Title
Demonstrating a Framework to Evaluate the Impacts of Energy Storage Strategies to Meet California Sustainability Goals

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Demonstrating a Framework to Evaluate the Impacts of Energy Storage Strategies to Meet California Sustainability Goals

THESIS

Submitted in partial satisfaction of the requirements
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By

Kate E. Forrest

Thesis Committee:
Professor G. Scott Samuelsen, Chair
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2016

Dedication

To my family

Immer geradeaus, Jamais arrière.

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List of Acronyms

AC alternating current

APEP Advanced Power and Energy Program

BEV battery electric vehicles

CAES compressed air energy storage

CARB California Air Resources Board

CEC California Energy Commission

CHP combined heat and power

CSP concentrated solar power

DC direct current

DG distributed generation

EV electric vehicle

EVSE electric vehicle supply equipment

FCV fuel cell vehicle

GHG greenhouse gases

HEV hybrid electric vehicle

HiGRID Holistic Grid Resource Integration and Deployment

IPCC Intergovernmental Panel on Climate Change

LCFS Low Carbon Fuel Standard

LDV light-duty vehicle

LEV Low Emission Vehicle

NHTS National Household Travel Survey

OECD Organization for Economic Cooperation and Development

PEV plug-in electric vehicle

PHEV plug-in hybrid electric vehicle

SOC state-of-charge

RPS Renewable Portfolio Standards

SES stationary energy storage

SONGS San Onofre Nuclear Generating Station

TIGER Transmission Integrated Grid Energy Resource

TOU time of use

TZEV transitional zero emission vehicle

VFB vanadium redox flow batteries

VMT vehicle miles traveled

V2G vehicle to grid

ZEV zero emission vehicle

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Abstract

Demonstrating a Framework to Evaluate the Impacts of Energy Storage Strategies to Meet California Sustainability Goals

by

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Master of Science in Engineering
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Professor Scott Samuelsen, Chair

Under global climate change, arid regions, like California, face higher temperatures and more extended droughts. In response, California is implementing policies for reducing GHG emissions from the electricity and transportation sectors, such as renewable and zero emission vehicle (ZEV) targets. Electricity and transportation have historically been treated as independent. However, emission strategies applied to either can affect both, as well as water resources, either aiding or hindering the advancement of mutual sustainability goals.

Expanding renewable utilization is increasing the need for stationary energy storage (SES) to manage renewable dynamics and shift energy to resolve the misalignment of supply and demand. The deployment of plug-in electric vehicles (PEVs) to meet ZEV targets introduces a new variable load and, at the same time, an alternative grid resource that, with intelligent charging, can be utilized as to manage grid dynamics, thereby achieving high renewable integration and reducing both electricity and transportation emissions.

This research employs an integrated platform to evaluate SES and PEV strategies to meet sustainability goals. The role of SES to facilitate renewable integration and meet emission targets under different scenarios is investigated. This is accomplished by (1) evaluating the effectiveness of SES to reduce emissions at high renewables, and (2) examining the impact of intelligent PEV deployment on SES requirements to reach renewable targets. The impact of water-intensive renewable technologies is also discussed. It is determined that intelligent PEV deployment provides an opportunity to further electricity and transportation emission targets by improving renewable integration and providing zero-emission energy for vehicles.

1.0 <u>Introduction</u>

1.1 The Energy Sector

The world's overall energy demand is projected to increase 33% by 2040, driven primarily by population growth and economic development in non-OECD (Organization for Economic Cooperation and Development) countries in the regions of Asia, Africa, and the Middle East. OECD countries will experience leveling off and, in some cases, decline in energy demand as population growth is countered by increased energy conservation and improved fuel efficiencies [1].

1.1.1 Electricity Supply and Demand

Even though world electricity demand, up 70% by 2040, will remain dominated by fossil fuels, the share of renewable energy technologies is expected to grow to 25% of total electricity generation in the same timeframe. The carbon intensity of electricity generation is projected to decline following this shift, but electricity emissions are still expected to increase by 16% (Figure 1) [2].

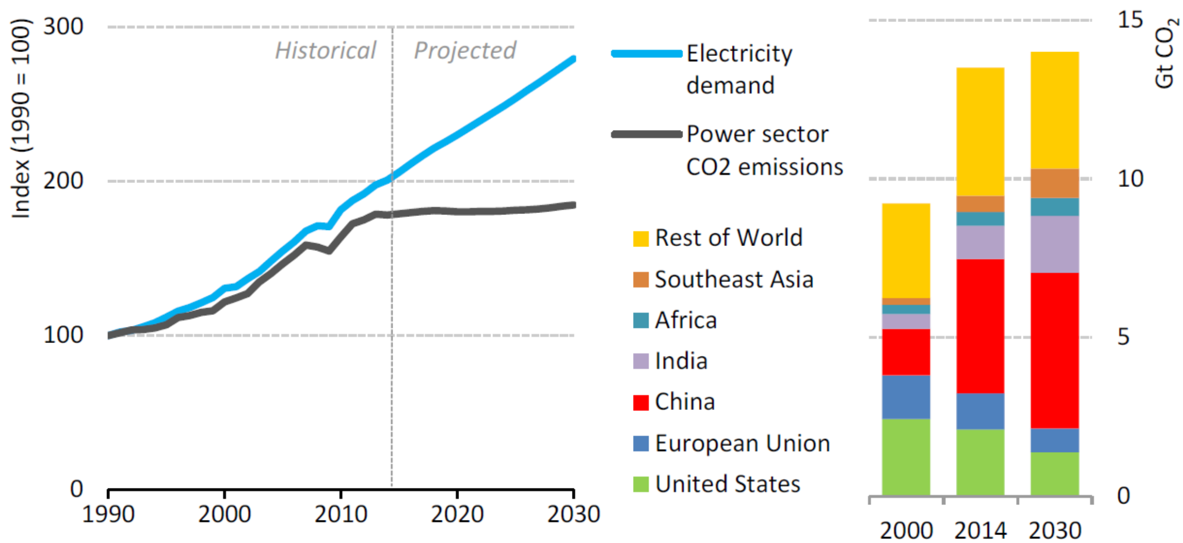


Figure 1. World Electricity Demand and Associated CO_2 Emissions [2]

The U.S. anticipates its electricity demand to increase by 20% from 2013 to 2040 [3]. This does not factor in the potential future impact of the electrification of the transportation sector (see next section). Depending on the strength of its economic growth and the price of oil, the U.S. renewable portion of electricity generation could reach up to 25% by 2040 [1], [3]. The growth of renewable energy technologies and the decrease in carbon intensity of fuels, in turn, will influence whether U.S. emissions decline or level off.

1.1.2 Transportation: Light-Duty Vehicles

Light-duty vehicles (LDVs), or passenger cars, make up 90% of all vehicle miles traveled (VMT) in the U.S and are responsible for about 60% of the transportation sector's energy use [3]. VMT-per-capita has historically increased, but it began to decrease in 2005 due to a multitude of factors, including fluctuating fuel prices and economic downturn. It has since leveled off, despite previous projections predicting it would continue to increase (Figure 2) [4]–[6].

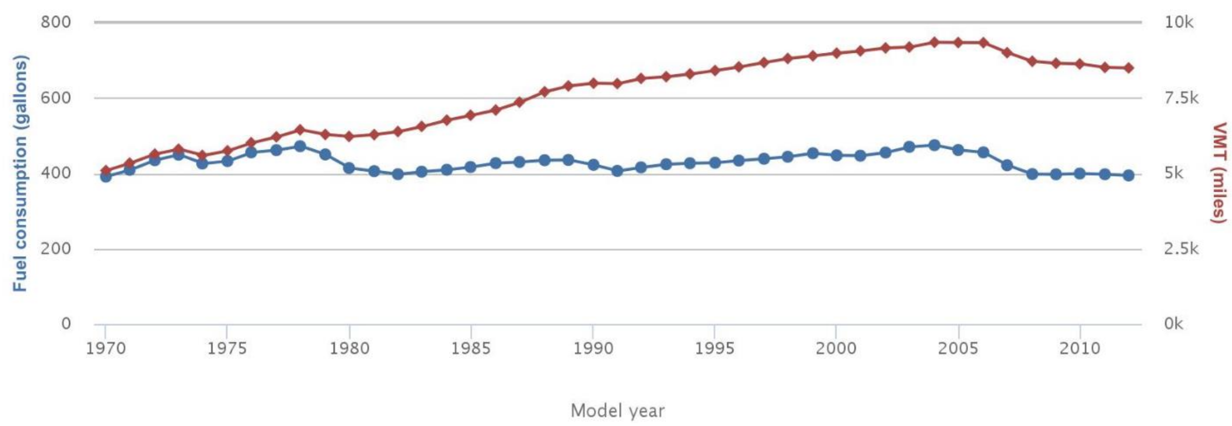


Figure 2. U.S. Light-Duty Fuel Consumption and Vehicle Miles Traveled per Capita [4]

Petroleum-based fuels have historically dominated the LDV market in the U.S. The current fuel stock is 96.8% gasoline, 2.7% diesel, and 0.5% alternative fuels [7]. The popularity of alternative fuels has grown in recent years, however, with more than 2 million hybrid electric (HEVs) and plug-in hybrid electric vehicles (PHEVs) [8] and 400,000 plug-in electric vehicles (PEVs) sold in the U.S. between 2011 and 2015 [9]. The rise of electric vehicles, spurred by federal and state regulations, has implications not only for transportation-related energy demand, but also for increased electricity demand. Meeting California's electric vehicle targets alone could add approximately 30 GW of new load [10].

1.2 Energy and the Environment

The reliance on fossil fuel energy has resulted in severe impacts to our natural environment, including habitat destruction, air pollution, and most importantly, the rise of anthropogenic-induced global climate change. While new, cleaner, and renewable technologies have emerged as promising alternatives to the conventional energy system, the continued use of fossil fuel worldwide indicates a sustained pattern of environmental damage.

1.2.1 Climate Change

Global climate change refers to the warming of the world's atmosphere spurred by the anthropogenic emissions of greenhouse gases (GHG). Climate change is affecting the natural environment in a myriad of ways, most notably: increased surface temperatures, shifting weather patterns leading to the increased frequency and severity of storms, flooding, and droughts, as well as decreased snowpack, rising sea level due to melting glaciers and thermal expansion of the ocean, and ocean acidification due to increased absorption of CO_2 [11], [12].

In quantifying the relative contribution of GHG emissions by different anthropogenic sources, the Intergovernmental Panel on Climate Change (IPCC) has determined that energy-intensive activities, such as electricity and heat production, transportation, and industry, contribute greatest to GHG emissions worldwide (Figure 3) [11].

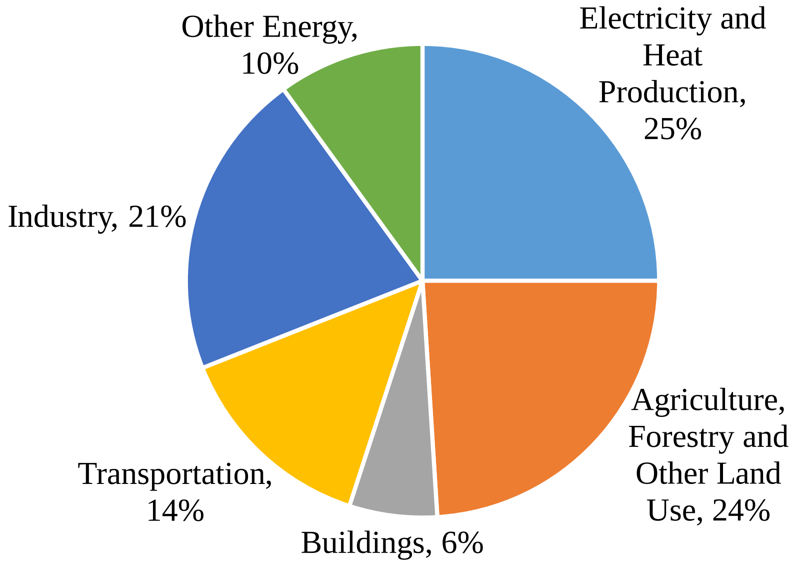


Figure 3. World GHG Emissions by Source [11]

In California, this trend holds (Figure 4) [13]. Not only do a majority of emissions come directly from electricity generation and transportation, but an additional 84% of emissions classified as industrial come from the extraction, processing, and on-site burning of fossil fuels, connected to the production of fuels for use in the electricity, transportation, residential, commercial, and agricultural sectors [14].

