with power demand, and in particular by those critical periods when the renewable energy available on the system is insufficient to supply power demand for prolonged periods of time.

Using software developed by MADA Analytics, the MADA Energy Processing Solution (MEPS), our model determines the least costly mix of available renewable resources and energy storage that would achieve any given level of renewable penetration.[2] It does so while respecting a key constraint, that power supply and power demand on the gird be balanced at all times. This continuous equivalence of power supply and demand is required to ensure that voltage levels on the grid remain within the narrow tolerance band of the electrical equipment and devices powered by the grid. An excess of power supply over demand can raise voltages to levels that damage or destroy this equipment, while insufficient supply relative to demand can lead to brownouts and blackouts.

Our model therefore seeks to ensure that in each scenario the power output of the conventional and renewable generating units on the grid, plus the discharge of energy storage, are capable of supplying the demand for electricity in every hour of the year. The model's objective is to supply hourly power demand with the lowest cost combination of:

(i) the output of existing hydroelectric, geothermal and biomass resources;
(ii) the output of a hypothetical fleet of wind and solar resources which, when added to the output of all other renewable resources, is adequate to supply the target level of renewable energy, complemented by
(ii) expanded energy storage capacity to capture excess renewable generation for later use, and supplemented by
(iii) the output of the existing conventional generation capacity, which can be relied upon to ensure a reliable supply of electricity even during prolonged periods of low renewable output.

We estimate hourly power demand in California and Texas based upon actual 2017 hourly power demand in CAISO (California Independent System Operator, which operates the bulk of California's power grid) and ERCOT (Electric Reliability Council of Texas, which operates the bulk of Texas' power grid). To forecast the output of the two state's new wind and solar generating fleets, our model uses the hourly wind and solar resources available in 2017 in typical locations in

[2] Please see the Appendix to this research report for more information on the MADA software and our model.

California and Texas.[3] Similarly, we estimate the output of existing hydroelectric and geothermal power plants based upon the historical track record of these resources: specifically, our analysis assumes that the volume of California's hydroelectric and geothermal generation will equal the average monthly output of these resources over the last 20 years.

In each of the scenarios modeled – 80%, 90% and 100% renewable penetration – the wind, solar and storage capacity required to meet these targets far exceeds the current installed capacity of these resources. Our analysis estimates the cost to build these new facilities, as well as the cost to operate and maintain them. Specifically, we have estimated the current levelized cost of energy (LCOE)[4] from new wind, solar, and storage resources and imputed these costs to the wind, solar and storage capacity required to meet the target levels of renewable generation. We have based our estimates of the capital and operating costs of new wind, solar and energy storage resources on *Lazard's Levelized Cost of Energy Analysis – Version 12.0* and *Lazard's Levelized Cost of Storage Analysis – Version 4.0*.

By contrast, we have not used new-build economics to estimate the cost of energy from existing nuclear, fossil fuel, hydroelectric and geothermal capacity. Rather, we impute a cost to this existing conventional generation equal to the around-the-clock price of wholesale power on CAISO and in ERCOT in 2017.

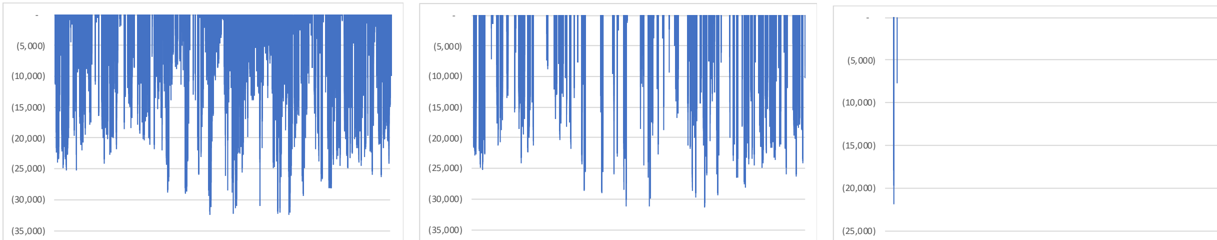
Based on these inputs, the MADA Analytics model identifies the lowest cost mix of wind, solar and energy storage sufficient to achieve the target level of renewable penetration. As we discuss in more detail below, this cost tends to increase rapidly as target levels of renewable penetration rise from 80% to 100%. As illustrated in **Exhibits 1** and **2**, renewable energy and storage resources capable of supplying 80% of all the electricity consumed on a system will nonetheless be insufficient to meet system demand during many hours of the year (see the left charts of **Exhibits 1** and **2**). During these "deficit hours," as we call them, the output of the renewable generation fleet, plus the discharge of the energy storage capacity on the system, is insufficient to meet prevailing demand. Achieving higher levels of renewable penetration requires bridging the gap between system demand and available renewable energy during a rising number of hours per year, thus whittling away at the number of these deficit hours (see the middle charts of **Exhibits 1** and **2**). The MADA Analytics model, figuratively speaking, bridges the smallest gaps first; it adds the lowest cost combination of renewable generation and storage capacity capable of achieving the next targeted level of renewable penetration. As the level of penetration rises, the deficit hours that remain are the highest cost to bridge (see the right hand charts of **Exhibits 1** and **2**). The cost of achieving each incremental percentage point of renewable penetration thus rises steadily higher.

[3] In California, these are Tehachapi Pass for wind and Los Angeles for solar; in Texas, Odessa for wind and Houston for solar.

[4] The levelized cost of energy is expressed in $/MWh and equals (i) the annual cash cost to build and operate a power plant, discounted back to the present, divided by (ii) the annual energy output of the plant over its useful life, also discounted back to the present. The LCOE can be regarded as the minimum fixed price at which a project's electricity must be sold in order to recover the total cost of the project, including construction cost, operation and maintenance expense, taxes and the target return on invested capital, over the lifetime of the project.

Exhibit 1: Hourly Shortfall of CAISO Renewable Generation Relative to Demand (MW)

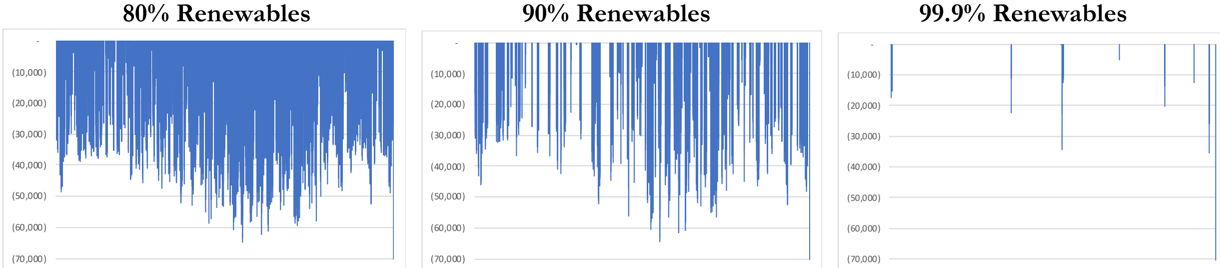
80% Renewables **90% Renewables** **99.9% Renewables**



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

Exhibit 2: Hourly Shortfall of ERCOT Renewable Generation Relative to Demand (MW)

80% Renewables **90% Renewables** **99.9% Renewables**



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

Finally, we should note here an important limitation of our model By using data from a single year (2017) to estimate electricity demand as well as wind and solar generation, we likely underestimate the scale of renewable resources required to ensure system reliability. Ideally, our model would assess several decades of data to estimate the highest probable level of power demand, and the lowest probable availability of renewable energy, during each hour of the year. To the extent the 2017 data fails to capture these maximum and minimum levels, our model will underestimate the renewable and storage resources, and thus the cost, required to achieve 80%, 90% and 100% renewable penetration, while preserving a standard of reliability comparable to that of CAISO and ERCOT today.

