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# Electric Fleet Adoption Strategies – Addressing Storage and Infrastructure Needs



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# Electric Fleet Adoption Strategies – Addressing Storage and Infrastructure Needs

July 2020

A Research Report from the National Center for Sustainable Transportation

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**16. Abstract**

Significant electrification of the transportation sector is necessary for the State to achieve several important greenhouse gas (GHG) reduction and renewable energy targets. The State's electricity generation and transmission capabilities must increase in order to meet the demand generated by increasing levels of fleet electrification. The increased demand, combined with the Renewables Portfolio Standard (RPS) targets will require significantly increased energy storage capabilities that can accommodate demand while integrating renewable power sources into the grid. This project evaluated the mid to long-term energy storage needs of the electric grid for select fleet electrification scenarios. The analysis was conducted using Resolve, a power systems planning model, for RPS targets of 60% and 80% by 2030 and 2042 respectively. The results show that Electrical Energy Storage (EES) capacity requirements depend on a number of parameters, including Demand Response (DR), Electric Vehicle (EV) charging flexibility, and total EV population. The EES requirements for the 60% RPS scenarios range from 3.9 to 4.3 GW while for the 80% RPS scenarios, the range is from 18.5 to 20.4 GW.

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# Electric Fleet Adoption Strategies – Addressing Storage and Infrastructure Needs

A National Center for Sustainable Transportation Research Report

July 2020

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## EXECUTIVE SUMMARY

Significant electrification of the transportation sector is necessary for the State to achieve several important greenhouse gas (GHG) reduction and renewable energy targets. California has a number of key GHG reduction and renewable energy targets that require decarbonization of the transportation sector to play an important role. Fleet electrification places new demands on the electric grid, which are further complicated by increasing renewables integration into the grid. Significant short and long-term energy storage along with load flexibility will be necessary to manage increased renewables to the grid while also meeting the supply and infrastructure demands of the growing electric fleet.

Traditional approaches to power system planning are built around the reliability and flexibility of fossil resources. These approaches are inadequate in their ability to model high renewables integration into the grid. In order to analyze high renewables integration, the planning models must have the ability provide adequate temporal, spatial, and operational resolution, and the ability to manage the necessary computational complexity. This project utilizes Resolve (Renewable Integration Solutions model), an investment and operations planning model aimed at addressing key planning challenges related to high renewables integration into the electric grid. A baseline analysis was conducted to evaluate the effect of key parameters on the electrical energy storage (EES) requirements of California's electric grid under varying GHG emission caps and other factors. Twelve RPS scenarios with varying levels of renewable generation and fleet electrification were also analyzed using the Resolve model. The analysis was conducted for RPS targets of 50-60% and 80% by 2030 and 2042 respectively. The results show that EES capacity requirements depend on a number of parameters, including the GHG cap placed on the specific scenario, the RPS target, Demand Response (DR), Electric Vehicle (EV) charging flexibility, and total EV population. However, the EES capacity requirement is heavily influenced by the GHG cap and the RPS targets and the EV deployment rates have a minimal effect on the overall storage needs and the costs associated with specific portfolios. The 80% scenarios require considerably higher EES capacity, likely due to the GHG reduction requirements.

There is considerable ongoing power curtailment in California throughout the year. Power-to-gas and other forms of long-term storage options can help mitigate curtailment losses while reducing the EES requirements. The most viable storage approaches including specific electrolysis technologies, hydrogen storage and transportation methods, and utilization technologies must be identified in order to realize the potential benefits of P2G. Incorporating both conventional and P2G based energy storage systems as part of future generating plants can help curtailment and increase the flexibility and resiliency of the electric grid.

# Introduction

Significant electrification of the transportation sector is necessary for the State to achieve several important greenhouse gas (GHG) reduction and renewable energy targets. California has a number of key GHG reduction and renewable energy targets that require decarbonization of the transportation sector to play an important role. Fleet electrification places new demands on the electric grid, which are further complicated by increasing renewables integration into the grid. California has a Renewable Portfolio Standard (RPS) mandate that requires all the state's electricity to be produced from renewable resources by 2045. Significant short and long-term energy storage along with load flexibility will be necessary to manage increased renewables to the grid while also meeting the supply and infrastructure demands of the growing electric fleet. Achieving these complex and sometimes divergent goals requires the ability to understand the nature of long-term demands, technology and market developments, resource and infrastructure requirements, and other factors.

The California Air Resources Board (CARB) has prepared and updated a Scoping Plan to achieve the state's climate goals. The Scoping Plan coordinates the state's efforts including actions and initiatives across various sectors to meet mid and long-term climate. Renewables integration into the electric grid along with changing demand patterns due to fleet electrification will likely place new requirements on the electric infrastructure. Short and long-term energy storage will play a critical role in managing the renewable power supply related challenges while meeting the supply and infrastructure demands of transportation sector electrification.

The goal of this study is to evaluate mid to long-term energy storage needs of the electric grid for select fleet electrification scenarios. We compare energy storage options, and examine the feasibility of long-term storage through the 'power to gas' approach. The project also provides recommendations on approaches to manage the increasing renewables integration in the fleet electrification context. The Resolve model, an advanced power system planning model developed for the California Public Utilities Commission was used to conduct the core analysis. Designed to answer planning and operational questions related to renewable resource integration, Resolve co-optimizes investment and dispatch over a multi-year horizon with one-hour dispatch resolution for a study area, and solves for the optimal investments in renewable resources, technologies, and energy storage options.

# Electric Grid Modeling

Traditional power system planning approaches are built around the reliability and flexibility offered by traditional fossil resources. These approaches are inadequate in their ability to model high renewables integration into the grid. New tools are under development that can account for the inherent unpredictability and distributed nature of renewable resources. The key requirements for power planning models include the ability provide adequate temporal, spatial, and operational resolution, ability to manage the necessary computational complexity, transparency and replicability. A number of power system planning models are available including some open source options. Resolve (Renewable Integration Solutions model) is an investment and operations planning model aimed at addressing key planning challenges related to high renewables integration into the electric grid.