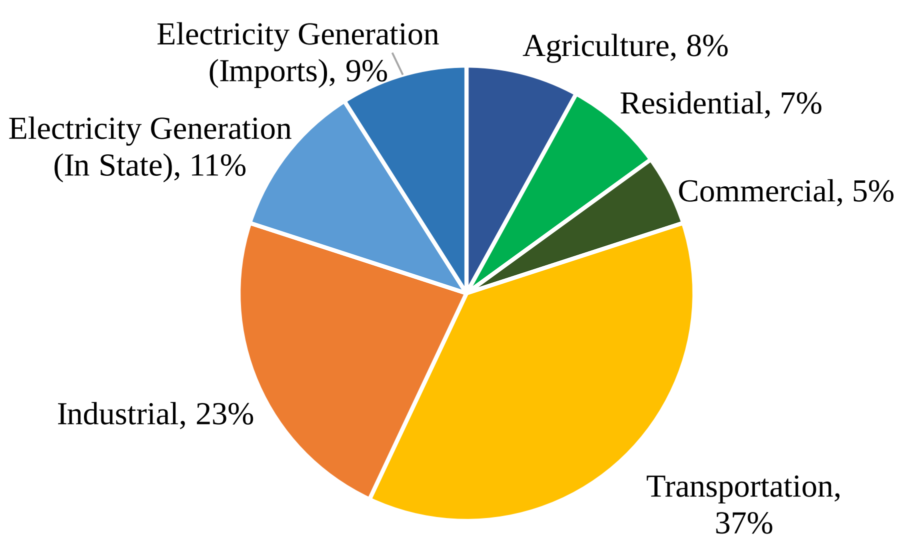


Figure 4. California GHG Emissions by Economic Sector, 2013 [13]

California mean temperatures are expected to rise over the next century, with an increase in extreme heat events in southern California [12]. Higher temperatures have been linked to increased demand for air conditioning and decreased power plant efficiencies, increasing electricity demand and potentially worsening GHG emissions [15].

In addition to higher temperatures, studies have predicted that California's snowpack in the Sierra Nevada will continue to decline due to decreased snowfall, as well as increased evaporation. Changing precipitation patterns will result in increased risk of flooding during the winter and decreased water availability in spring and summer [12], [16]. This will result in an overall decline in water reservoir levels, greatly reducing the state's hydropower capacity [15].

To successfully combat global climate change, it is crucial to address both electricity and transportation-related emissions given their dominant role in total emissions. In fact, achieving goals for deep de-carbonization will require near-zero GHG electricity generation and transportation [17]. Decreasing our reliance on conventional power plants and internal combustion engines can not only decrease our emissions directly related to those applications, but can also remove the emissions of upstream processes tied to fuel production. This can further decrease our total GHG emissions in order to help meet our sustainability goals. Also, given the uncertainty of water availability under climate change conditions, the energy sector's evolving reliance on water becomes an increasingly necessary consideration in order to meet sustainability targets without further exacerbating water stresses.

1.3 Sustainability Goals

Independently and as a whole, the world's nations have adopted a series of policies aimed at combating climate change by targeting the unsustainable reliance on fossil fuel energy.

California has set progressive targets to reduce its greenhouse gas (GHG) emissions. Successful strategy implementation at the state level can serve as a model for action nationally and internationally.

1.3.1 Overarching Goals

California Assembly Bill (AB) 32 outlines a suite of aggressive sustainability objectives for its resource sectors that will require creative and far-reaching changes. The bill commissions the California Air Resources Board (CARB) to implement a scoping plan to coordinate the reduction of annual statewide greenhouse gas (GHG) emissions to 1990 levels by 2020 [18]. Governor Brown's Executive Orders S-30-15 and S-3-05 further set a midterm target of emissions 40% below 1990 levels by 2030 and a final target of 80% below 1990 levels no later than 2050, respectively. The First Update to the Scoping Plan discusses that although there is a wide range of options available to achieve emissions reductions, reaching our goals will require, first and foremost, swift and decisive action to decarbonize the energy sector [17].

1.3.2 Electricity Generation Targets

The California Energy Commission (CEC) has determined that the achievement of a near zero GHG electricity grid cannot be accomplished by a single approach, rather it must be through the coordinated application of a suite of technologies and management strategies. The CEC has identified its preferred strategies to manage demand and meet California's energy sector climate change goals. This loading order is by preference: energy efficiency, demand response, renewables, and distributed generation [19]. Each of these strategies is supported through their own programs and initiatives. In particular, California has supported the large-scale deployment of renewable energy technologies as the preferred means of decarbonizing electricity generation through Renewable Portfolio Standard (RPS) mandates (SB 1058, SB 107, SB 2, SB 350), which have established targets for 25% renewables by 2016, 33% by 2020, and 50% by 2030.

As the level of renewables has increased, there has been growing concern that wind and solar power variability will threaten the reliability of our grid, that over-generation will force renewable curtailment, and that periods of under-generation will require a significant investment in new dispatchable, clean resources, such as energy storage, or an increased reliance on dispatchable but high-emitting natural gas power plants, or “peakers.” In addition, California recently experienced a setback in reaching GHG emission reduction goals, when San Onofre Nuclear Generating Station (SONGS), which had provided reliable baseload, zero emission electricity generation, was shutdown indefinitely. The SONGS closure also created grid reliability concerns, which have still not been fully resolved [20].

In order to address these key concerns, California is investing in alternative, complementary advanced technologies that can support renewable integration and low-emission generation. One key example is AB 2514, which mandates that California’s three investment-owned utilities (IOUs)—Southern California Edison, Pacific Gas and Electric, and San Diego Gas and Electric—procure 1.325 GW of energy storage capacity by 2020. This legislation focuses on reducing peak demand and the need for peaker plants, and provides an opportunity to gauge the long-term economic and technological viability of large-scale implementation of energy storage to support grid sustainability goals.

1.3.3 Transportation Targets

Governor Brown’s Executive Order B-16-12 mandates that California reduce its transportation emissions to 80% below 1990 levels, parallel to the target set for the state as a whole. California seeks to meet this reduction target through a multipronged approach involving: low carbon fuels, increased fuel efficiencies, zero-emission vehicles, and improved city infrastructure that decreases vehicle travel demand and increases access to cleaner, more efficient modes of transportation [17]. Specific improvements for LDVs have been at the forefront of regulations, given their dominant contribution to transportation emissions [17], [21].

Since 1990, California has implemented a series of Low Emission Vehicle (LEV) regulations focused on reducing emissions from LDVs [22]. To support low carbon fuels, California's Low Carbon Fuel Standard (LCFS) (re-adopted in 2015) is set to reduce the average carbon intensity of transportation fuels each year to reach a 10% decrease by 2020, equivalent to 88.62 g CO_2e/MJ for gasoline/gasoline substitutes [23]. To support the second strategy of increased fuel efficiency, California's Advanced Clean Cars regulations, coming into effect in 2017, will require that new LDVs reduce their GHG emissions (grams CO_2e) per mile by 4.5% each year until 2025 [First Update]. From 2025 to 2035, this percentage is increased to a 5% reduction per year under the LEV IV standard, resulting in a final emission standard of 100 g CO_2e/mi in 2035 (less than half that of today's new LDVs) [22].

In addition to improving fuel economy, the Advanced Clean Cars program revised previous Zero Emission Vehicle targets, now requiring automakers to scale up the sale of transitional zero emission vehicles (TZEVs), such as hybrid electric vehicles, and zero emission vehicles (ZEVs), such as fuel cell vehicles and plug-in electric vehicles, in order to support Governor Brown's target of 1.5 million zero emission vehicles (ZEVs) in California by 2025 (E.O. B-16-2012). This target is equivalent to 6.5% of the LDV fleet. However, the California Air Resources Board projects that 87% of the light-duty fleet will need to be ZEVs in order to meet the transportation sector's 2050 emissions reduction target (Figure 5) [24]. While no specific targets for battery electric vehicle (BEV) or fuel cell vehicle (FCV) adoption have been established beyond 2025, recent research (the State Alternative Fuels Plan) and legislation (SB 350) support further ZEV deployment, going on to state that meeting our state-level emission reduction goals for 2030 and 2050 will require "widespread" electrification of our transportation sector [21].

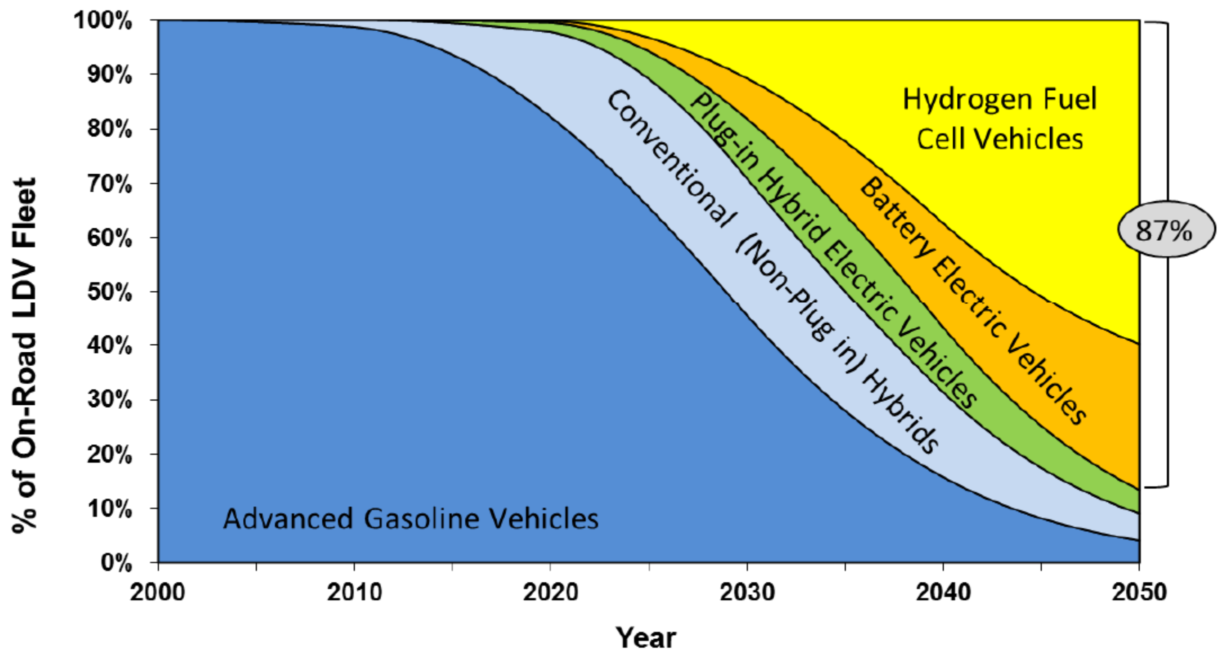


Figure 5. Proposed LDV Fleet Transition to ZEVs, California Air Resources Board [24]

1.3.4 Advantages of an Integrated Approach

The sustainability goals introduced in AB 32 must be met across all sectors; therefore, the strategies adopted in one sector must be evaluated for their impacts on other sectors to ensure the mutual advancement of state-level objectives. As the First Update to the Scoping Plan acknowledges, strategies applied across the electricity and transportation sectors will increasingly affect one another, given the future deployment of plug-in electric vehicles (PEVs).