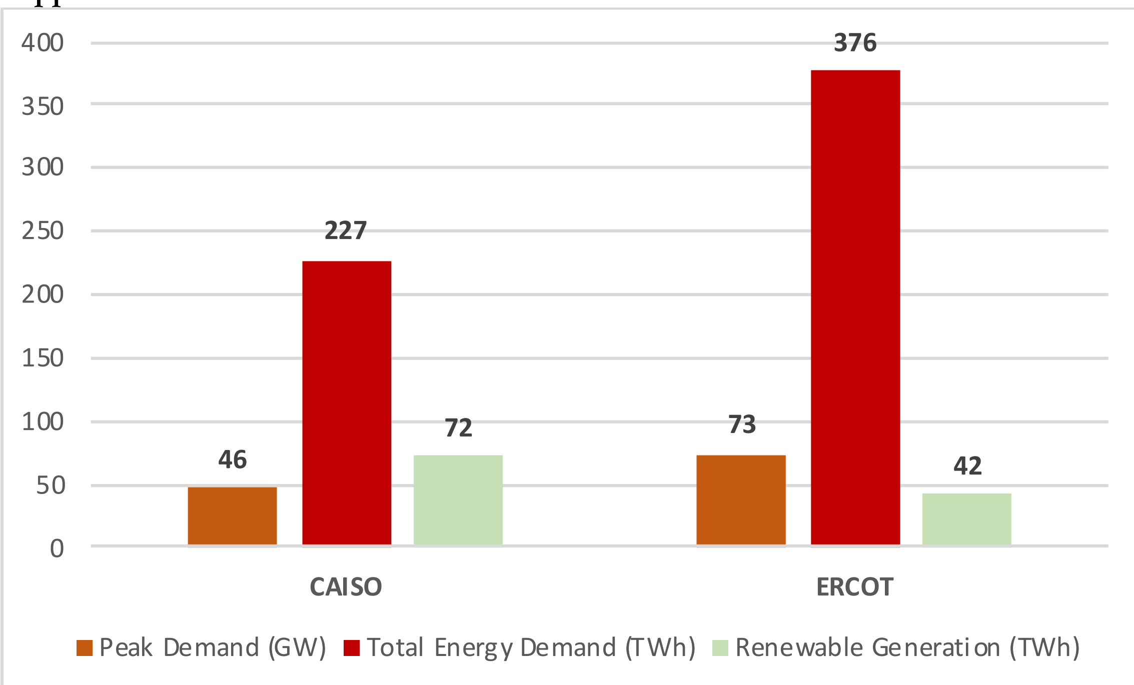
The Cost of Achieving High Levels of Renewable Penetration on CAISO and ERCOT

In this section we will compare the scale of the CAISO and ERCOT power markets, the composition of their existing renewable and conventional generating fleets, and the cost of achieving 80%, 90% and 100% renewable penetration in both markets. To frame our discussion of the rapidly rising cost of higher levels of renewable penetration, we will focus on the degree to which the output of each state's renewable resources coincides with power demand, and on particular by those critical periods when the renewable energy available on the system is insufficient to supply power demand for prolonged periods of time.

Exhibit 3 contrasts the scale of the CAISO and ERCOT power markets, as well as the degree of renewable penetration in each. As the chart illustrates, ERCOT is a significantly larger market than

CAISO: in 2018, peak system demand for power in ERCOT was 73 GW, 58% more than CAISO's peak system demand of 46 GW. The total amount of electric energy supplied in ERCOT in 2018 was 376 TWh (millions of MWh), or 66% more than the 227 TWh of energy supplied by CAISO. Only in the supply of renewable generation does CAISO lead ERCOT: the total renewable energy supplied by CAISO, including imports of renewable energy, was 72 TWh in 2018, or 32% of total energy supplied, as against 42 TWh in ERCOT, or 11% of total supply.

Exhibit 3: 2018 Peak Demand, Total Energy Supplied and Renewable Energy Supplied in CAISO and ERCOT

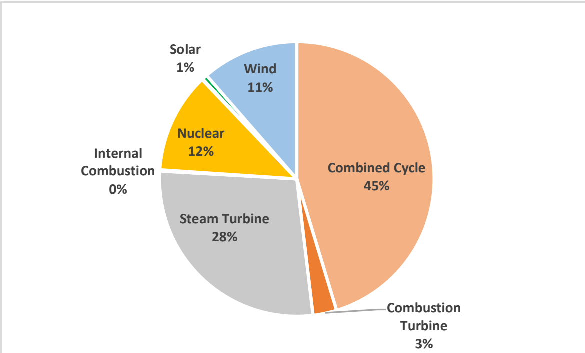


Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

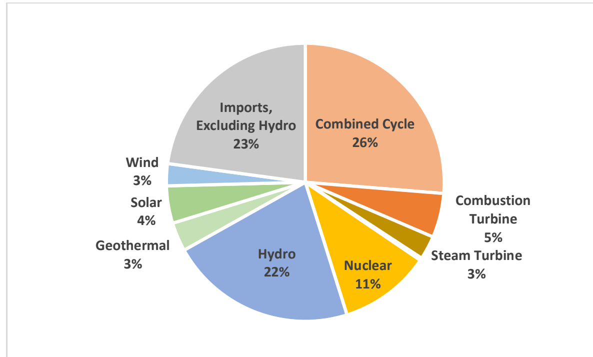
Interestingly, the bulk of California's renewable generation is supplied by hydroelectric and geothermal resources, primarily built in the first and second halves of the 20th century, respectively, while its 21st century fleet of wind and solar resources is smaller than Texas'. As can be seen in **Exhibit 4**, wind and solar generation accounted for approximately 7% of CAISO's total energy supply in 2018, as against 11% for ERCOT. Hydroelectric generation, most of it imported from the Pacific Northwest, supplies the bulk of CAISO's renewable energy, accounting for 22% of CAISO's total electricity supply, while in-state geothermal resources contribute another 3%.