The model description is quoted from the documentation published in July 2016 as part of the CAISO SB350 study [2]. "The Resolve model is one of a growing number of models designed to answer planning and operational questions related to renewable resource integration. In general, these models fall along a spectrum from planning-oriented models with enough treatment of operations to characterize the value of resources in a traditional power system to detailed operational models that include full characterization of renewable integration challenges on multiple time scales but treat planning decisions as exogenous. Resolve co-optimizes investment and dispatch over a multi-year horizon with one-hour dispatch resolution for a study area, in this case the California Independent System Operator (ISO) footprint. The model incorporates a geographically coarse representation of neighboring regions in the West in order to characterize and constrain flows into and out of the ISO. Resolve solves for the optimal investments in renewable resources, various energy storage technologies, new gas plants, and gas plant retrofits subject to an annual constraint on delivered renewable energy that reflects the RPS policy, a capacity adequacy constraint to maintain reliability, constraints on operations that are based on a linearized version of the classic zonal unit commitment problem as well as feedback from ISO, and scenario-specific constraints on the ability to develop specific renewable resources."

The scenarios evaluated in this study are based on the State's mandated and proposed GHG reduction, renewable energy, and transportation targets. The targets include 5 million ZEVs on the roads by 2030 and 250,000 electric vehicle charging stations by 2025.

## Energy Storage Needs Assessment

The fleet electrification scenarios, including many of the underlying assumptions and forecasts are based on the RPS analysis performed by the California Public Utilities Commission as part of the Integrated Resource Planning (IRP) process. A brief summary of the key assumptions and inputs, from the CPUC's 2017 IRP documentation, are provided below. Details and additional information are available in the references [1-3]. The analysis performed here to assess high RPS scenarios have not been evaluated previously.

The annual load forecasts by Resolve are based on the California Energy Commission (CEC)'s 2016 Integrated Energy Policy Report (IEPR). The Resolve model represents the annual forecast in the form of baseline consumption with a number of demand side modifiers including electric vehicles, energy efficiency, building electrification and other factors. The baseline resources, i.e., existing resources, included in the analysis fall under the categories of conventional generation (thermal sources using fossil fuels), renewables, large hydro, energy storage and demand response. The candidate resources that can be used to build the optimal portfolio include natural gas, renewables, energy storage and demand response (DR). Each candidate resource includes multiple technology options such as combined cycle gas turbine, reciprocating engine, solar, wind, battery storage, pumped storage, shed and shift DR. Details of load and renewable profiles, including electrification and energy efficiency profiles, operating characteristics, reserve requirements, fuel costs and other parameters are available in the CPUC documentation. Resolve also allows the user to enforce a GHG cap on each scenario.

The following scenarios from the IRP analysis were used to assess the baseline electrical energy storage (EES) needs, effect of select parameters on EES needs, and underlying trends. EES as defined here includes both battery storage and pumped hydro storage but not other forms of storage.

- 30 MMT Scenario: The electric sector achieves an emissions level by 2030 equivalent to what is attributed to it in CARB's Alternative 1 scenario; this implies that additional electric sector investments beyond those included in the Draft Scoping Plan Scenario are used to achieve the state's GHG emission reduction goals.
- 42 MMT by 2030: The electric sector achieves an emissions level by 2030 that is equivalent to the lower end of the range attributed to it in CARB's Draft Scoping Plan Scenario.
- 99 MMT Scenario: This scenario assumes that there are no GHG target constraints on the California electric grid. The RPS targets, as defined, are valid throughout the analysis.

Each scenario analyzed by Resolve involves a number of assumptions and input parameters. The IRP uses the Large Share of Economy-Wide Emissions Reductions (42 MMT $CO_{2e}$ GHG) scenario as the base case for IRP assessments. Some of the key parameters for 42 MMT scenario are listed below. Curtailment of excess power is allowed under all the scenarios unless otherwise specified. Additional information and details are available in the references [1-3].

- Electric Vehicle Adoption: CARB Scoping Plan
- Building Electrification: California Energy Commission (CEC) 2016 Integrated Energy Policy Report (IEPR) - Mid Demand
- Hydrogen: No Hydrogen
- Behind-the-meter photovoltaic (PV): CEC 2016 IEPR - Mid PV
- Energy Efficiency: CEC 2016 IEPR - Mid Additional Achievable Energy Efficiency (AAEE) + Assembly Bill 902 (AB 802)
- Existing Demand Response (DR): Mid
- Time of Use (TOU) Adjustment: High
- Workplace Charger Availability: Mid
- Electric Vehicle (EV) Charging Flexibility: Low

As part of the IRP proceedings, the CPUC has conducted extensive modeling of California's electric grid including the California Independent System Operator (CAISO)'s balancing authority area, especially until 2030. This modeling has been performed using the Resolve model by Energy and Environmental Economics, Inc. (E3), an energy consulting firm [1]. As mentioned earlier, the Resolve model was also used in the CAISO study for Senate Bill 350 (SB 350) to evaluate ratepayer benefits from expanding the CAISO footprint. SB 350 (Clean Energy and Pollution Reduction Act) was signed into law in 2015 and establishes, among other actions, targets for energy efficiency and renewable electricity aimed at reducing GHG emissions.