While charging PEVs adds a new load to the electric grid, the intelligent charging of PEVs could provide an opportunity to coordinate EV load with the availability of renewable generation in order to better manage renewable variability. Allowing PEVs to provide this grid service may offset the need for SES. Full evaluation of the potential impacts of SES and PEVs in meeting sustainability targets requires an integrated and holistic simulation of all interactions and feedback mechanisms of the grid.

The purpose of this research is to examine the role of energy storage in reducing grid GHG emissions, quantify the appropriate scale of stationary energy storage to support renewable integration at increasing levels of renewables, understand the impact of the electrification of light-duty transportation on energy storage requirements, and identify areas where renewable deployment can put undue stress on water resources. This analysis uses the California electric grid as an example system to demonstrate the importance of considering co-dependencies between interrelated sectors when evaluating strategies to meet holistic sustainability goals.

1.4 Goal

The goal of this thesis is to:

> Critically assess the roles of stationary energy storage (SES) and plug-in vehicle storage in stabilizing the grid dynamics associated with a high penetration of solar and wind renewable generation in the context of meeting air and water sustainability goals.

1.5 Objectives

To address this goal, the following research objectives will be achieved:

1. Garner data from previous studies and establish a foundation for use of HiGRID related to energy storage and water demands of renewable energy deployment.
2. Develop and compare the scenarios of SES deployment with and without scaled electric vehicle deployment.

3. Compare California concentrated solar power (CSP) potential with regional availability of water to evaluate whether water availability is a limiting factor for CSP deployment in high renewable potential areas.
4. Capture data from the projected renewable energy mix to determine if the GHG emission reduction goals set in AB 32 are realistic with that mix, or whether new strategies would need to be investigated.

2.0 Background

2.1 Reducing Grid GHG Emissions

Numerous strategies have been proposed to help reduce grid GHG emissions, encompassing both demand and generation-side changes. Demand-side strategies, such as energy efficiency and demand response, focus on reducing and/or shifting electric load to decrease the need for carbon-intensive electricity generation resources [25]. Generation-side strategies, on the other hand, such as low carbon fuels and renewable energy deployment, focus on reducing the overall carbon-intensity of electricity generation [17]. The following is an overview of the leading generation-side technologies that show potential in reducing grid GHG emissions.

2.1.1 Renewable Energy Technologies

Renewable energy technologies—solar, wind, geothermal, small hydro, etc.—are all promising sources of zero GHG emission electricity. Geothermal and small hydropower plants can provide reliable baseload power; however, these resources are site-limited and difficult to permit. They, therefore, do not have the scalability of other renewable technologies [25], [26]. Solar and wind, as the most widely available renewable resources, show the greatest potential for providing renewable electricity, despite the significant challenges in the deployment and management of technologies that harness these resources [27].

Firstly, solar and wind power have relatively low capacity factors, 20-25% [28] and 20-40% [29], respectively, which means greater installed capacity is required to achieve the same annual electricity generation compared to conventional power plants. This higher power capacity for equivalent energy generation is compounded by large area requirements, leading to high development costs that initially hindered renewable technology growth [30]. However, advancements in materials and design as well as cost reductions associated with economies of scales have since lowered barriers for adoption.

A continued issue of concern is that wind and solar generated power varies, causing electricity power output fluctuations as the availability of wind and solar changes throughout the day, independent of changes in electric load demand. Solar availability varies by location, but follows distinct diurnal and seasonal patterns (Figure 6) [31]. Daily solar power output increases and decreases in response to the rising and setting of the sun. Wind power availability varies regionally, based on topography and climate [29]. Wind patterns can fluctuate greatly between days, driven by shifting weather conditions (Figure 7) [32].

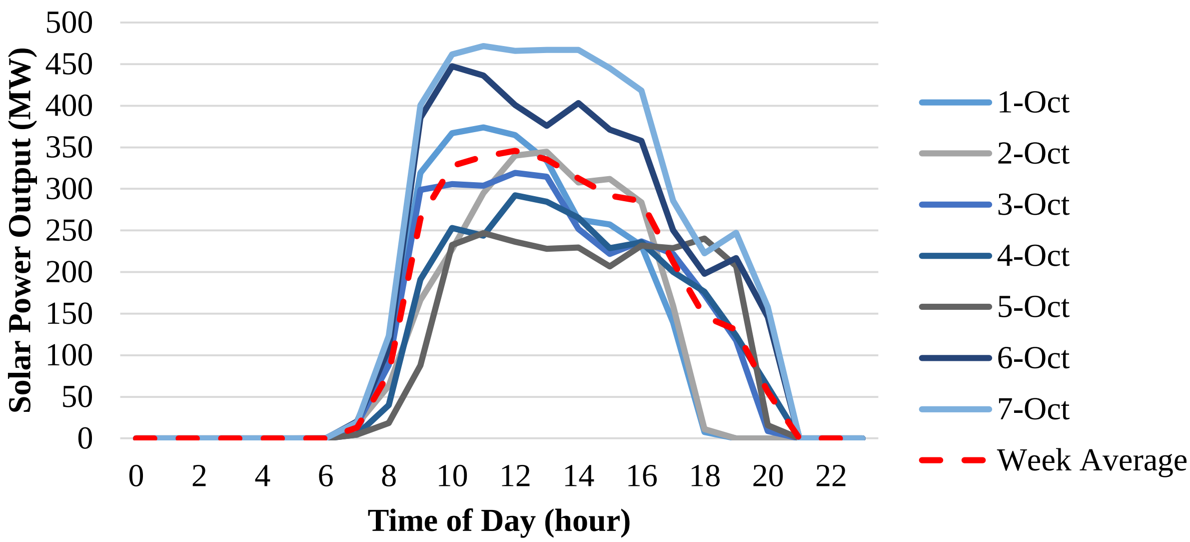


Figure 6. Hourly California Solar Power Output for a Week in October, 2011 [31]

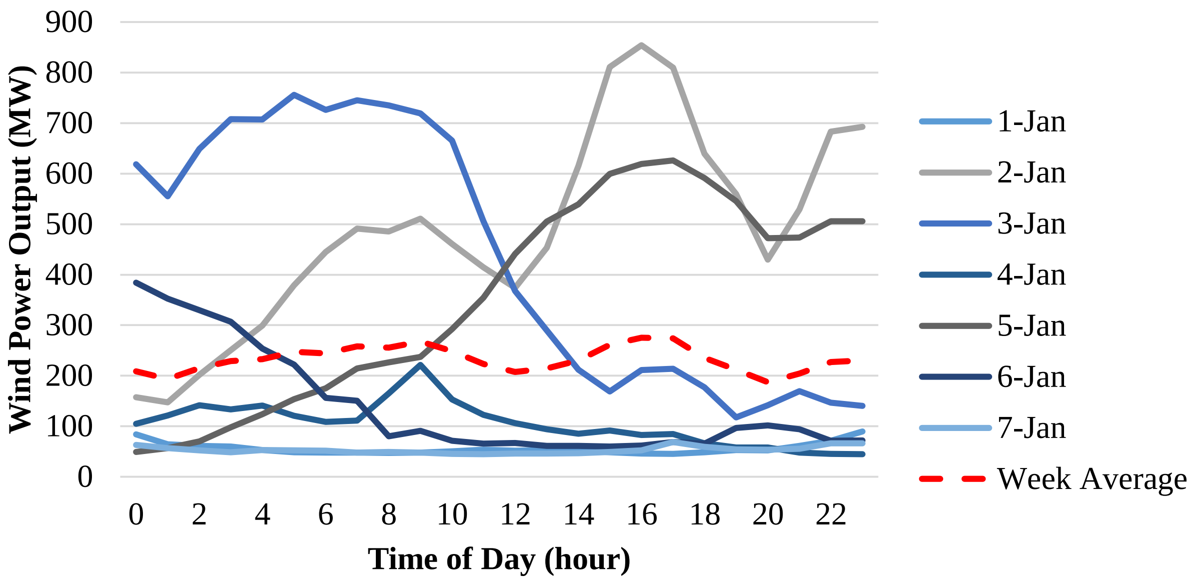


Figure 7. Hourly California Wind Power Output for a Week in January, 2009 [32]

This variability requires greater dynamic management of supply to the grid than was necessary when relying primarily on fossil fuel power plants. Interconnecting multiple distributed wind and solar farms helps smooth variability, and wind and solar forecasting allow for pre-scheduling of other resources to compensate for fluctuations in renewable power [33]. Other power plants are signaled to turn on, ramp up, ramp down, and turn off in order to balance the electric load; however, operating power plants at lower power levels can result in lower efficiencies and subsequently higher emissions, partially offsetting gains made by renewable integration [34]. Also, if renewables serve more than a third of the electricity load in a given period, this approach becomes more difficult to implement [33], [35].

2.1.2 Stationary Fuel Cells

California has supported a number of distributed generation (DG) technologies as a part of its “loading order” as discussed in Section 1.3.2. Stationary fuel cells have several advantages over competing DG technologies. Firstly, they produce low GHG emissions compared to other

DG, have high efficiencies (eg. solid oxide fuel cells have efficiencies greater than 50%), and provide baseload power with greater than 95% capacity factor [36]. Fuel cells that operate as combined heat and power (CHP) can achieve even higher combined thermal efficiencies of 85-90 percent [15], [36]–[38]. While most fuel cells run on natural gas, they have a flexible fuel requirements, meaning that they can be run on alternatives fuels such as biogas and renewable hydrogen, which can further reduce electricity emissions [39]. Fuel cells can be placed in urban areas, adjacent to high load demand locations without taking up significant space, producing discernable noise pollution, or being visually invasive [37], [38]. The fuel cell stack design allows for flexible power capacity ranging from kWs to 10s of MWs that can be scaled to match local load demands. Prime locations are places that have high electricity and heating loads, so that CHP can be utilized, such as hospitals and shopping centers, as well as places that can produce biogas, such as wastewater treatment plants (WWTP), landfills, and farms [36].

Fuel cell groupings, ranging from 10 to 100 MW, can be placed at grid substations to provide reliable generation with high control at key points in the distribution network. This type of fuel cell deployment is termed Transmission Integrated Grid Energy Resource (TIGER) stations [40]. Previous studies examining fuel cells in distribution networks found that these TIGER stations could alleviate reliability issues [40], [41], reduce overall grid GHG emissions, and improve air quality [42], [43]. While stationary fuel cells have traditionally been run in baseload "steady-state" operation, experimental and modeling research have demonstrated the effective dynamic performance of fuel cells [44], [45]. Operating TIGER stations with this increased power output flexibility can potentially further GHG reduction goals by increasing renewable integration and decreasing the reliance on other dynamic resources with higher carbon-footprints [40].

2.1.3 Energy Storage Technologies

Energy storage technologies are a diverse group of technologies that vary in terms of energy type, size, and function (Figure 8) [46], but are categorized by their ability to store and discharge energy on command. Types include mechanical (pumped hydro), electromagnetic (capacitors), electrochemical (flow batteries), electrical (li-ion batteries), chemical (hydrogen), and thermal (molten salt) [47]. Energy storage power capacity can range from kilowatts to gigawatts. Some energy storage technologies have specific power-to-energy ratios dictated by energy density and size, while others can be rated independently for power and energy. Therefore, maximum energy discharge times can range from minutes to days.