Exhibit 4: Breakdown by Generation Technology of Total 2018 Energy Supply

ERCOT



CAISO



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

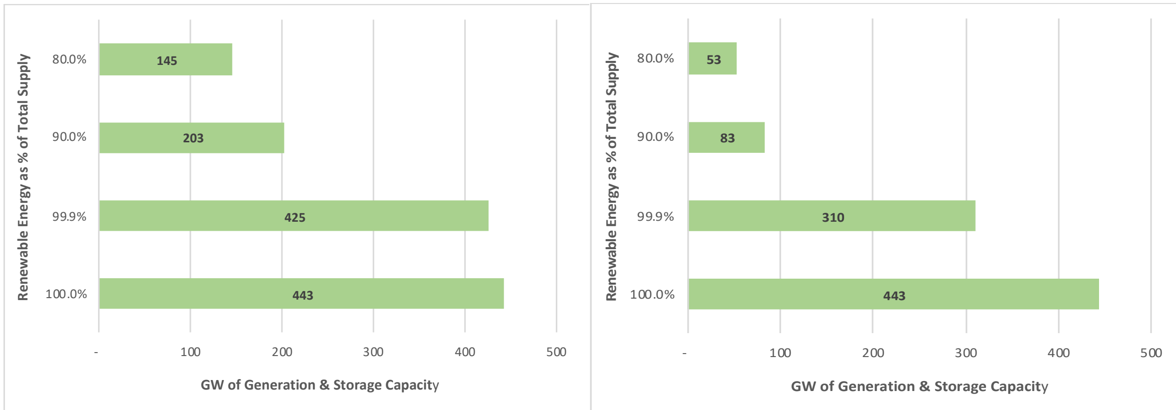
In estimating the all-in cost of achieving higher levels of renewable generation, we assume that CAISO and ERCOT maintain access to their existing hydroelectric and geothermal resources as well as their large existing gas fired generation fleets. The dispatchable capacity that these resources offer significantly reduces the cost of achieving 80% and 90% levels of renewable penetration, as the conventional power plants can backstop the supply of energy to the grid during hours of low wind and solar generation. By contrast, transitioning to an all-renewable energy system (100% renewable penetration), requires the addition of sufficient renewable generation and storage capacity to meet demand during every hour of the year. As we explain below, to achieve this goal with intermittent wind and solar resources is difficult, expensive and wasteful. Because the cost of this transition is economically prohibitive, even in states with ample renewable resources such as Texas and California, we believe it unlikely to be achieved for the foreseeable future.

We begin by estimating the lowest cost mix of wind, solar and energy storage that, in tandem with existing hydroelectric and geothermal generation, would raise the share of renewable energy to 80% of the system's electricity demand. We find that in CAISO the optimal mix comprises 25 GW of wind capacity, 25 GW of solar capacity and 3 GW of storage capacity (equivalent to 12 GWh, given the typical four hour duration of discharge of lithium ion batteries). (See the right hand charts in **Exhibits 5** and **6**.) These requirements imply a near tripling of the current installed fleet of 9 GW of wind, a near doubling of CAISO's 14 GW of solar capacity, and an increase of 15x in CAISO's existing energy storage capacity of 0.2 GWh.

The much larger size of the ERCOT power market, combined with its lack of large scale hydroelectric and geothermal resources, requires even larger additions of wind and solar capacity if 80% renewable generation is to be achieved: we estimate that to do so ERCOT would require a renewable generation fleet comprised of 60 GW of wind, 65 GW of solar and 20 GW (80 GWh) of storage. (See the left hand charts in **Exhibits 5** and **6**.) This implies a near tripling of ERCOT's 23 GW of currently installed wind capacity, a thirty-fold increase in its 2 GW solar fleet and the construction of massive energy storage capacity.

Exhibit 5: Total Wind, Solar & Storage Capacity Required at Different Levels of Renewable Penetration (GW)

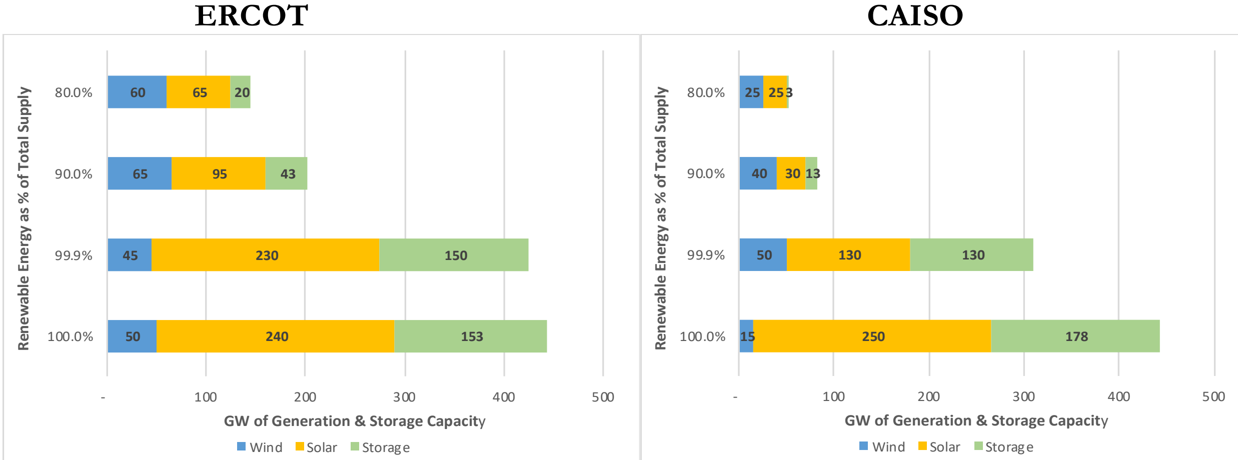
ERCOT **CAISO**



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

Exhibit 6: Lowest Cost Combination of Wind, Solar & Storage Resources at Different Levels Of Renewable Penetration (GW)

ERCOT **CAISO**



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

Reflecting its larger endowment of existing renewable resources, CAISO's cost to achieve 80% renewable penetration will be significantly less than ERCOT's. We calculate the capital cost of the ~53 GW of wind, solar and storage capacity that CAISO requires at some $62 billion; offset by the fuel and power cost savings resulting from the 137 million MWh that these resources would generate, we calculate that this expansion of CAISO's renewable fleet would add only $68 million to the annual cost of meeting CAISO's electricity demand. Spread across CAISO's ~230 million MWh of electricity supplied, this would increase CAISO's levelized cost of energy supplied by a fraction of a dollar, to an estimated $54/MWh versus the 2018 cost of full requirements power on CAISO of ~$53/MWh . (See the right hand charts of **Exhibits 7** and **8**).

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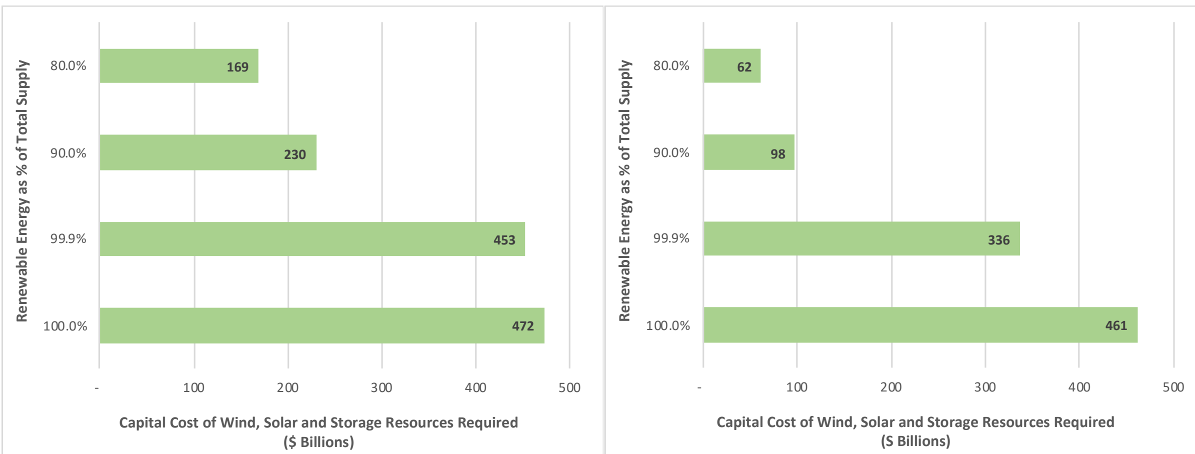
By contrast, we estimate that ERCOT, to achieve 80% renewable penetration, will require wind, solar and storage capacity totaling 145 GW, and will incur a cost $169 billion to build it. Even allowing for the offsetting fuel and power cost savings resulting from the additional 285 million MWh of renewable generation, we estimate the net levelized cost of this capacity expansion at ~$8.7 billion annually. Spread across ERCOT's ~375 million MWh of annual electricity supply, this is enough to increase the levelized cost of energy on the system to an estimated $71/MWh. Compared to the 2018 cost of full requirements power on ERCOT of ~$47/MWh, this represents an increase of over 50%. (See the left hand charts of **Exhibits 7** and **8**).