The CPUC has released 231 specific scenarios evaluating 50% RPS by 2030 consisting of 77 different approaches for each of the 30 MMT, 42 MMT and 99 MMT scenarios described earlier. The results from these scenarios were analyzed using key parameters to evaluate the EES requirements under varying conditions and the effect of key parameters on the EES capacity needs. The detailed assumptions, inputs, and results from these scenarios are available in the references. Only the analysis results are presented here. It should also be noted that the CPUC has released additional scenarios exploring specific conditions that are not included in the analysis. EES is defined as the total installed capacity of battery and pumped water electricity storage systems. The renewable energy capacity, particularly solar and wind power sources, have a significant impact on the EES needs of the system. To quantify this effect, Variable Renewable Energy (VRE) capacity of the portfolio. VRE is defined as the total installed capacity of wind and solar power generation divided by the overall power generation capacity [4]. VRE does not take into account the EES capacity of the portfolio. Further, as discussed by Cebulla et al., the generation profile also has an effect on the required EES and other flexibility measures [4]. The power mixes are further categorized to identify the dominant renewable energy resource. The power mix definitions are listed below:

- Very PV dominated (PV++): Ratio of installed PV to wind capacity is 6:1
- PV-dominated (PV+): Ratio of installed PV to wind capacity is 2:1
- Very wind-dominated (Wind++): Ratio of installed PV to wind capacity is 1:3
- Wind-dominated (Wind+): Ratio of installed PV to wind capacity is 1:1.5
- Balanced mix: Ratio of installed PV to wind capacity is between the PV+ and Wind+ categories

All scenarios assessed have similar number of electric vehicle deployment rates, based on the mid-level EV deployment values from the 2016 CEC IEPR proceedings. **Error! Reference source not found.** shows the VRE percentages for the scenarios analyzed and the corresponding EES values. As could be anticipated, higher VRE percentages typically require higher EES capacities. The plot shows that there is a significant increase in installed EES capacity for scenarios with VRE values higher than 55%. For VRE value of 45 to 55%, the EES capacity remains relatively same. With the exception of a few specific cases that will be discussed later, the EES capacity increases with the stringency of the GHG caps. Thus, the 30 MMT scenarios have the highest EES requirements followed by the 42 MMT scenario with the GHG cap free scenarios (99 MMT) having the lease EES requirements.

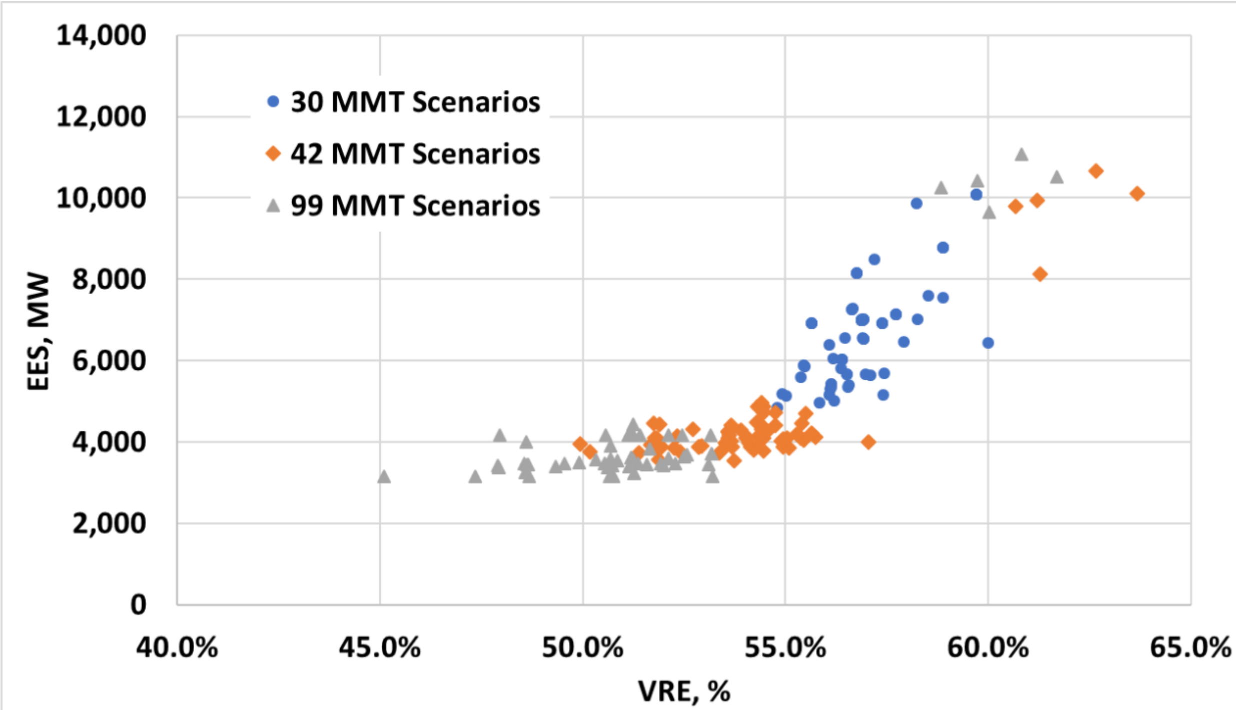


**Figure 1. Total installed EES capacity for varying VRE percentages**

Figure 2 shows the effect of installed PV to wind power capacities of portfolios on the EES capacity needed for different VRE percentages. The EES/VRE ratio has the units of GW over %. The plot shows that the PV/Wind ratio has a meaningful impact on the EES capacity requirement only for the 30 MMT scenario. For the 42 and 99 MMT scenarios, the EES/VRE ratio stays relatively the same for the entire range of PV/Wind capacity ratios. This indicates that the EES requirement is more heavily influenced by the GHG cap than by the dominance of solar or wind generation in the energy mix.