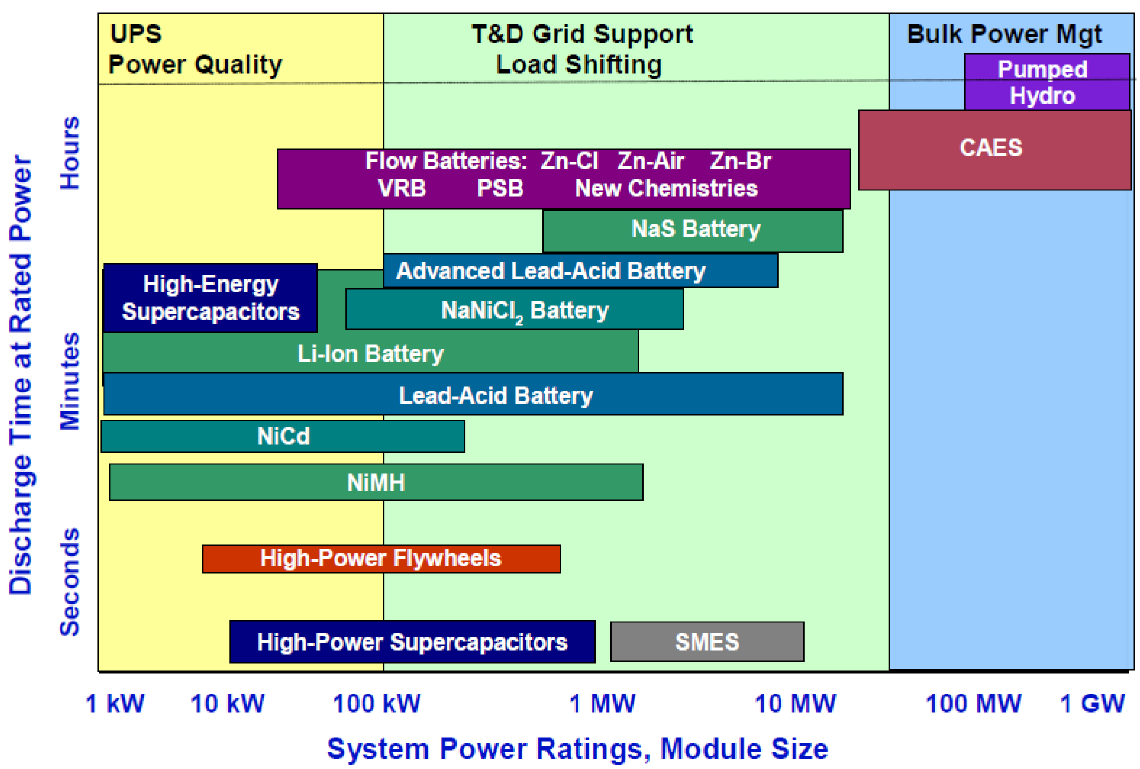


Figure 8. Energy Storage Technologies by Power Capacity and Discharge Time [46]

Energy storage can perform many grid services, including frequency regulation, power quality support, ramping assistance, peak shaving, load shifting, renewable integration, and reserve capacity. If charged with zero emission resources, energy storage can provide these benefits without increasing grid emissions [48]–[50]. The grid functions a given energy storage technology can perform depends on its power rating, energy capacity, and discharge time, as well as whether the storage is applied in front of or behind the meter (Figure 9) [50], [51]. Energy storage installed behind the meter is controlled by an end user or DG provider and can maintain power quality as well as regulate variable power sources such as renewable energy generation. These benefits are indirectly observable by the grid operator as improved power reliability [50]. Conversely, front of the meter energy storage capacity installed at generation, transmission, and distribution networks can be directly regulated by the grid operator and therefore allow for greater functional control [52].

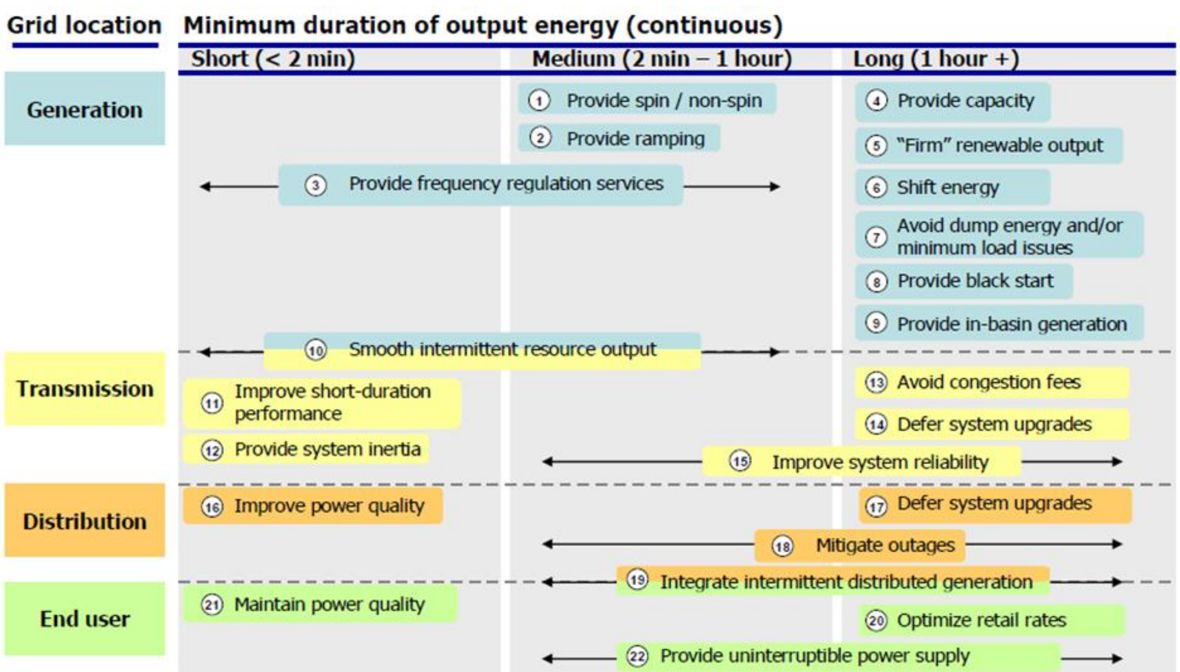


Figure 9. Potential Energy Storage Functions Based on Dispatch Times [50]

Most energy storage technologies have experienced limited deployment due to grid market constraints and high costs [51]. Of the portfolio of energy storage technologies available, pumped hydro has been most widely deployed with a worldwide capacity greater than 145 GW, followed distantly by compressed air energy storage (CAES) and batteries [53]. Like pumped hydro, compressed air energy storage (CAES) and flow batteries can have independent scaling of their power and energy capacity providing flexibility to size their capacity to match the needs of the electric grid system [54], [55]. Present understanding of potential energy storage benefits comes from existing projects (about 99% of these studies involve pumped hydro) [47], [56] as well as modeling studies [35], [48], [57], [58].

As installed renewable capacity has increased, interest in energy storage to support renewable integration has also increased. Energy storage technologies have the potential to utilized renewable energy during periods when this generation would otherwise be curtailed. They can discharge this captured energy to balance the net load when renewable generation is low or non-existent. This leads to higher renewable energy integration and partially offsets conventional power generation [48], [59]. The appropriate power-energy capacity of energy storage to provide these functions is, as of yet, uncertain, because the scale of energy storage required is dependent on the shape of the load demand and generation profiles, as well as the size of the grid system in question [35], [60].

2.2 Achieving High Renewable Utilization

The grid has always had to manage the temporal fluctuations of electricity demand. Previously, the balance of load has been achieved by calling on reliable generation resources whose power output could be scheduled [33], [61]. At low renewable penetrations, grid operators have been able to manage the variability of solar and wind, as discussed in Section 2.1.1. However, as the portion of electricity coming from renewable resources grows, issues surrounding the misalignment of renewable generation and electricity demand will become more severe, requiring new grid management strategies.

At a high penetration of solar and wind, temporal fluctuations in electricity generation may outstrip the capacity of existing power plants to ramp up and down effectively [35]. For high solar penetration, the diurnal ramping requirements—the ramping down of other power plants in the morning and the ramping up in the late afternoon—pose a significant challenge. The sharp drop in solar availability in the afternoon is compounded by the simultaneous spike in electricity demand associated with people returning home for the evening. In California, ramp rates associated with this phenomenon are expected to reach above 4,000 MW/hr by 2020 (Figure 10) [62], [63].

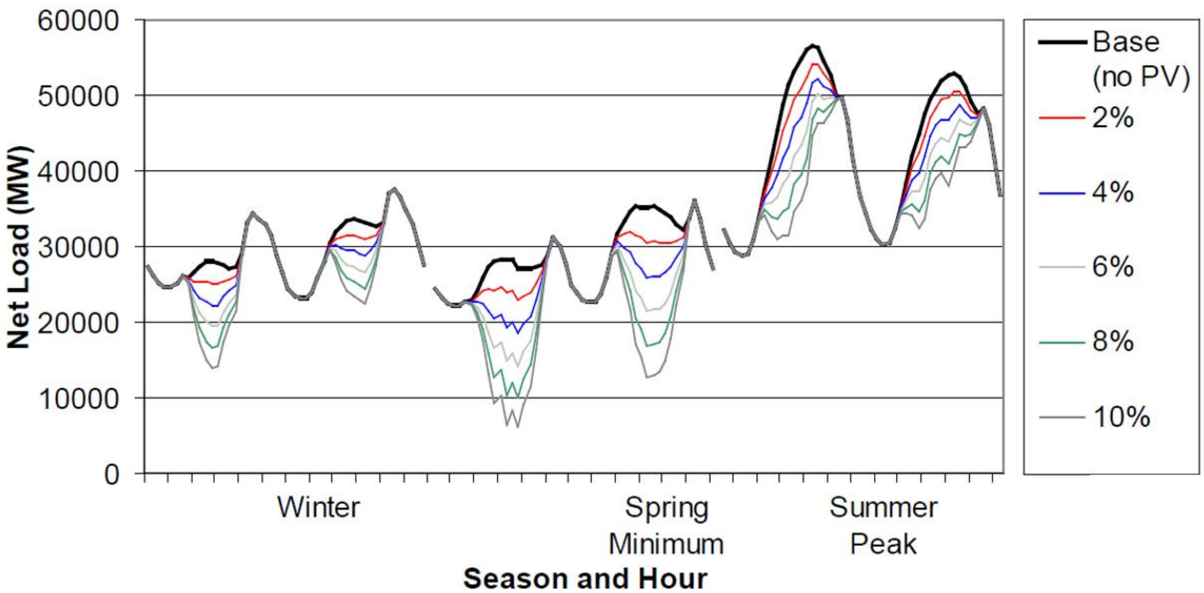


Figure 10. California Net Load for Increasing Solar PV Penetration [63]

Wind power output patterns tend to be less severe than solar, with large fluctuations occurring less frequently and at a slower rate of change that is still significant. For example, the average ramp rate (MW/h) associated with wind power in Texas is about 2.5% of wind power capacity.

For a power capacity of 9 GW, that equates to an average ramp rate of 220 MW/hr with extremes of about ±400 MW/h [64]. The combined impact of wind and solar power variability with demand fluctuations can create more severe changes in net load than grid operators have previously encountered, requiring new management strategies and grid infrastructure to support [29], [62].