Exhibit 7: Capital Cost to Achieve Various Levels of Renewable Penetration ($ Billions)

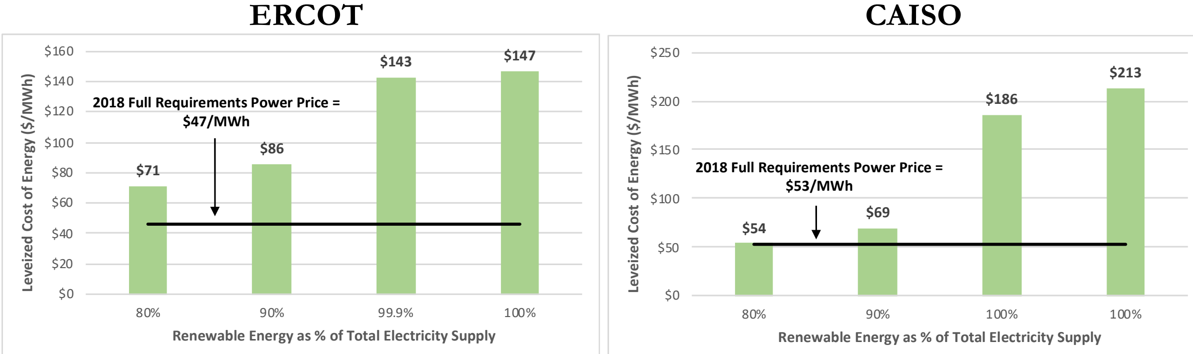
ERCOT **CAISO**



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

Exhibit 8: System Levelized Cost of Energy at Various Levels of Renewable Penetration

ERCOT **CAISO**



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

At levels of renewable penetration above 80%, our modeling finds that the cost of electricity rises rapidly. As renewable penetration approaches 100%, it becomes necessary to supply renewable energy to meet demand even during those hours when the available wind and solar energy is extremely low. Such conditions can persist for several consecutive days or even weeks. In 2017, for example, California suffered a dearth of renewable energy for eight consecutive days from January 7 through 15. January is a month when daylight hours are limited and the sun is low in the sky, limiting the available solar resource under the best of conditions; over these eight days, the normally poor solar resource was further limited by a prolonged period of cloudy and rainy weather. Aggravating the deficit in renewable generation, this eight day period also included many consecutive hours with no or light wind.

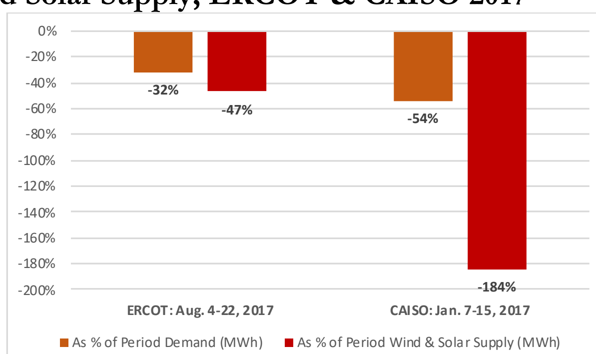
Even assuming a wind and solar fleet designed to assure 80% renewable penetration, and the continued availability of CAISO's substantial hydroelectric and geothermal resources, CAISO's total renewable generation would have fallen short of system demand over these eight days by 2.5 million MWh. This deficit is equivalent to 54% CAISO's electricity demand over the eight day period. In the absence of CAISO's existing fossil fuel capacity, such as shortfall would have precipitated blackouts across the state. (See **Exhibit 9**.)

Overcoming this deficit with additional wind and solar resources is inefficient and expensive, due to the low available supply of wind and solar energy that precipitated the shortfall in the first place. The shortfall in renewable generation over these eight days was equivalent to 184% of the estimated output of the wind and solar fleet over the same period. (See **Exhibit 9**.) Consequently, to ensure CAISO's renewable generation is sufficient to meet 100% of system demand, even during prolonged periods of low wind and solar output, a substantial investment in storage capacity will be required. As this storage capacity must be charged with renewable generation in excess of that dedicated to meet prevailing electricity demand, the installed base of solar capacity must be increased as well. The transition from 80% to 100% renewable generation thus requires an increase in CAISO's energy storage capacity from 3 GW to 178 GW and, to charge this larger fleet of batteries, an increase in CAISO's solar generation capacity from 25 GW to 250 GW. (See the right hand chart of **Exhibit 6**.) As a result, we estimate the cost of full requirements power on CAISO rises to $213/MWh, or four times the cost of full requirements power on CAISO today. (See **Exhibit 7**).

Exhibit 9: Largest MWh Shortfalls in the Supply of Renewable Generation Relative to Then Prevailing System Demand and Wind and Solar Supply, ERCOT & CAISO 2017

Largest Cumulative Shortfall of Renewable Generation vs. Demand

	Dates	Millions of MWh	As % of Period Demand (MWh)	As % of Period Wind & Solar Supply (MWh)	As % of Total Annual Demand (MWh)
ERCOT	Aug. 4-22	(7.3)	-32%	-47%	-2.0%
CAISO	Jan. 7-15	(2.5)	-54%	-184%	-1.1%



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

The path from 80% to 100% renewable generation in ERCOT confronts a similar challenge, although it occurs at a different time of year and under circumstances that render it less costly to address. From August 4 through 22 of 2017, a long (but not atypical) series of extremely hot days, combined with windless nights, produced high system loads while suppressing wind generation.

Even assuming a wind and solar fleet designed to assure 80% renewable penetration, ERCOT's total renewable generation would have fallen short of system demand over these eight days by 7.3 million MWh. This deficit is equivalent to 32% ERCOT's electricity demand over the same period. Only ERCOT's existing fossil fuel capacity could prevent such a shortfall from causing blackouts across the state.

Unlike CAISO, however, ERCOT's maximum deficit occurred in August, when days are relatively long and the sun still high in the sky, implying that an abundant solar resource is available to be captured and stored to offset the lack of wind at night. The shortfall in renewable generation over the August 4-22 period was equivalent to just 47% of the estimated output of ERCOT's wind and solar fleet over these days; during CAISO's worst deficit days, by contrast, the shortfall of renewable generation was equivalent to 184% of the estimated output of the wind and solar generation available over the same period.

The more abundant renewable generation available during ERCOT's deficit period permits a smaller expansion of ERCOT's renewable and storage fleet to overcome the deficit. We calculate that the transition from 80% to 100% renewable generation in ERCOT would require an increase in ERCOT's energy storage capacity from 20 GW to 153 GW, as compared to the expansion from 3 to 178 GW required in CAISO. To charge this larger fleet of batteries, we estimate that ERCOT's solar generation capacity would need to increase from 65 GW to 240 GW, as compared to the increase from 25 to 250 GW required in CAISO. (See **Exhibit 6**.) Reflecting the smaller scale of the capacity additions required to transition from 80% to 100% renewable energy in ERCOT, we estimate the capital cost of this expansion at ~$300 billion in ERCOT versus at ~$400 billion in CAISO. More importantly, ERCOT can spread this capital cost over a base of electricity supplied that is two thirds larger that CAISO's: 376 million MWh in ERCOT versus 227 million MWh in CAISO. As a consequence, we estimate ERCOT's levelized cost of energy at 100% renewable penetration at $147/MWh, or almost a third lower than our estimate of $213/MWh for CAISO. While lower, this cost is not cheap; an LCOE of $147/MWh for 100% renewable generation in ERCOT is equivalent to 3x our estimate of the $47/MWh price of full requirements power on ERCOT in 2018.