The installed EES capacity to VRE ratio also shows a dependence on the installed natural gas to total renewable generation capacity of the energy mixes, especially at lower gas to renewable energy ratios. The EES requirement appears to be relatively constant for the 42 and 99 MMT scenarios except at very low gas to renewable energy ratios. These results correspond with the previous figures as the 30 MMT scenarios will have the lowest natural gas capacities and higher EES capacity to manage the variability of solar and wind generation. These results show that the installed EES capacity of a power mix depends on a number of factors, with the GHG cap imposed on the mix being the most dominant of the parameters evaluated.

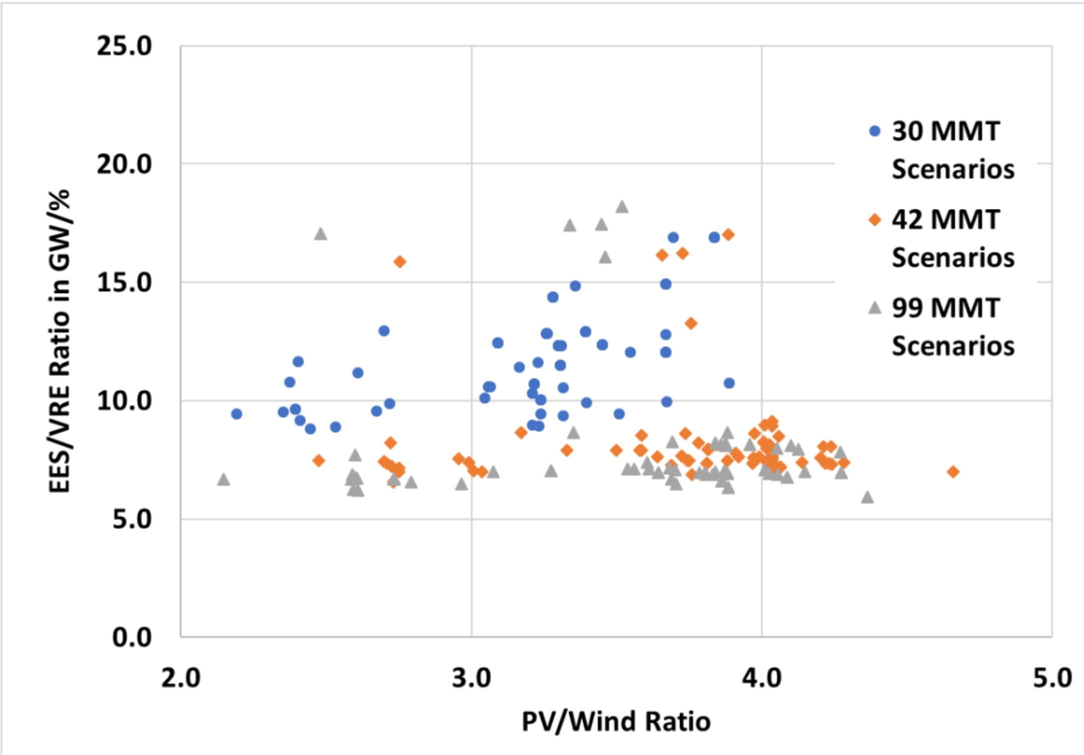


**Figure 2. Ratio of EES to VRE in GW over % for varying PV to Wind generation capacity ratios**

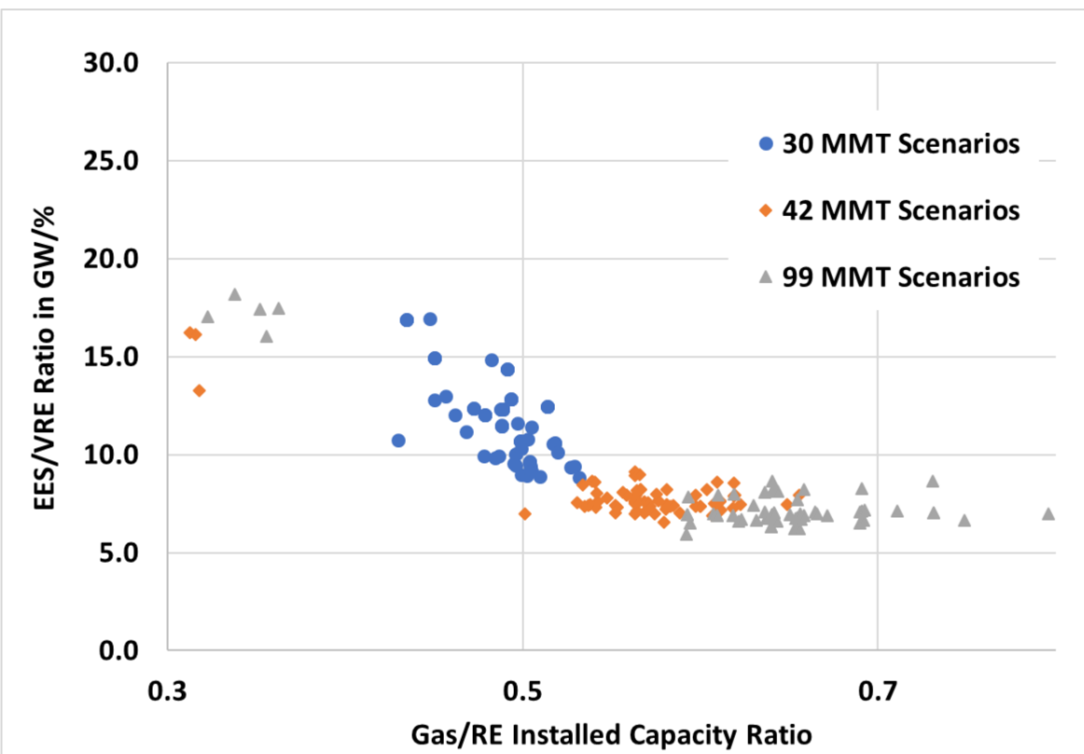


**Figure 3. Ratio of EES to VRE in GW over % for varying natural gas to renewable power installed capacities**

## Assessment of EES Needs for Fleet Electrification

Twelve RPS scenarios with varying levels of renewable generation and EV deployment were analyzed using the Resolve model. The key assumptions for the twelve scenarios are summarized in Table 1. The scenarios evaluated range from 50% RPS target by 2030 to 80 RPS target by 2042, consistent with the current RPS mandate. EV deployment is assumed to be between 3.3 to 5 million vehicles by 2030 and from 8.7 to 13.4 million vehicles by 2042. The definitions used in the previous section are applicable throughout this report. Scenario 1 follows the EV deployment trend from the 42 MMT reference scenario from the CARB Scoping Plan whereas Scenario 2 follows the Mid-level projections from the 2016 CEC IEPR proceedings. The rest of the scenarios are based on the 42 MMT reference scenario from the CARB Scoping Plan with changes shown in Table 1.

**Table 1. Electrification Scenario Assumptions**

| Scenario Name | Timeframe | RPS | | Batteries | | EVs deployed (millions) | | EV Load (1000 GWh) | |
|---|---|---|---|---|---|---|---|---|---|
| | | 2030 | 2042 | Li-ion | Flow | 2030 | 2042 | 2030 | 2042 |
| Scenario 1 | 2030 | 50% | NA | Mid | Mid | 3.29 | NA | 9.15 | NA |
| Scenario 2 | 2030 | 50% | NA | Mid | Mid | 3.32 | NA | 9.23 | NA |
| Scenario 3 | 2030 | 50% | NA | Mid | Mid | 3.50 | NA | 9.75 | NA |
| Scenario 4 | 2030 | 60% | NA | Mid | Mid | 5.00 | NA | 13.93 | NA |
| Scenario 5 | 2030, 2042 | 60% | 80% | Mid | Mid | 5.00 | 11.01 | 13.93 | 30.65 |
| Scenario 6 | 2030, 2042 | 60% | 80% | Mid | Mid | 5.00 | 13.40 | 13.93 | 37.32 |
| Scenario 7 | 2030, 2042 | 60% | 80% | High | High | 5.00 | 13.40 | 13.93 | 37.32 |
| Scenario 8 | 2030, 2042 | 60% | 80% | Mid | Mid | 5.00 | 8.70 | 13.93 | 24.23 |