In addition to ramping concerns, the misalignment of generation versus demand means that there will be periods when renewable generation exceeds demand and times when it drops below demand (Figure 11) [31]. When renewable electricity generation exceeds demand, steps must be taken to lower generation and/or increase demand in order to maintain balance. Conversely, when generation of renewables is insufficient to meet demand, demand must be decreased or other grid resources must be turned on. Whereas load following, combined cycle plants can ramp up and down to help balance the grid load at low renewable penetration, the ability of these plants to respond becomes limiting at high renewable levels due to physical, regulatory, and market constraints [33], [35]. Additional strategies already in effect to address ramping include: renewable generation curtailment, turning on/off simple cycle peaker plants, and importing/exporting electricity [30]. Some grids rely on curtailment (eg. China) [65], while others export (eg. Denmark) [66] or store the energy either with SES or as hydrogen fuel for later use (eg. Germany) [41]. Renewable curtailment and reliance on high emitting peakers undermines renewable and GHG reduction targets; therefore, other strategies need to be explored in order to overcome renewable variability and ensure that enough renewable electricity generation coincides with electric demand to achieve high target renewable penetration.

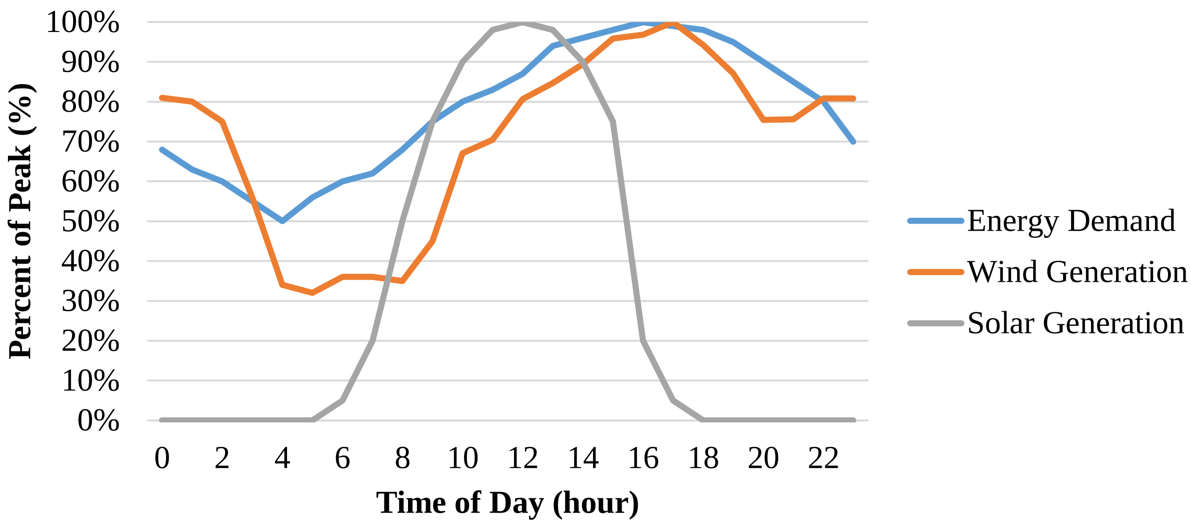


Figure 11. Misalignment of Renewable Generation and Electricity Demand [31]

Most studies exploring solutions for achieving high renewable levels consider the combined dynamic control of supply and demand—tuning flexible loads and relying on dispatchable generation resources to balance renewable generation [35], [61], [67]–[69]. Key strategies include load shifting, which could help resolve the mismatch of renewable generation and electricity demand by scheduling flexible loads to coincide with predicted renewable availability. Rescheduling load can either be done through direct communication between the grid operator and the end user, or through time of use (TOU) tariffs, which refers to a tiered cost structure that charges more for electricity consumption during peak demand periods. A complementary strategy is shifting renewable supply by capturing excess renewable generation (using energy storage) to be discharged during low renewable availability [33]. A summary of proposed strategies are in Table 1 ([25], [28], [30], [39], [70]).

One study of the Texas grid by Denholm and Hand (2011) [35] explored the simultaneous deployment of multiple strategies—load shifting, baseload power removal, and energy storage—to achieve high renewable integration (up to 80%). They were able to achieve their target renewable penetration with moderate curtailment (>10%), when they deployed energy storage capacity with a maximum discharge time of four hours. The leading cause of curtailment was the misalignment of demand and renewable generation. They found that increasing energy storage capacity above this level could recover additional curtailment, but with diminishing returns, such that it required a capacity equivalent to a day of electricity demand to decrease curtailment below 10%.

Table 1. Supply and Demand Strategies to Manage the Grid Load Profile

Market Controls	**Physical Controls**	**Heating & Cooling**	**Buildings & Appliances**
Time of use (TOU) charges	Load shifting	Smart controls	Conservation
Demand charges	Demand curtailment (eg. peak shaving)	Segmented control	Improved efficiency
Tiered energy pricing	Smart controls (grid scale)	Combined heat and power	Smart controls
Incentives	Spinning reserve: frequency and power quality control	Thermal storage and absorption chillers	Dynamic feedback systems
Discounts Tariffs/Taxes	Self-generation/ Distributed generation	Solar heating/ PV hybrid	Occupancy sensors
	Intelligent charging (smart, Vehicle-to-Grid (V2G))	Passive heating and cooling	LED lighting
	Energy storage technologies		Phone apps to monitor and control systems
			Address standby power demand

While some studies [33], [35] found that decreasing baseload power increases the flexibility of the grid to allow for greater renewable integration, this strategy may only reduce emissions as long as the power sources removed are carbon-intensive. For the case of California, where in-state coal-fueled electricity generation is all but gone, the removal of baseload power would imply removing nuclear and hydropower plants, which are already zero GHG emission resources. Removal of these resources then becomes a trade-off between established zero emission, baseload generation and new renewable installations with their dynamic behavior. The net impact of baseload removal on grid GHG emissions and reserve capacity requirements may depend on the grid system in question.

While the combination and scale of appropriate measures may vary across grid systems, some basic principles hold:

1. Resources that are able to dynamically respond are key given the fast rate at which solar and wind power can fluctuate.
2. Energy shifting technologies are crucial in providing renewable power to non-flexible loads that do not correspond with renewable generation peaks.
3. Implementing both supply and demand-side controls can maximize the flexibility of the grid to respond to changes.
4. No single technology can meet all the requirements necessary for a balanced grid with high renewable penetration, rather multiple strategies must be employed to support renewable integration and GHG reduction targets [40], [48], [71].
5. New strategies and potential synergisms are bound to emerge as research in this area matures. For example, researchers have begun to investigate the potential role of plug-in electric vehicles to utilize excess renewable energy simultaneously increasing renewable integration and decreasing transportation emissions.

2.3 Electrification of the Transportation Sector

The electrification of transportation is being pursued as a preferred measure to reduce GHG emissions from vehicles. Light-duty vehicles (LDV)—cars, vans, SUVs, and pick-up trucks—

have been the focus of these efforts, given their dominant contribution to transportation emissions [17]. Depending on the advancement of other transportation technologies, principally fuel cell vehicles, and the success of energy efficiency as well as other electricity reduction measures, between 3 million and 36 million PEVs will be required to meet California's 2050 emission reduction goals [72]. However, so far, 159,000 PEVs have been sold in California since 2011, making up roughly 1% of California's light-duty fleet [9]. This low penetration level provides limited insight into how widespread adoption of PEVs will affect state-level grid dynamics, although local impacts on distribution networks have been observed [10]. The rapid, widespread adoption of PEVs requires better understanding of how mass PEV charging will affect electricity demand and renewable integration.

2.3.1 Travel Patterns, Charging Infrastructure, and Charging Intelligence

The 2009 National Household Travel Survey (NHTS) [73] documented U.S. LDV travel patterns, providing a detailed account of driver behavior that can be applied to PEV deployment scenarios. While the behavior of individual drivers varies, there are distinct daily trends in vehicle travel. A majority of VMT occur during the day as people commute to and from work, run errands, and socialize (Figure 12) [74]. The average trip length is under 10 miles, with the average driver traveling about 29 miles per day [73]. Cars spend the majority of their time not in use, dwelling at home (75% of idle time), at work (14%), or at other locations (eg. shopping centers) (11%) [75]. Home and work have the longest dwell times, at an average of 11 and 6 hours, respectively. The next longest average dwell time is at school and church at about 4 hours. Almost all other locations see dwell times less than 2 hours.

PEVs have a limited travel range, much shorter than conventional LDVs. VMT per full charge varies by model, with around 60-90 mi/charge being standard to the outlier of 286 mi/charge for the Tesla Model S [76]. This range is acceptable for a majority of trips and exceeds the average distance travelled in a day [73], [75]. Longer trips would require switching to a different vehicle type with a longer range or charging during the trip [77].

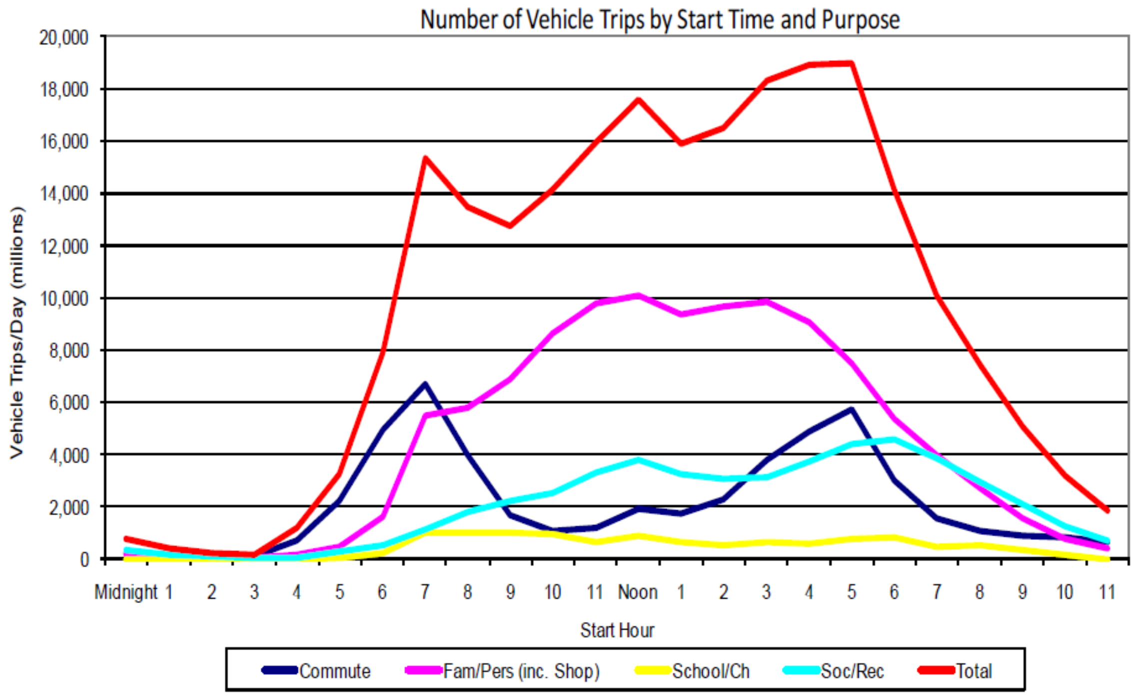


Figure 12. Time Distribution of VMT by Trip Purpose, U.S. 2009 (NHTS) [74]

There are three types of electric vehicle supply equipment (EVSE) for charging, categorized by their rated power output: Level 1, Level 2, and DC Fast Charging. Level 1 (L1) is rated for 120 V, which matches residential outlets. Charging at 1.44 kW, L1 corresponds to 2-5 mi per hour of charging. Level 2 (L2) has higher voltages, 240/208V (6.6 to 19.2 kW), and an hour of charging provides 10-20 miles worth of energy. L2 EVSE can be installed at residential and commercial buildings. Whereas L1 and L2 EVSE charge using alternating current (AC), DC fast chargers provide direct current, allowing for higher charging rates up to 70 miles per 20 minutes of charging. DC fast charging stations are being installed along major highways to provide quick charging for long trips. Time to a full charge depends on the battery's state-of-charge (SOC) (how full the battery is at plug-in), the rated power input to the PEV, and charging intelligence.