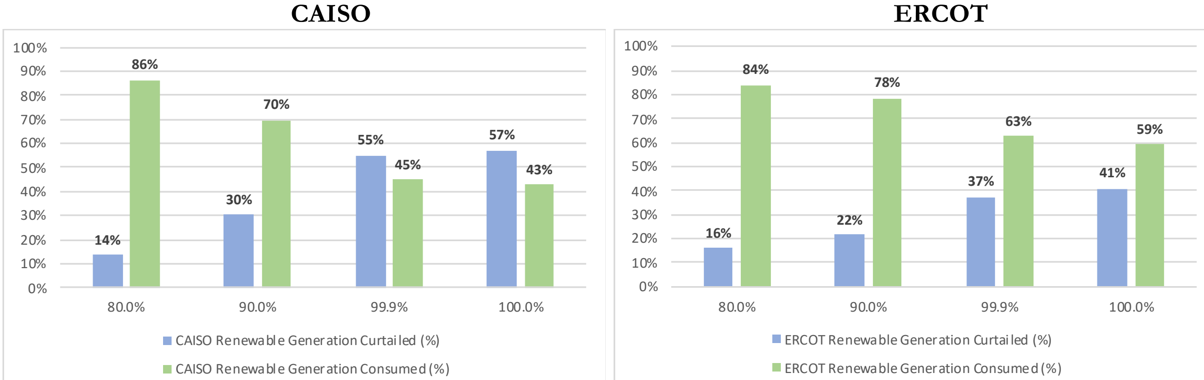
As the examples of CAISO and ERCOT illustrate, the scale of the resources required to bridge the shortfall of renewable generation relative to demand can vary dramatically from region to region, reflecting the coincidence of wind and solar energy with prevailing demand. As solar penetration approaches 100%, the very largest shortfalls of renewable energy relative to demand become key drivers of the scale of renewable and storage resources required, and thus of the levelized cost of energy on the system. The specific characteristics of these large deficit days are also critical. The very high cost to CAISO of meeting demand during eight days in January, when demand is relatively low, reflects the extended dearth of renewable energy during these short, cloudy windless days. ERCOT's deficit days in August are characterized by very high weather-related demand, windless nights, but also abundant solar energy. When renewable resources are available during and immediately before deficit hours, as in ERCOT in August, they can be harnessed with additional generation capacity. When they are not, as in CAISO in January, additional generation capacity must still be built, so as to capture, at times when wind or solar are more abundant, the energy required during the deficit days, but these new generation resources must be complemented by sufficient storage capacity to ensure the availability of this energy for later use.

The resources required to bridge the gap between demand and the supply of renewable energy during the largest deficit days have important implications for the operation of the system during the rest of the year. The expansion of the renewable generation fleets to meet demand during those hours when the supply of wind and solar energy is at its lowest necessarily implies much higher levels of renewable generation during those hours of the year when wind and solar energy are abundant. Achieving higher and higher levels of renewable penetration thus drives a rising tide of excess energy. To avoid over-loading the grid, the output of the renewable fleet must be curtailed or, if possible, exported to surrounding states.[5]

One way to quantify the problem of excess energy is to calculate the percentage of renewable generation that goes to supply demand, as opposed to being curtailed or exported. On this measure, the efficiency of utilization of renewable generation fleets declines as renewable penetration rises. As illustrated in **Exhibit 10**, at 80% renewable penetration the renewable generating fleets of CAISO and ERCOT are relatively efficient, with 86% and 84% of their output, respectively, allocated to meet current demand and only 14% and 16%, respectively, being curtailed. At 100% penetration, by contrast, the share of renewable generation that can be used to meet demand falls to 43% in the case of CAISO and 59% in the case of ERCOT; the remaining renewable generation would have to be curtailed or, where feasible, exported.

Exhibit 10: Percentage of Renewable Generation Consumed vs. Curtailed

CAISO **ERCOT**



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

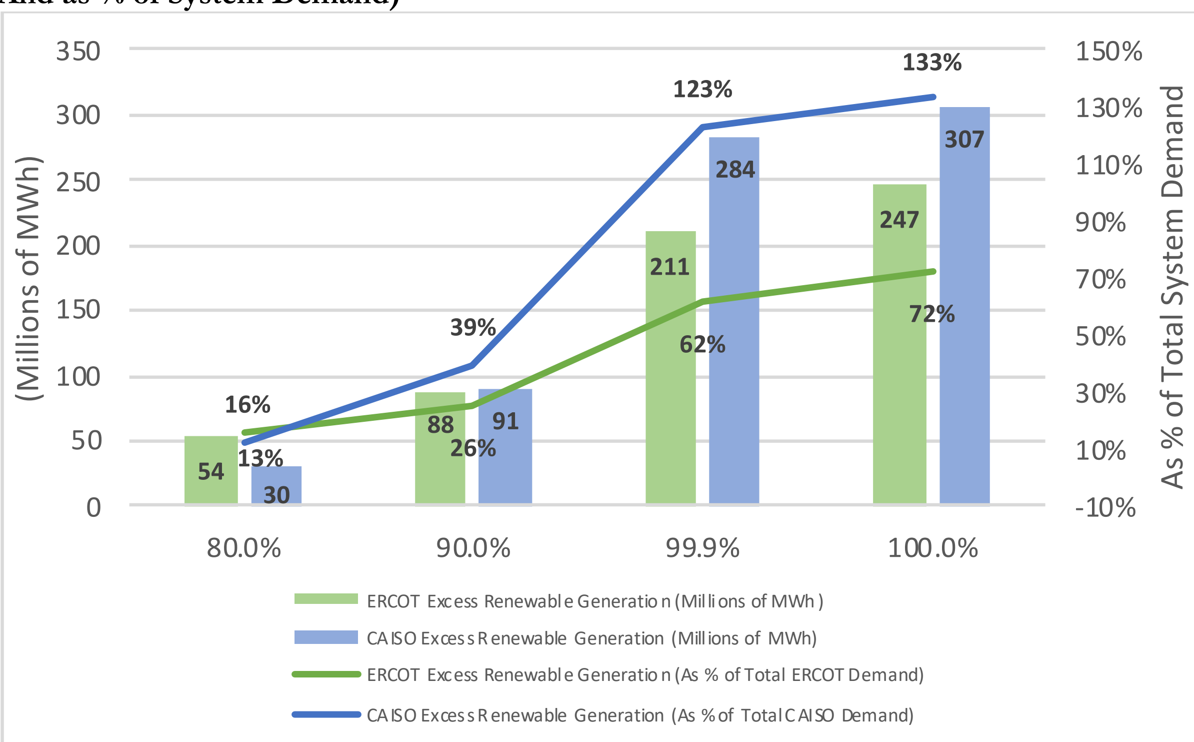
While utilization of both the CAISO and ERCOT renewable generation fleet becomes less efficient as penetration rises, the efficiency of utilization of CAISO's renewable generation falls much further. (See **Exhibit 10**). This reflects the huge storage and renewable generation capacity required by CAISO to bridge the gap between renewable generation and demand during its worst deficit days, January 7 through 15, 2017. During these days, the shortfall of renewable generation versus demand was equivalent to 184% of the wind and solar generation available over the same period. ERCOT's efficiency of utilization declines less dramatically, reflecting the smaller imbalance between system demand and renewable generation during ERCOT's worst deficit days, August 4 through 22, 2017.