| Scenario 9 | 2030, 2042 | 60% | 80% | Mid | Mid | 5.00 | 13.40 | 13.93 | 37.32 |
| Scenario 10 | 2030, 2042 | 60% | 80% | High | High | 5.00 | 13.40 | 13.93 | 37.32 |
| Scenario 11 | 2030, 2042 | 60% | 80% | Mid | Mid | 5.00 | 13.40 | 13.93 | 24.23 |
| Scenario 12 | 2030, 2042 | 60% | 80% | High | High | 5.00 | 13.40 | 13.93 | 24.23 |

The results from the analysis are presented in Table 2. The results show that the installed EES capacity for the scenarios range from approximately 3.94 to 4.32 GW by 2030 with 50 to 60% RPS targets and from 11.26 to 20.4 GW for the 80% RPS by 2042 scenarios. The ratio between installed PV to wind generation capacities and of the power mixes and the ratios of installed EES capacities and VRE percentages are also given in the Table. The results show varying EES capacity requirements but do not show a strong dependency on the number of EVs deployed. As discussed earlier, the scenarios include demand response and other advanced balancing and management techniques that can address the variability in renewable generation and reduce the dependence on conventional EES alone to manage the grid. However, the 80% RPS scenarios still show significant EES requirements in addition to these techniques.

**Table 2. Electrification Scenario Results**

| Scenario Name | RPS | | EVs deployed (millions) | | EES capacity (GW) | | VRE % | | Dominant Tech (PV-Wind Ratio) | | EES/VRE (GW/%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2030 | 2042 | 2030 | 2042 | 2030 | 2042 | 2030 | 2042 | 2030 | 2042 | 2030 | 2042 |
| Scenario 1 | 50% | NA | 3.29 | NA | 4.14 | NA | 54% | NA | 4.04 | NA | 7.61 | NA |
| Scenario 2 | 50% | NA | 3.32 | NA | 4.14 | NA | 54% | NA | 4.04 | NA | 7.61 | NA |
| Scenario 3 | 50% | NA | 3.50 | NA | 4.15 | NA | 54% | NA | 4.04 | NA | 7.64 | NA |
| Scenario 4 | 60% | NA | 5.00 | NA | 4.25 | NA | 54% | NA | 3.84 | NA | 7.81 | NA |
| Scenario 5 | 60% | 80% | 5.00 | 11.01 | 4.32 | 20.10 | 55% | 65% | 3.92 | 5.13 | 7.86 | 31.15 |
| Scenario 6 | 60% | 80% | 5.00 | 13.40 | 4.19 | 20.40 | 55% | 65% | 3.91 | 5.28 | 7.63 | 31.34 |
| Scenario 7 | 60% | 80% | 5.00 | 13.40 | 3.94 | 19.94 | 55% | 65% | 3.92 | 5.38 | 7.18 | 30.45 |
| Scenario 8 | 60% | 80% | 5.00 | 8.70 | 4.25 | 18.47 | 55% | 65% | 3.92 | 4.94 | 7.73 | 28.20 |
| Scenario 9 | 60% | 80% | 5.00 | 13.40 | 4.26 | 19.41 | 56% | 67% | 4.16 | 5.80 | 7.58 | 29.02 |
| Scenario 10 | 60% | 80% | 5.00 | 13.40 | 4.08 | 13.69 | 52% | 63% | 3.40 | 4.63 | 7.88 | 21.88 |
| Scenario 11 | 60% | 80% | 5.00 | 13.40 | 4.26 | 17.36 | 56% | 66% | 4.18 | 5.51 | 7.59 | 26.28 |
| Scenario 12 | 60% | 80% | 5.00 | 13.40 | 4.08 | 11.26 | 52% | 61% | 3.41 | 4.29 | 7.87 | 18.43 |

Figures 4 and 5 show the installed generating capacity and the new build requirements for Scenario 1 [5].