Charging intelligence is classified by the level of communication between the grid and the vehicle. There are currently multiple strategies to manage electric load imposed by electric vehicle charging. The types evaluated in this study are as follows:

Immediate Charging. Immediate Charging refers to full power charging at time of plug-in until full capacity reached or car unplugged, whichever comes first.

Smart Charging. Smart charging refers to coordinated charging, where drivers provide information on their travel schedule and charging demand to the electric grid operator. Vehicle charging is optimized based on cost (TOU rates), grid support needs, travel considerations, and vehicle constraints.

V2G Charging. Vehicle to grid (V2G) charging incorporates the functionality of smart charging with the added ability to discharge to the grid. Travel patterns and vehicle constraints still apply.

Preliminary data on PEV charging behavior has provided an opportunity to evaluate different intelligent charging strategies. Currently, almost all public and private charging in the U.S. is immediate, with many drivers taking into account time-of-use (TOU) rates at home (PG&E, SCE, SDGE TOU Tariffs). Switching from immediate charging to a TOU rate structure can reduce peak load [78]; however, this type of charging signal is not dynamic enough to manage near-real time grid fluctuations. Instead, full smart charging provides an improved communication network that can not only decrease peak load demand, but also better integrate variable renewable generation [79], [80]. There are select pilot projects for smart and vehicle-to-grid (V2G) charging [8], [81], [82]. V2G charging incorporates smart charging vehicle-grid communication and adds the grid service of allowing vehicles to discharge back to the grid. Preliminary results from these studies have found significant opportunities to utilize PEVs for grid management and renewable integration. For example, when vehicles are charged at home, average dwell times far exceed the few hours required for reaching a full charge (Figure 13). Under this scenario, delaying and/or coordinating charging with grid fluctuations has little to no impact on the vehicle owner, but can have significant impacts to the grid [10].

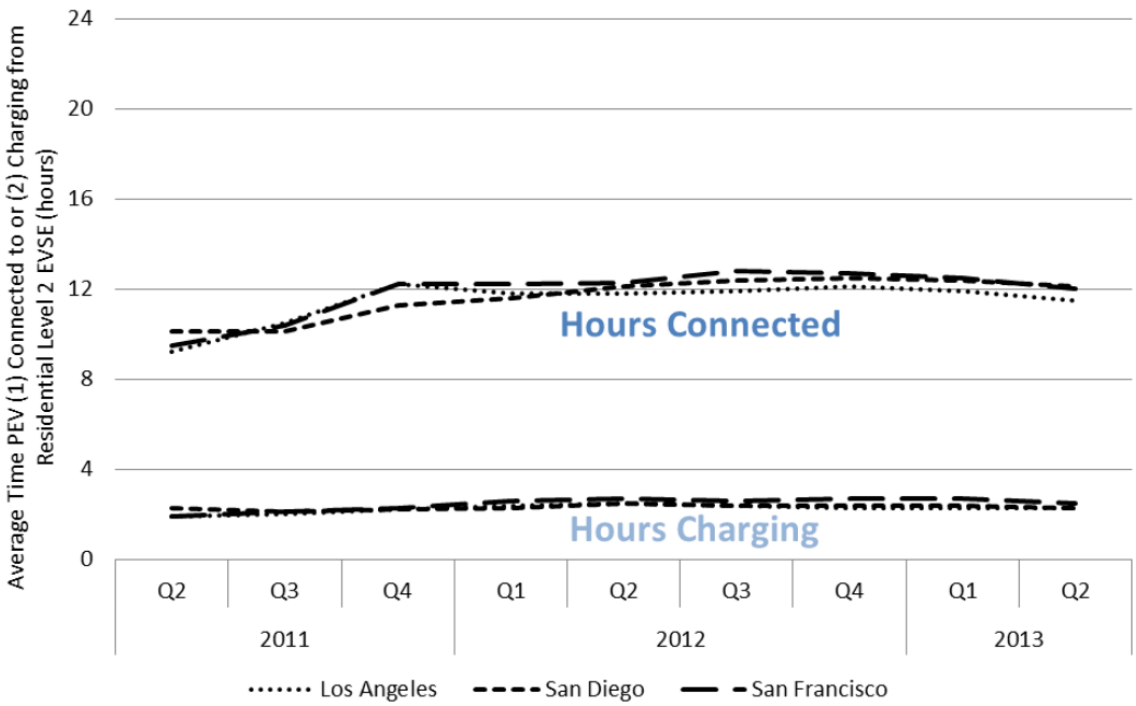


Figure 13. California PEV at Home Charging Patterns [10]

Using LDV travel statistics as well as PEV and EVSE characteristics, California is currently developing the appropriate infrastructure to support widespread deployment of PEVs. Work is also in progress for the development of charging standards and the communication infrastructure required to coordinate intelligent charging (and discharging for V2G). PEV charging standards and permitting protocols are evolving as public utilities and government agencies work to install EVSE at homes, businesses, and public spaces, such as shopping centers and parks [78], [83]. The key strategy is to place EVSE at high-use destinations that have high dwelling times (primarily work and home), in order to maximize charging availability and facilitate PEV adoption.

2.3.2 Impacts on Electricity Demand and Grid Services

The impact of widespread PEV deployment on the grid has previously been assessed by modeling studies [59], [75], [84]–[86], case studies, and pilot projects [78], [81], [85]. The electrification of the LDV fleet is expected to increase electricity demand and change the demand profile [84]. Total electric load demand increases proportional to the PEV fleet size. Changes to the shape of the demand profile depends on travel patterns, EVSE level and location, as well as charging intelligence. Researchers looking at California and Germany, where travel patterns are similar to the U.S., found that PEV deployment not only increases electricity demand, but relying on immediate charging of vehicles leads to increased demand fluctuations, because peak EV charging times corresponded to peak stationary load demand [59], [79]. As detailed in Figure 14, an analysis examining the impact of charging PEVs using immediate charging in Germany shows that increasing the size of the PEV fleet charging on the grid increases the scale and rate at which generation must compensate for changes in electricity demand [59]. With 42 million PEV fleet, the grid must now support a much higher peak demand and must ramp up more severely to follow the load, increasing output by 40 GW over the course of a few hours.

A higher electric load is counter-productive to meeting renewable targets, since it increases the amount of renewable capacity required to meet the target percentage of total demand. Increased peak demand further exacerbates ramping problems associated with high renewable utilization. However, managed charging can provide an opportunity to mitigate these impacts and employ PEVs for grid services.

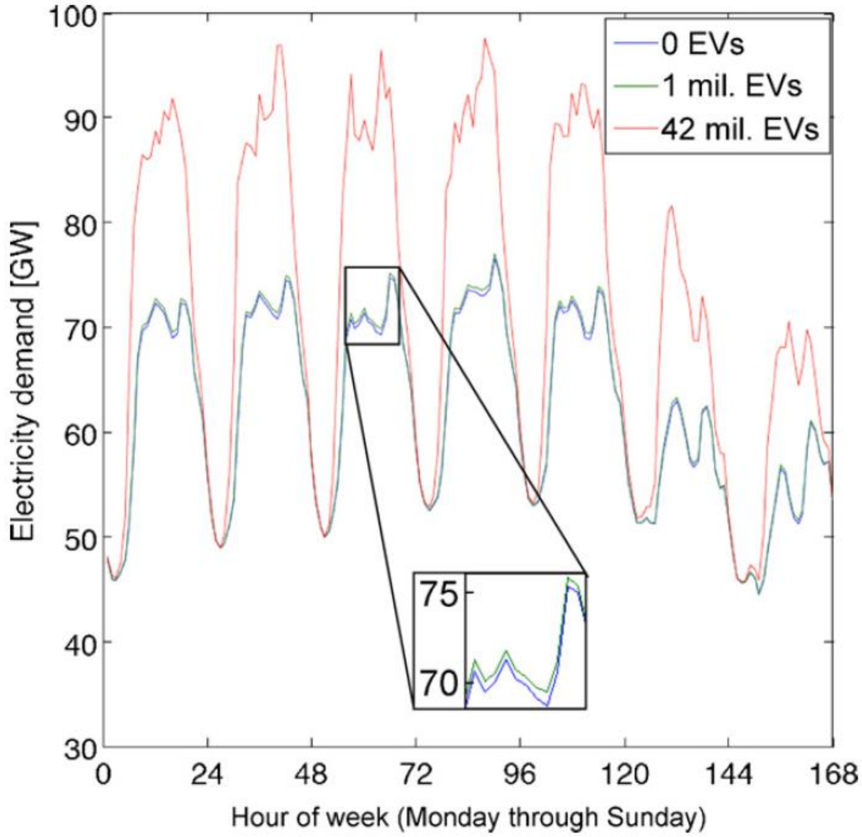


Figure 14. Impact of PEV deployment on Load Profile, mil EV = million electric vehicles [59]*

*Reprinted from Journal of Power Sources, vol. 196 no. 4, N. Hartmann and E. D. Özdemir, "Impact of Different Utilization Scenarios of Electric Vehicles on the German Grid in 2030," pp. 2311–2318 © 2011, with permission from Elsevier.

Management of PEVs on the grid can provide support services, such load shifting, peak shaving, frequency regulation, power quality support, ancillary services, and renewable integration. The degree to which PEV batteries can provide these services is limited by fleet characteristics, fleet size, travel patterns [84], [86], charging infrastructure [75], and charging intelligence [59], [85]. While studies have found that medium to high penetration of PEVs (> 1 million vehicles) is required to provide some grid services at the state/national level [66], [79], [87]; at a low penetration of PEVs, services can still be provided at the micro-grid scale

[80].These services are contingent on the high availability of EVSE, as grid support can only be provided when the vehicles are connected.

One grid service, increased renewable integration, has become a key area of research. Studies have found that smart and V2G charging allow for planned charging based on load and TOU market signals. This strategy can, therefore, be applied to improve renewable integration by optimizing the timing and intensity of vehicle charging to maximize capture of otherwise curtailed renewable energy [66], [79], [87]. Although intelligent charging of PEVs compared to immediate charging allows for better alignment of demand with renewable generation, the degree to which PEV load profiles align with renewable generation depends on the charging strategy (smart or vehicle to grid, “V2G”) and charging locations (at home, work, and/or public spaces) [59]. Studies examining PEV utilization of renewable generation [66], [79], [88] found that PEVs increase renewable utilization through peak shaving and load shifting functions at medium to high deployment of PEVs under smart and vehicle to grid (V2G) charging strategies. V2G has demonstrated improved functionality over smart charging by allowing for added benefit of flexible discharging back to the grid [59], [80]. The impact of V2G on battery degradation and driver behavior is, as of yet, unclear, although preliminary research suggests that V2G operations may decrease the useful lifetime of the PEV battery [89]. These considerations may affect to what degree smart or V2G charging is adopted as a strategy.

2.4 Combining Stationary Energy Storage and Plug-in Electric Vehicles

The implications of the widespread adoption of PEVs are not well understood in terms of the impact on SES requirements [72]. PEV deployment creates an alternative grid resource to SES, as the PEV batteries may be able to provide similar grid services such as renewable integration.