[5] Exports of renewable energy often face constraints, however: ERCOT has only limited high voltage transmission links with the eastern or western power grids, while California is bounded to west by the Pacific Ocean and to the east by desert and mountain regions with much lower population density.

Due to the good solar resource available in Texas during August, the shortfall in renewable generation over August 4-22 was equivalent to only 47% the estimated output of ERCOT's wind and solar fleet over these days. As explained above, the greater availability of renewable energy during and immediately before its worst deficit allows ERCOT to bridge the gap renewable energy/demand gap during these days with a smaller amount renewable generation and storage capacity than was the case for CAISO, whose deficit days occurred during a period of extremely low renewable energy supply.

Despite these differences in the efficiency of utilization of their renewable fleets, once 100% renewable penetration is achieved, the scale of excess generation in both CAISO and ERCOT would be truly enormous: in California, a 100% renewable system would be capable of generating an estimated 307 million MWh of electricity in excess of the needs of the state – an excess equal to 133% of the annual electricity consumption of California and over 80% of the combined electricity consumption of the surrounding states (Washington, Oregon, Idaho, Nevada, Utah and Arizona). In Texas, assuming 100% renewable penetration, our estimate of excess renewable generation is 247 million MWh, or 72% of the annual electricity consumption of the state. (See **Exhibit 11**.)

Exhibit 11: Excess Renewable Generation in CAISO and ERCOT (Millions of MWh And as % of System Demand)



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

Options to avoid or absorb this tsunami of electricity could include:

- setting a lower target for renewable penetration, such as 80%, which would not only limit excess renewable generation but materially reduce the levelized cost of energy relative to higher penetration scenarios;
- exporting excess generation to regions with non-coincident peaks in demand;
- importing renewable generation from these states, allowing reduced in-state generation;
- accelerating the transition of the region's vehicle fleet from internal combustion to electric motors, thereby reducing carbon emissions from transportation and increasing demand for power;
- developing other sources of demand for electricity by promoting regional investment in such electricity intensive industries as the smelting of aluminum, copper or steel; oil refining and the production of basic chemicals; and the manufacture of pulp, paper and cement.

The import and export of renewable energy can be more difficult that it sounds: ERCOT has only limited high voltage transmission links to either the eastern or western power grids, while California is bounded to west by the Pacific Ocean and to the east by desert and mountain regions with much lower population density. As levels of renewable penetration rise, so will the economic impetus to connect high renewable energy regions with ever more distant population centers whose longitude and latitude create complementary patterns of renewable generation and electricity demand.

The Implications for the Cost of Curtailing CO2 Emissions

The primary objective of achieving high levels of renewable penetration is to reduce the carbon dioxide emissions of the power sector. In this section, therefore, we relate the cost of achieving various levels of renewable penetration to the reduction in CO2 emissions achieved. In CAISO, we find that the low cost of achieving 80% renewable penetration suggests that this is a highly efficient means of reducing CO2 emissions. Above that level, however, the rapidly rising cost of achieving higher levels of renewable penetration cannot be justified on the basis of CO2 emissions avoided, given the lower cost alternatives available and the relatively low social cost of CO2 emissions. In ERCOT, it is questionable whether even 80% renewable penetration is an economic means of curtailing CO2 emissions; higher levels of renewable penetration clearly are not.

As illustrated in **Exhibit 8**, our analysis indicates that CAISO could achieve 80% renewable penetration at a levelized cost of energy of only $54/MWh, just above our estimate of the 2018 full requirements price of electricity of $53/MWh. This is equivalent to an annual increase in the cost of electricity sold on CAISO of only $68 million, suggesting that achieving 80% renewable penetration is a highly economic means of reducing carbon dioxide emissions. California's fossil fired generating fleet, which is predominantly gas fired, emits an average of 0.49 metric tons of carbon dioxide per MWh produced. Our modeling finds that, in a scenario where 80% of California's power demand is supplied by renewable resources, the need for fossil fired generation is reduced by some 54 million MWh, with a corresponding reduction in CO2 emissions of 26 million metric tons. The $68 million cost of achieving this 26 million metric ton reduction in CO2 emissions translates into a cost per ton of CO2 avoided of only ~$2.60/metric ton. (See **Exhibit 12**).

Exhibit 12: Average Cost per Metric Ton of CO2 Avoided

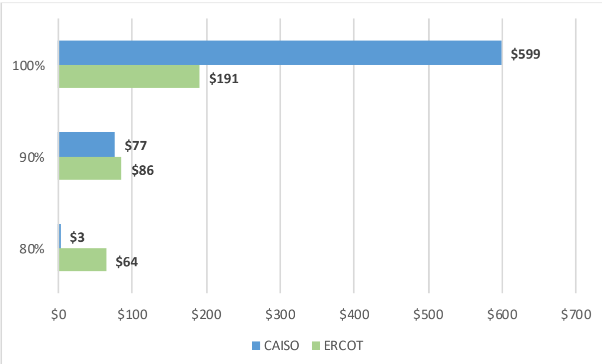
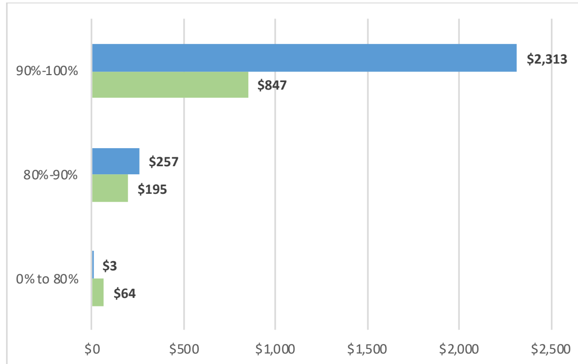


Exhibit 13: Incremental Cost per Metric Ton of CO2 Avoided



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

However, the rapidly rising cost of achieving higher levels of renewable penetration on CAISO raises the question of whether further increases in renewable penetration are the most cost effective means to reduce CO2 emissions. We estimate that achieving 90% renewable penetration would allow California to decrease its dependence on fossil fuel generation by 76 million MWh, cutting CO2 emissions by a total of 37 million metric tons annually. The average cost of CO2 emissions avoided, however, would rise to $77 per metric ton. (See **Exhibit 12**.) More importantly, as renewable penetration increases from 80% to 90%, the *incremental* cost of CO2 emissions reductions hits $257 per metric ton. (See **Exhibit 13**.) Similarly, moving to a 100% renewable system would reduce fossil fuel generation by 99 million MWh, cutting CO2 emissions by a total of 49 million tons annually. Yet in the 100% scenario, the average cost of CO2 emissions avoided rises to some $600 per metric ton. The incremental cost to curtail CO2 emissions reductions, as renewable penetration rises from 90% to 100%, exceeds $2,300 per metric ton. (See **Exhibits 12** and **13**.)