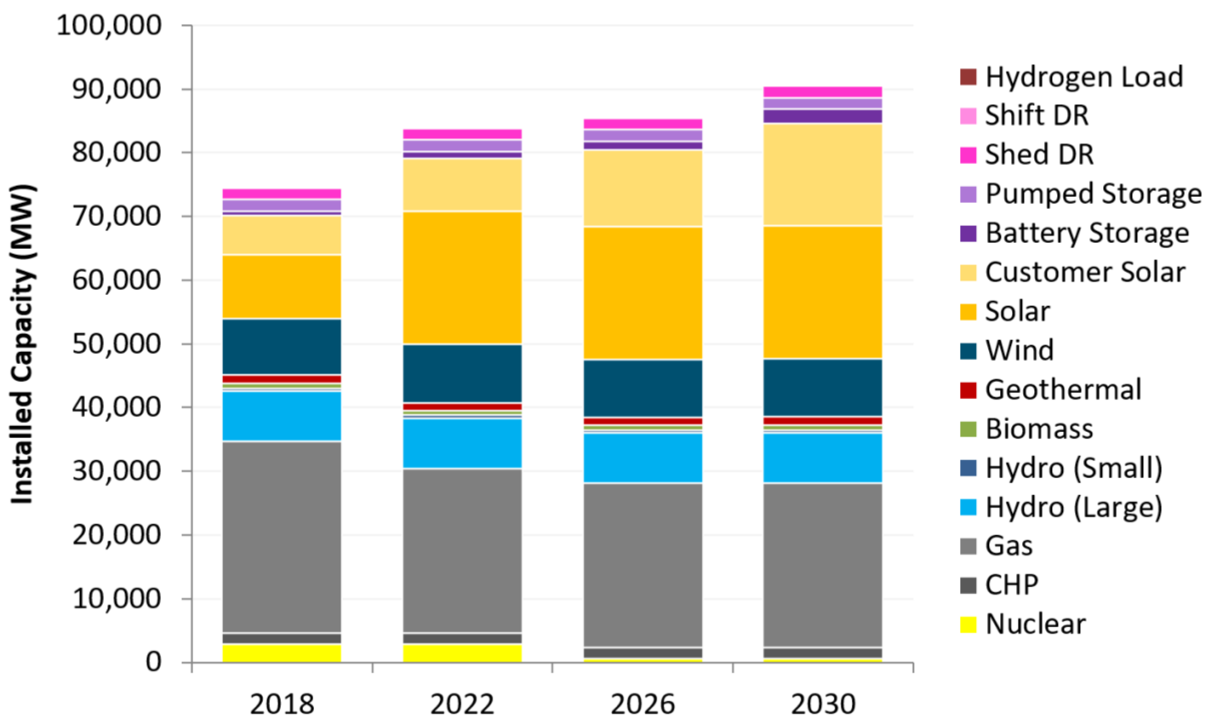


**Figure 4. 50% RPS by 2030 Total CAISO installed generating capacity**

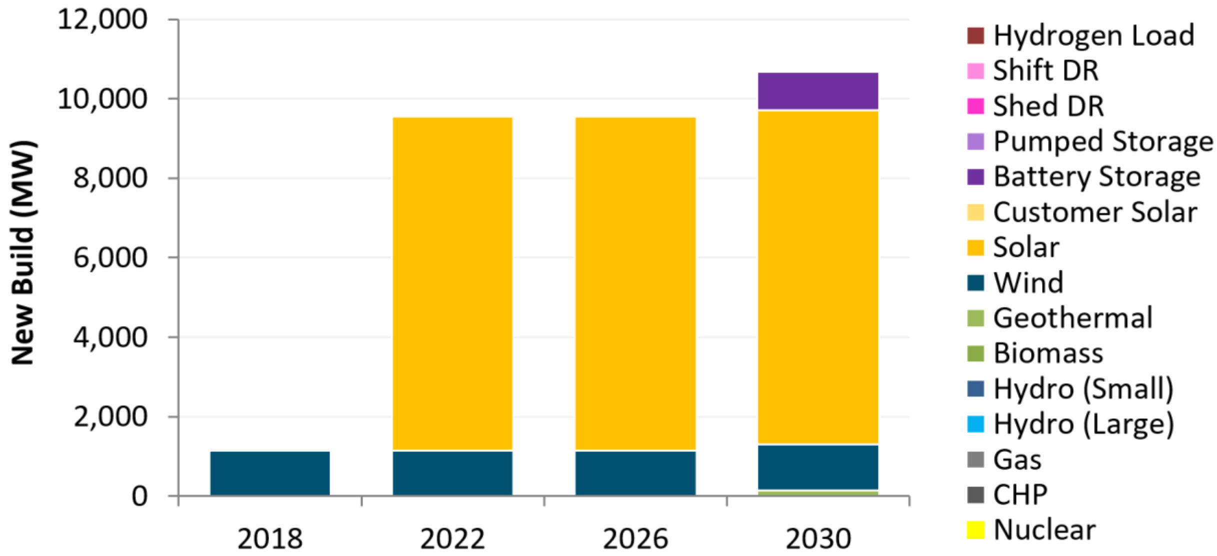


**Figure 5. 50% RPS by 2030 Total CAISO new build**

Although significant fossil generating capacity exists under the 50% RPS scenario, new builds over the analysis are only in the wind, solar, and battery storage categories [5]. Figure 6 shows the total cumulative investment over the analysis period and the electric costs, ranging from 15.6 to 20 ¢/kWh as shown in Figure 6. This represents a 28% increase over 12 years. By comparison, California's average electric costs increased from 11.35 to 15.23 ¢/kWh from 2004 to 2016, which is a 34% increase. The results anticipate a trend of decreasing electric costs as the cost of solar and wind power have considerably decreased over the years [5].