Successfully coordination of PEV charging with renewable availability could reduce or even fully remove the need for SES capacity.

In evaluating the potential role of PEVs versus SES, it is first important to acknowledge the overlapping roles and inherent trade-offs between these two types of technologies. While both have been shown to increase renewable utilization, reduce GHG emissions, and provide other grid services such as load shifting and power quality control, PEVs are more efficient, leading to lower round trip efficiency losses and greater renewable utilization per capacity installed. On the other hand, SES has fewer charging/discharging restrictions, compared to PEVs whose primary purpose is transportation, leading to better balancing of power on the grid [90]. PEVs also have more limited dispatch times than some SES technologies, with maximum dispatch times in the day range [79], [91]. Therefore, SES may be better suited if load shifting is required across multi-day periods.

Of the studies exploring the dual adoption of PEVs and SES, none has analyzed how the charging intelligence of PEVs can affect the capacity of SES required to reach high renewable levels. A few studies [67], [90], [91] discuss the potential role of PEVs to decrease the reliance on SES to achieve high renewable integration. By charging during periods when renewable generation would otherwise be in excess, intelligent PEVs reduce the amount of renewable energy that needs to be shifted by SES to meet electric load demands and reach a target renewable level. Going further, Tarroja et al 2016 [90] found that smart charging of the PEV fleet required half the number of vehicles to reach a target renewable level compared to immediate charging. This finding suggests that charging intelligence decreases the overall storage capacity (mobile or stationary) required to reach high renewable levels.

The dual availability of PEVs and SES has the potential for applying PEVs for short-duration grid services, while allowing for SES to provide longer duration services, combining the advantages of both technologies while minimizing the capacity requirements of expensive large-scale energy storage installations. Jacobson and Delucchi (2011) [67] suggest that instead of relying solely on PEVs, the addition of a diverse portfolio of SES technologies and an oversized renewable generation capacity to feed hydrogen production to power fuel cell vehicles would strengthen the resiliency and sustainability of the electricity and transportation sectors. (The exact scale of SES required is not discussed.) This approach is supported by the California Air Resources Board in its Scoping Plan for AB 32. A diverse portfolio of resources creates a more secure and stable energy sector and allows for the market and consumer preference to be deciding factors in which emerging technologies play a dominant role in the future transportation and electric grid systems.

2.5 Water Resource Availability

Previous studies exploring the water-energy nexus have highlighted the interdependency of water and energy systems, particularly the energy requirements for transporting and transforming water resources [92] and the water requirements to support fuel extraction, processing, and transport, as well as power plant operations [93]. With the uncertain future of water availability under climate change conditions, energy production's evolving water demand becomes an increasingly necessary consideration in evaluating renewable energy potential and future pumped hydro capacity. While power generation capacity is realized at the state level, each energy technology has its own operational water requirements that will need to be met regionally [94]. Locating renewable technologies to optimize power output can lead to a disproportionate stress on local water resources, incongruent with water sustainability objectives [95]. Also, while pumped hydro may provide cost competitive, relatively low impact energy storage, potential capacity may fall short of future demand.

2.5.1 Renewable Energy Operational Water Demands

Operational water demands vary by technology, with most renewable technologies have low water requirements, especially compared to conventional power plants (Figure 15) [94]. One of the important exceptions to this trend is concentrated solar power, “CSP”. CSP refers to a suite of technologies that rely on mirrors to concentrate solar radiation to heat a working fluid that is then used to power a Rankine cycle (or Stirling cycle in the case of parabolic dish reflectors) to produce electricity. The types of CSP technologies that use Rankine cycles—parabolic troughs, linear Fresnel, and power towers with heliostat collectors—typically have high water consumption rates, at approximately 900 gallons per MWh [94]. Water “consumption” refers to the amount of water used during electricity production that is evaporated/rejected into the environment and therefore is not returned back to where it was withdrawn [96]. An overwhelming majority of the water consumed by CSP operations is used for cooling, with a small amount used for cleaning. (For the case of parabolic dish/Stirling design, the system is air cooled and water is only used for cleaning.) The exact amount of water consumed per MWh is dependent on plant design and cooling method. There are several cooling system designs commonly used for power generators: once-through cooling, recirculating cooling, cooling ponds, dry cooling, and hybrid cooling [94]. Most CSP plants in operation rely on recirculating cooling [97].

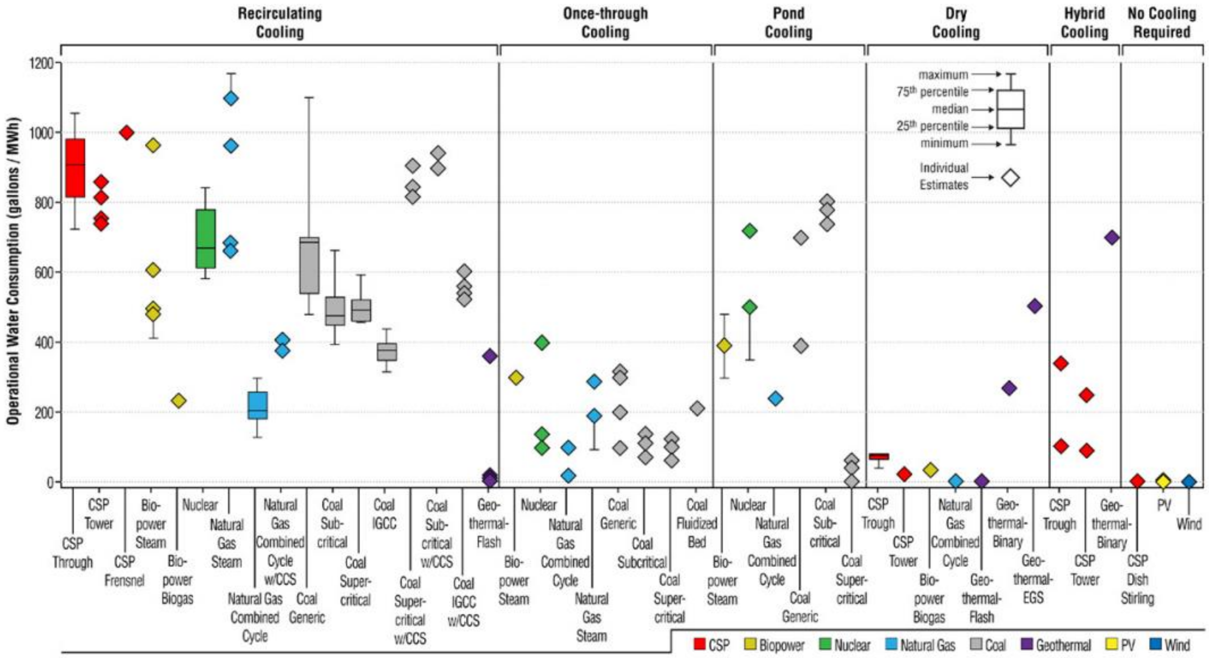
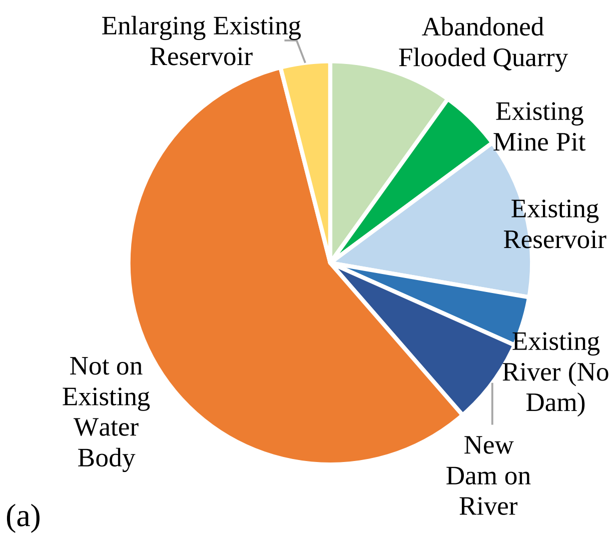


Figure 15. Operational Water Consumption by Generation Type (Gallons/MWh) [94]

In order to address water demand issues, there has been a shift towards dry and hybrid cooling. Dry cooling uses air as the cooling fluid instead of water, removing the majority of water demand for the plant. Hybrid cooling systems use a combination of water and air, only using water for cooling during hot days. These cooling strategies result in increased costs and decreased thermal efficiencies, resulting in lower plant performance. However, in arid regions, they represent the best alternatives for ensuring continued power generation in the face of increasingly limited water supply [98]. Plants using dry cooling consume 40 to 90 gal/MWh, and plants using hybrid systems, 90 to 450 gal/MWh. Studies have shown that reducing water demand by 90% will on average reduce performance by 3% and increase costs between 2 to 10%. Lost performance can be regained by increasing plant capacity [98], [99]. Although these modifications to plant design may make CSP plants less cost competitive with other generation resources, they could potentially increase the sustainability of CSP operations.

2.5.2 Pumped Hydro Potential

Evaluating California's pumped hydro potential is not straight forward. Pumped hydro plants have traditionally been open-loop systems, built on or near easy-to-access, natural-flowing waterways. Sites must have topography that can support upper and lower reservoirs with significant holding capacity. Potential sites must also avoid critical and sensitive habitat, endangered species, and protected lands. These environmental restrictions as well as financial issues have been the main factors limiting pumped hydro deployment [100], [101]. Concerns over the environmental impacts of near and on-stream pumped hydro plants have spurred greater focus on closed-loop and underground systems (Figure 16) [100].



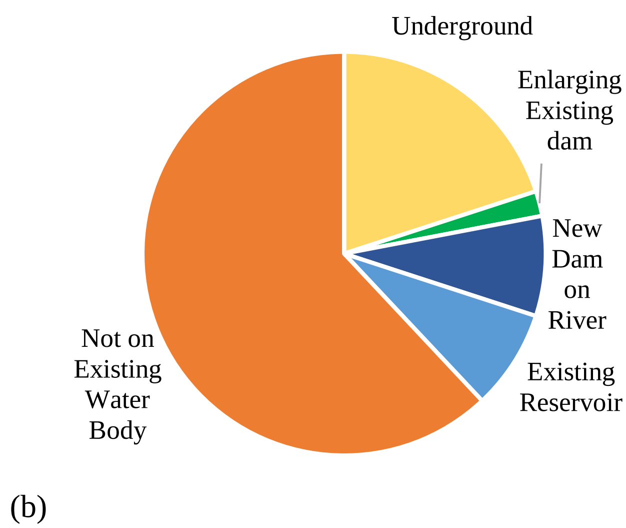


Figure 16. Hydro Potential by Reservoir Type, (a) Upper and (b) Lower Reservoir [100]

Closed-looped systems can be constructed independent of natural water systems, as long as water can be delivered to fill the reservoirs and supply supplemental water as it evaporates. Underground systems use excavated or existing caverns for one or both of its reservoirs. These systems have fewer topographic restrictions and a potentially lower environmental impact than their open-looped counterparts [100].

Under these restrictions, California pumped hydro potential is approximately 10,450 MW, according to the U.S. Department of Energy. If existing hydropower was converted to pumped storage, an additional 10,300 MW would be available [101]. If existing non-power dams were converted, another 195 MW would be available, resulting in a total potential of 20,930 GW [101], [102]. (See Table 2 for more details.)