By comparison, the price of CO2 emissions allowances in California is only $15 per metric ton, suggesting that far less costly means of reducing CO2 emissions are currently available. Moreover, the U.S. EPA has estimated the social cost of carbon dioxide emissions, assuming a 3% real discount rate, to be $42 per metric ton in 2020 and $69 per metric ton in 2050. To incur costs to reduce CO2 emissions that exceed these levels has a negative social impact. Californians would be better off funding lower cost emissions reductions in other industries, states or countries rather than trying to achieve higher levels of renewables penetration. [6]

As discussed above, ERCOT's smaller endowment of existing renewable generation relative to CAISO implies the need to build a large wind and solar fleet to achieve 80% renewable penetration, implying a higher levelized cost of energy than CAISO and, in turn, a higher cost per ton of CO2

[6] A lower cost means of reducing emissions of CO2, as well as other air pollutants, would be to increase the electrification of the Californian vehicle fleet. The 26 million ton reduction in CO2 emissions achieved by increasing the proportion of non-emitting power generation on CAISO from ~40% today to 80% could also be achieved by replacing 5.6 million vehicles, or 20% of California's fleet of light and heavy duty vehicles, with electric vehicles. While internal combustion engines rely on highly carbon intensive fuels, gasoline and diesel, California's power is today supplied in large part by non-emitting renewable and nuclear energy (~40% of the total) and low emitting gas fired power plants (~30%). Once 80% renewable generation has been achieved, vehicle electrification would be a much a lower cost alternative to increased renewable penetration.

emissions avoided. As illustrated in **Exhibit 8**, the cost of these new renewable resources is sufficient to drive the levelized cost of energy on ERCOT up to $71/MWh, an increase of some 50% compared to the 2018 price of full requirements power on ERCOT, which we estimate at $47/MWh. This increase in price is equivalent to an annual increase in the total cost of electricity sold on ERCTOT of $8.7 billion. Texas's coal and gas fired generating fleet emits an average of 0.74 metric tons of carbon dioxide per MWh produced, and our modeling finds that, in a scenario where 80% of California's power demand is supplied by renewable resources, the need for fossil fired generation would be reduced by some 183 million MWh, with a corresponding reduction in CO2 emissions of 135 million metric tons. The $8.7 billion cost of avoiding these 135 million metric tons of CO2 emissions translates into a cost per ton of CO2 avoided of ~$64/metric ton. (See **Exhibit 12**). This is well above the price of CO2 emissions allowances in California ($15/metric ton) and the European Union ($28/metric ton), suggesting that far less costly means of reducing CO2 emissions are currently available. We note that $64/metric ton also exceeds the EPA's estimate of the social cost of CO2 emissions in 2020, which is $42/metric ton, but is slightly below the EPA's estimate for 2050 of $69 metric ton.

As with CAISO, the incremental cost of reducing CO2 emissions by achieving levels of renewable penetration above 80% in ERCOT is clearly uneconomic, reaching $195/metric ton of CO2 avoided at 90% renewable penetration and ~$850/metric ton at 100% renewable penetration. (See **Exhibit 13**). Should Texas one day seek to reduce CO2 emissions by targeting higher levels of renewable penetration, it is clear that 80% penetration is a prudent level at which to stop.

The Implications for Non-Renewable Power Generation Capacity

The rapidly rising cost of achieving higher levels of renewable penetration points to the economic advantage of the alternative: depending upon existing nuclear and fossil fuel power plants to ensure a reliable supply of electricity during all hours of the year, rather than attempting to replicate current levels of reliability using intermittent wind and solar resources backstopped by energy storage.

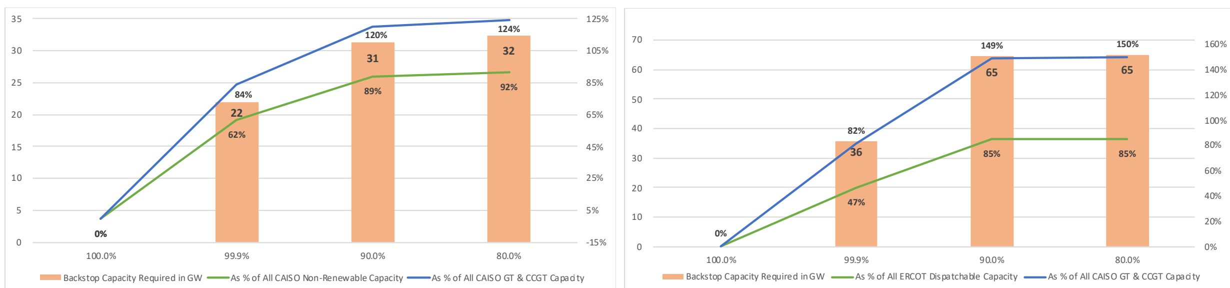
Even at very high levels of renewable penetration, the difficulty of ensuring an adequate supply of renewable energy to meet demand during every hour of the year implies the need for a surprisingly large amount of non-renewable, dispatchable capacity. As **Exhibits 1** and **2** illustrate, even at 90% renewable penetration, the excess of demand over available renewable generation and storage capacity in some hours could exceed 30 GW in CAISO and 60 GW in ERCOT.

Exhibit 14 compares the scale of these shortfalls to the non-renewable generation capacity currently available on CAISO and ERCOT. In CAISO, at 80% renewable penetration, the maximum shortfall of renewable generation relative to demand is 32 GW; bridging this gap would require the output of 92% of California's existing non-renewable generation capacity. (See the left hand chart of **Exhibit 14**.) Yet large portions of California's existing non-renewable generating fleet are being phased out as a result of increasingly stringent environmental regulations governing the intake of cooling water required by steam turbine generating plants. California's 2.25 GW of nuclear generation capacity will be fully retired by 2025; by that year, over 4.0 GW of existing fossil fuel steam turbine capacity is expected to be retired as well.

Over time, therefore, California will become increasingly reliant on its fleet of simple and combined cycle gas turbine generators to bridge future shortfalls between available renewable generation and the level of demand prevailing on the grid. California's 26 GW gas turbine fleet, however, is insufficient to bridge the 32 GW shortfall evident in the 2017 data. This suggests that California will need to build additional gas turbine capacity, or procure commitments of such capacity from other states, to offset the loss of an estimated 6 GW of nuclear and fossil fuel steam turbine capacity by 2025.

Exhibit 14: Backstop Dispatchable Capacity Required (GW)

CAISO **ERCOT**



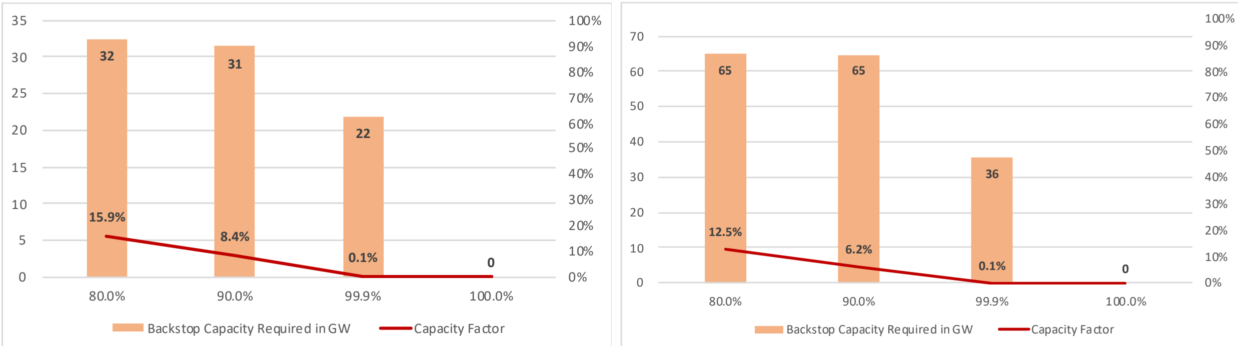
Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

ERCOT has not yet chosen to mandate higher renewable penetration or lower CO2 emissions from the power sector. Were it do so, however, it would face a similar challenge. At 80% renewable penetration, the maximum shortfall of renewable generation relative to demand is estimated at 65 GW; bridging this gap would require the output of 85% of ERCOT's existing non-renewable generation capacity. Much of this capacity, however, is comprised of aging nuclear and coal fired power plants, most of which are likely to be retired over the next two decades. On its own, ERCOT's 43 GW gas fired generation fleet is insufficient to bridge the 65 GW shortfall between renewable generation and demand. (See the right hand chart of Exhibit 14.)