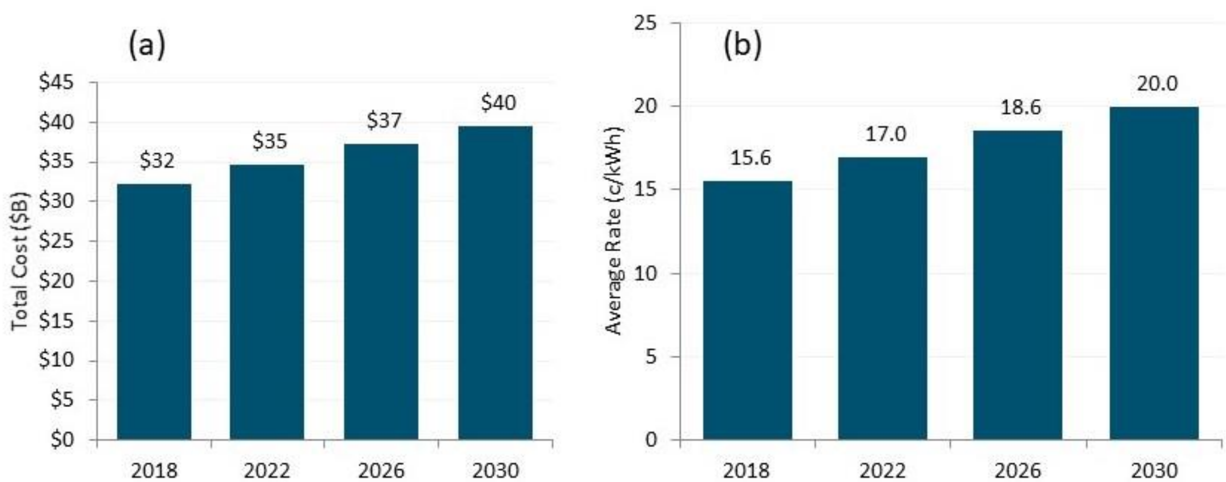


**Figure 6. 50% RPS by 2030 scenario (a) Total cumulative investment; (b) Electric costs**

The total investment and the electricity costs for the 80% RPS reference scenario are shown in Figure 7. As mentioned earlier, the higher RPS scenarios rely on significant added storage capacities and other mechanisms such as demand response in order to manage the renewable resources and mitigate curtailment. Considerable uncertainty is seen higher RPS scenarios, especially above 50%, with significant variation in new buildouts and costs. The high renewables scenarios considered result in up to 10% curtailment of renewables with the curtailment increasing considerably under options without significant storage capacity.

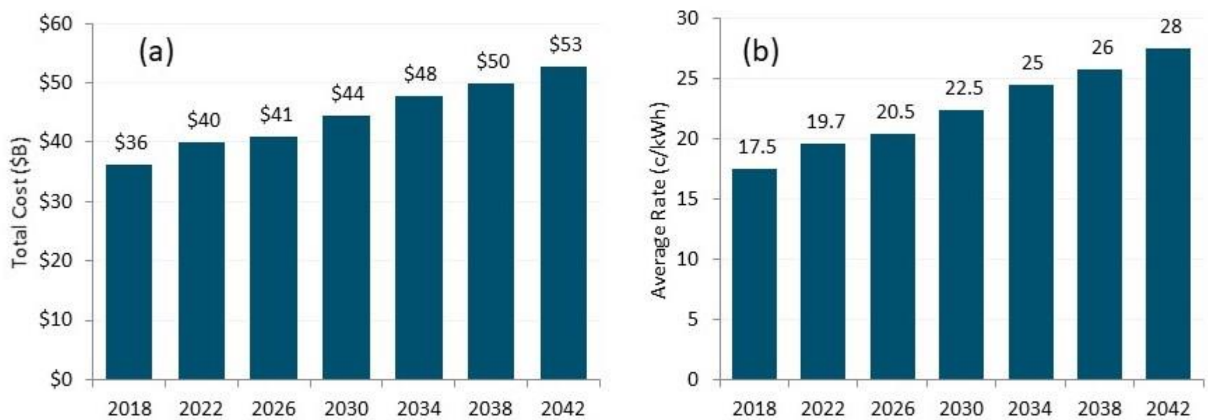


**Figure 7. 80% RPS by 2042 scenario (a) Total investment; (b) Electric costs**

## Discussion and Recommendations

The results of the modeling analysis show that the EES capacity requirements are significantly influenced by parameters such as the GHG cap placed on specific scenarios, the RPS mandates, and the flexible generating capacity of the mixes. The variation in storage requirements for varying fleet electrification cases appear to be minimal. These results are in line with studies available in the literature that evaluate similar scenarios.

Cebulla et al. performed an analysis of 17 studies with 405 scenarios for the US, Europe and German electric grids with the goal of evaluating the EES needs of different power mix scenarios [4]. The analysis showed a broad range of EES requirements, for example a range of 15-530 GW for the US for scenarios with 80% or higher VRE shares. However, after eliminating outliers and specific conditions, for example: no curtailment, they identified that the EES requirements are approximately similar for the different scenarios. The EES capacity to VRE% ratios from Cebulla et al. for the 80% VRE shares are given below [4].