Ensuring an economic return on these backstop generation resources, and providing an economic incentive to add additional backstop capacity over time, would be a policy challenge for both states, particularly for Texas, which has relied on an energy-only market structure. As we have seen, high levels of renewable penetration do not eliminate the need for large amounts of backstop generation capacity; they do, however, radically reduce the output of these resources. As a result, we expect the average capacity factor of the backstop generating fleet in California to fall to levels typical of peaking plants today (see **Exhibit 15**). As long as market economics continue to support the construction of new wind and solar in Texas, we would expect declines in the average capacity factors of the existing fossil fuel generating fleet, as well.

Exhibit 15: Capacity Factor of the Backstop Dispatchable Capacity Required

CAISO **ERCOT**



Source: MADA Analytics, Lazard's *Levelized Cost of Energy and Levelized Cost of Storage 2018*, S&P Global, SSR analysis

At high levels of renewable penetration, therefore, we expect that backstop dispatchable generation capacity will require capacity payments, through a resource adequacy market or similar mechanism, to ensure sufficient cash flow for these plants to stay online. It may be possible to rely on CAISO's and ERCOT's current market structures, although in the case of the latter this would require an increase the number of hours that energy prices spike to the $9,000 cap. However, the new backstop generation resources required to maintain system reliability over time would likely need to be supported either (i) by long term power purchase agreements capable of ensuring the return of and on invested capital, or (ii) through the inclusion of these assets in the rate base of regulated utilities, whose cost-of-service-based rates would achieve a similar result.

In summary, one of the primary conclusions of our analysis is that both California and Texas will find it economic to continue to depend upon their existing non-renewable generation capacity to ensure a reliable supply of electricity during each hour of the year. We expect that this conclusion applies generally to the rest of the United States. The combination of high renewable penetration rates and the continued need for substantial backstop generation capacity will drive the average capacity factor of these resources down to levels where they would be uneconomic to build on a merchant basis. Future additions of backstop generation capacity, similar to the future additions of renewable generation and storage, will therefore need to be included in the rate base of regulated utilities or supported by long term PPAs.

Exhibit 16: Heat Map: Preferences Among Utilities, IPP and Clean Technology

Preferences Among Utilities, IPPs and Clean Technology			
Sector	Weighting	Favorites	Concerns
Regulated Electric Utilities	Overweight	AEP, EIX, ETR, FE, PCG, PNW	ALE, IDA, POR, SO
Hybrid Electric Utilities	Neutral	EXC	
IPPs	Underweight		
Renewables	Underweight		
Yieldcos	Neutral	NEP	

Source: SSR analysis

Appendix: Software and Inputs

The Software

The modelling software we used to perform our analysis is MADA Energy Processing Solutions (MEPS), and was developed by MADA Analytics, a data-analytics energy-storage software company, of which Eric Selmon is a co-founder, shareholder and director. MEPS is designed to optimize combinations of various renewable generating technologies with energy storage to achieve a defined goal (usually highest return or lowest cost). It does so by conducting an hourly analysis of all of the different possible combinations of the generation and storage technologies within a user-set range, and calculating the power output, performance and financial results of each combination across all of the hours over the life of the projects.

For this analysis, we assumed that only solar, wind and battery storage, plus existing hydroelectric, geothermal and biomass generation, would be used to meet demand. We optimized for the lowest cost combination of these resources that was able to meet system demand in every hour of the year. We also ran an alternative scenario where renewables supply only 99.9% of demand, allowing us to quantify the impact on cost as the targets for renewable penetration decrease, as well as the dispatchable peaking capacity (i.e. gas fired peakers) required for system reliability as renewable targets fall.

Critically, MEPS' focus on the balance between hourly supply and demand provides allows for a much more accurate result than an analysis that uses only the aggregate annual or monthly data on peak demand and resource availability, because it addresses the fundamental need of the power grid to match supply and demand at all times. Based on the hourly output of typical wind and solar resources in California in 2017, and CAISO's hourly load in that year, we were able to identify those hours of the year when the system was most vulnerable to a shortfall of supply as a result of prolonged periods of low renewable generation, resulting in the full discharge of the system's battery storage capacity.

MEPS can also incorporate the cost of conventional generation capacity to backstop the supply from intermittent renewable resources. As discussed in the body of this research report, the output of a system designed to meet 99.9% California's power demand with renewable energy would have fallen short of demand for 20 hours in 2017. MEPS allow us to design the lowest cost solution to offset this gap (using gas fired generation to meet the shortfall in supply during these 20 hours), and to calculate an adjusted LCOE that includes the cost of these additional resources.

Hourly Data Inputs

To operate, the MADA software requires hourly data on solar insolation, windspeed and demand for each location. While the software can handle tremendous levels of complexity, we used an Excel-based pilot version of the software, so the time to run each simulation increased greatly with the complexity. Therefore, to simplify the analysis, we used data for solar insolation and windspeed from a single, typical location (Tehachapi Pass for wind and LA for solar) and we used only a single year of data (2017) for the solar, wind and demand data.

To account for the availability of existing hydroelectric, geothermal and biomass generation, we reduced the hourly demand required to be met by the wind, solar and storage resources in the model by the average hourly hydro and geothermal output since 2000, and average hourly biomass over the most recent full year, 2017.

Possible Biases in the Data

Using a single location and year to estimate the volatility of renewable generation, and a single year to estimate the volatility of system load, may introduce distortions in our analysis.

In particular, measuring solar and wind generation at a single location will tend to underestimate the stability of the state-wide supply of renewable energy, thus causing the model to overestimate the scale of solar and wind resources required to meet demand during every hour of the year. That said, using a single location and year to estimate the amount of hourly solar generation should have only a limited impact on the results of our analysis, as solar insolation does not vary much in California from year to year, nor is there high regional variation across the state during any given hour. By contrast, windspeeds can vary significantly from year to year and are very location specific. Relying on windspeed data from just the Tehachapi Pass, therefore, likely underestimates the stability of the California's total wind output from hour to hour and therefore overestimates the resources required to meet demand. However, because weather fronts, which drive the general presence or absence of wind at any time, cover large areas, we believe the impact is limited.

Importantly, other assumptions used in our analysis will tend to understate the resources required to meet demand during each hour of the year, thus introducing a contrary bias. Our use of a long term average for hydroelectric generation means that we have not accounted for the full impact of drought conditions, which would require additional resources to offset. Critically, also, our use of a single year of demand data tends to underestimate the volatility of demand, again causing our model to underestimate the need for generation and storage resources.

Finally, given the enormous scale and cost of the renewable and storage resources required to meet hourly demand, we are confident that the overall conclusions of our analysis are robust despite the potential biases in the data.