- Very PV dominated (PV++) EES Power capacity (GW/%VRE) = 6-9
- PV-dominated (PV+) EES Power capacity (GW/%VRE) = 4-6
- Very wind-dominated (Wind++) EES Power capacity (GW/%VRE) = 1
- Wind-dominated (Wind+) EES Power capacity (GW/%VRE) = 2
- Balanced mix EES Power capacity (GW/%VRE) = 3

Thus, the Wind++ power mixes require the minimum EES capacity while the PV++ mixes require the highest EES capacities. As shown earlier, California's power mix under all the scenarios range from PV+ to Wind+ with a majority of the scenarios being relatively balanced or PV dominated. Comparing the results to the scenarios evaluated in this study, it can be seen that

EES capacity requirements for the 50% RPS scenarios are within the range of values reported by Cebulla et al. However, the 80% RPS scenarios require significantly higher EES capacities, ranging from 3 to 5 times higher than the values reported by Cebulla et al. This increase corresponds with the higher costs of the 80% RPS scenarios and is primarily driven by the GHG targets imposed on the scenarios. The results show that multiple grid management techniques including advanced demand response and EES will be required to achieve the renewable energy and GHG targets simultaneously.

## Power-to-Gas Assessment

The Power-to-Gas (P2G) pathway converts excess renewable electricity into hydrogen that can then be stored or used as a fuel, including in the transportation sector. Converting excess renewable electricity into hydrogen offers a means to addressing the well-known grid capacity and curtailment challenges associated with portfolios that have high renewable generation. The P2G pathway has the potential to decarbonize all major sectors including commercial, residential, and transportation [6].

Although power curtailment has been a part of grid management in the recent past, it is becoming increasingly important with consequences on infrastructure and the economy [7]. A study by Schoenung et al., analyzed the potential of excess renewable power based hydrogen to fulfill the hydrogen fuel demand for fuel cell electric vehicles (FCEV) in California [8]. The study predicts 12,000 GWh of excess electricity by 2030 which can potentially produce 243 million kg of hydrogen [8]. The price of excess electricity is assumed to be near zero or even negative during oversupply [7,8].

The gross amount of curtailed power is considered to be excess electricity that is potentially available for other purposes. A total of 615 solar power plants and 128 wind power plants are currently under operation in the state [9,10]. Generation from geothermal, biomass, biogas and small hydro can provide baseload power but is significantly less than solar and wind generation during the 24-hour day period. Table 3 shows the amount of real-time power curtailment in 2018 and 2019. There is significant curtailment throughout the year with monthly values up to 223 GWh. During the total twenty-four-month period, approximately 1,422 GWh of power was curtailed in California. Power-to-gas and other forms of long-term storage integrated into the electric grid can mitigate these losses and expedite the integration of additional renewables into the grid.

**Table 3. Solar and wind power curtailment in 2018 and 2019**

| Month | 2018 curtailment (MWh) | 2019 curtailment (MWh) |
|---|---|---|
| Jan | 11,890 | 12,763 |
| Feb | 36,763 | 82,611 |
| Mar | 94,778 | 122,225 |
| Apr | 71,562 | 190,070 |
| May | 72,064 | 223,195 |
| Jun | 19,683 | 48,609 |
| Jul | 8,713 | 20,819 |
| Aug | 14,321 | 14,153 |
| Sep | 14,297 | 59,637 |
| Oct | 83,413 | 48,190 |
| Nov | 25,020 | 69,758 |
| Dec | 8,550 | 69,313 |
| **Totals** | **461,054** | **961,343** |

## Conclusions and Recommendations

Analysis of RPS scenarios with varying levels of renewable generation and fleet electrification shows that Electrical Energy Storage (EES) capacity requirements depend on a number of parameters, including the GHG cap placed on the specific scenario, the RPS target, Demand Response (DR), Electric Vehicle (EV) charging flexibility, and total EV population. However, the EES capacity requirement is heavily influenced by the GHG cap and the RPS targets and the EV deployment rates have a minimal effect on the overall storage needs and the costs associated with specific portfolios. The 80% scenarios require considerably higher EES capacity, likely due to the GHG reduction requirements.

There is considerable ongoing power curtailment in California throughout the year. Power-to-gas and other forms of long-term storage options can help mitigate curtailment losses while reducing the EES requirements. The most viable storage approaches including specific electrolysis technologies, hydrogen storage and transportation methods, and utilization technologies must be identified in order to realize the potential benefits of P2G. Incorporating both conventional and P2G based energy storage systems as part of future generating plants can help curtailment and increase the flexibility and resiliency of the electric grid.

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# Data Management

## Products of Research

The product of this project is an assessment of the potential electrical energy storage (EES) capacity requirements of the California electricity grid under various Renewable Portfolio Standard (RPS), greenhouse gas (GHG) emission targets, and fleet electrification scenarios.

## Data Format and Content

The data is presented in a two Excel files. The 'Energy Storage Needs Assessment' data based on scenarios published by the California Public Utilities Commission is compiled in the spreadsheet titles 'Energy Storage Needs Assessment Data'. The results comparing the data from the 30, 42, and 99 Million Metric Tonnes (MMT) of $CO_2$ equivalent GHG scenarios, detailed results of select individual 30, 42, and 99 MMT scenarios and data analysis based on the parameters listed in the main report are presented in separate tabs.

The EES requirement data for various fleet electrification scenarios are presented in the 'Electrification EES Assessment Data' spreadsheet. Results for the specific scenarios discussed in the main report and a comparison of the key parameters and EES requirement outcomes are shown in separate tabs.

## Data Access and Sharing

The data is accessible to the public through the Dryad data repository. See: https://doi.org/10.6086/D1667N

## Reuse and Redistribution

The data is accessible to the public and open for reuse and redistribution with appropriate citation:

> Raju, Arun S.K.; Vu, Alexander (2020), California grid electrical energy storage requirements for select renewables integration and fleet electrification scenarios, v3, UC Riverside, Dataset, https://doi.org/10.6086/D1667N