Table 2. California Existing and Potential Pumped Hydro Capacity [101]

	Capacity (MW)	Generation (MWh)
Potential near stream (>1 MW)	4,029	22,108,000
Potential near stream (<1 MW)	3,025	15,879,000
Existing Conventional hydro	10,292	34,034,000
Existing Pumped Hydro	3,393	

There are emerging opportunities for pumped hydro beyond this estimation. Key innovative designs include pumped hydro with wastewater as demonstrated by Mulqueeney Ranch [100] and with ocean water as done by Okinawa Yanbaru Seawater [47], [103]. These types of plants could utilize water sources previously not included in the DOE estimates. In addition, the water shortage in California has led to propositions, such as the California Emergency Drought Relief Act, that support the investment in new water storage projects, which may extend to the expansion and creation of new water reservoirs to store water for periods of drought [104]. If constructed, these new reservoirs could be operated as pumped hydro power plants, serving the dual purpose of water and energy storage. The potential capacity for these types of pumped storage are unclear as the technologies and regulations surrounding them are in development.

2.6 Scope of Current Work

This study addresses the state-level issues of renewable integration and GHG emissions reductions through an integrated platform in order to provide a holistic analysis of strategies proposed to achieve sustainability targets. It builds on the established knowledge of the benefits of distributed generation, energy storage, and intelligent PEV charging to help meet these targets.

While these technologies have been studied individually, they have not been compared together to gauge their relative effectiveness in reducing overall grid GHG emissions in both the near term and at high renewable levels. The scale of SES as well as its potential benefits, including helping to meet high renewable penetration levels has previously been examined in the literature, as well as the integration of PEVs with varying charging intelligence levels. However, there has not been a study in which the dynamic interactions of these strategies when deployed together at the state level is explored. Only a few studies focusing on PEV deployment considered the additional application of SES to achieve high renewable penetration levels, but these studies did not evaluate the impact of increased PEV charging intelligence on SES capacity requirements [91]. Examining the impact of intelligent PEV charging on the grid as well as on additional storage capacity required to achieve high renewable utilization is important for understanding the scale of EVSE and other infrastructure required to meet current and future RPS targets.

This study also explores the potential impact of renewable energy deployment on regional water demand. In particular, it provides a cursory analysis of the scale of water consumption for CSP renewable generation required to reach target renewable penetration levels. The disproportionate installation of CSP plants in the southeast region of the state where water is limited can lead to increased stress on local water resources, exacerbating drought conditions and counteracting current water conservation measures, incongruent with overarching sustainability goals.

Therefore, the current work aims to evaluate the relative effectiveness of sustainability strategies related to renewable integration, energy storage, and the electrification of light-duty transportation from a systems approach, to identify direct and indirect impacts of strategies on the advancement of grid-centric sustainability objectives.

3.0 Approach

The following tasks encompass the approach taken to meet the objectives previously stated.

Task 1: Garner data from previous studies and establish a foundation for the use of HiGRID related to energy storage and water demands of renewable energy deployment.

Relevant studies will be identified and potential scenarios will be developed, drawing from the parameters and data provided from these previous studies.

Task 2: Compare the scenarios of energy storage deployment with and without scaled electric vehicle deployment to capture interaction of EV deployment and energy storage-specific technologies.

First, SES scenarios will be developed considering increased renewable energy levels in the near term (without electric vehicle deployment). Then, scenarios regarding SES deployment will be developed, considering the impact of future population growth and increased renewable deployment to meet RPS targets for the years 2030 and 2050, again without electric vehicles. These scenarios will be paralleled with scenarios regarding renewable energy and storage deployment with scaled electric vehicle deployment. All these scenarios will be run using the Holistic Grid Resource Integration and Deployment (HiGRID) tool. Data from the scenarios will be compared and the impact of electric vehicles on storage requirements will be characterized. The amount of SES that will need to be available to the grid in 2050 to meet AB 32 goals will be determined. The SES capacity required for each scenario is compared to the state's pumped hydro potential.

Task 3: Compare California concentrated solar power (CSP) potential with regional availability of water to evaluate whether water availability is a limiting factor for CSP deployment in high renewable potential areas.

The amount of CSP generation needed in 2050 to meet high renewable penetration under each scenario is garnered from the previous tasks. Using CEC and NREL solar resource data, the spatial distribution of solar thermal potential is determined at the county level. The relationship between CSP power production and water demand is drawn and the varying impact of CSP generation with wet, hybrid, and dry cooling is compared.

Task 4: Capture data from the projected renewable energy mix to determine if the GHG emission reduction goals set in AB 32 are realistic with that mix, or whether new strategies would need to be investigated.

Based on the results of Tasks 2 and 3, there will be an assessment of which scenarios meet policy goals and in which cases additional strategies need to be investigated.

4.0 <u>Methodology</u>

4.1 Electricity Demand Load Profile and Future Electricity Demand

The California electricity demand load profile is extrapolated from 2005 FERC data. California has shown a historic trend of steady per capita demand for electricity (Figure 17) [105]. Therefore, it is assumed in this study that total stationary electricity demand (not including vehicle electrification) for the state will grow proportional to population growth.

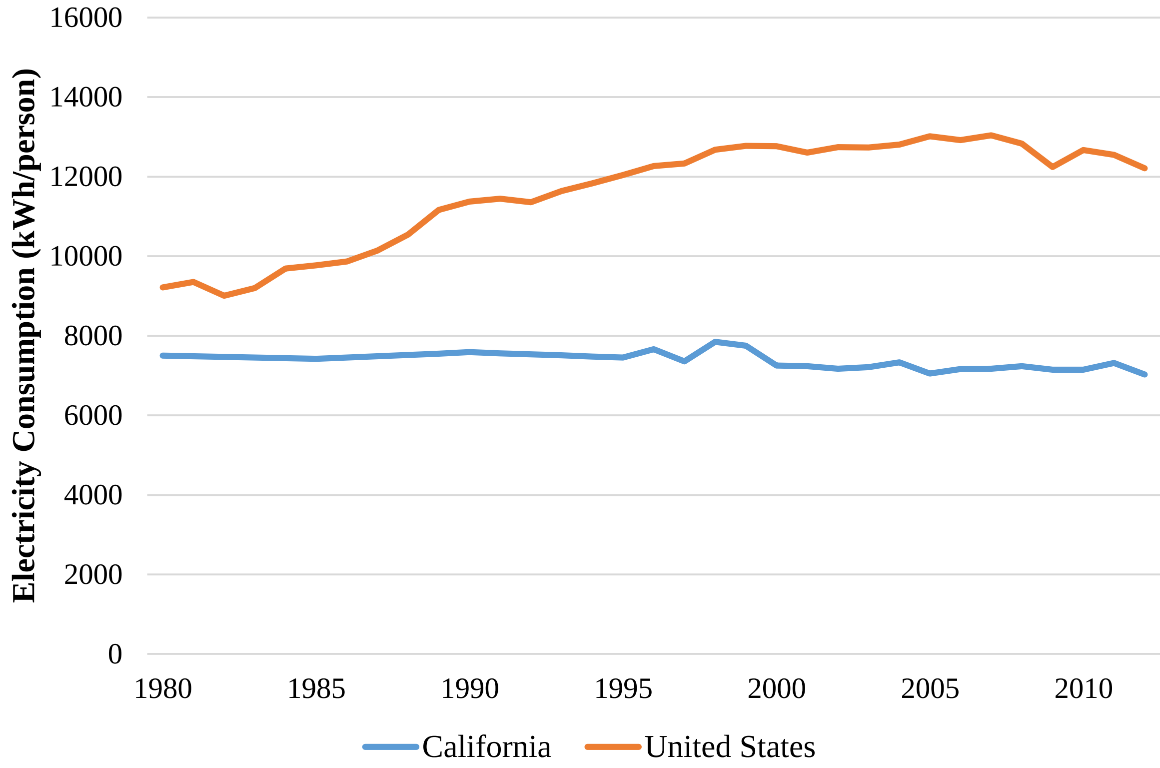


Figure 17. California and U.S. Residential Energy Use per Capita [105]

4.2 Vehicle Miles Traveled and Future Trends

As discussed previously in Section 2.3, the vehicle miles traveled (VMT) per capita is influenced by several factors, including gas prices and economic well-being. This study assumes that per capita VMT remains consistent. Therefore, total VMT is assumed to grow in proportion to the population.

4.3 Dispatch Model: Holistic Grid Resource Integration and Deployment Tool

This work employs the Holistic Grid Resource Integration and Deployment Tool (HiGRID), developed at the University of California, Irvine within the Advanced Power and Energy Program (APEP), to evaluate the impact of dispatching renewable energy and other advanced technologies on the California electric grid. HiGRID is a temporally resolved, multi-module platform that simulates California grid operations and the dynamic dispatch of grid resources to balance electricity load demand. A flowchart of the model is presented in Figure 18 [106].

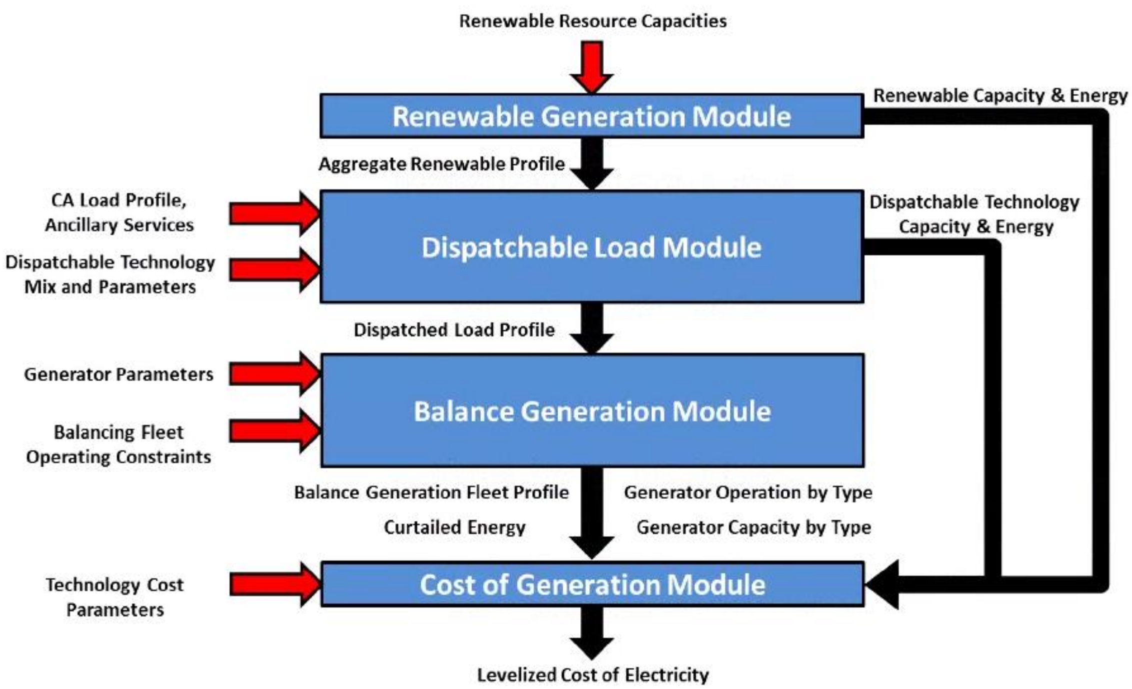


Figure 18. HiGRID Flowchart [106]

Given an input electricity demand, the net load is determined in the renewable generation module based on the defined renewable mix. The net load profile is then sent to the dispatchable load module where dispatchable grid resources are deployed to meet the electric load demand. Outputs of the dispatchable load module are fed into the balance generation module, where baseload generation is added as well as additional load following and peaker generation to ensure load and regulatory reserves are sufficiently served. The final generation portfolio is then run through the cost of generation module to determine the levelized cost of electricity (LCOE).

Table 3. HiGRID Technologies Used in Study by Module

Module Name	**Technology**
Renewable Module	Regional, Utility 1-axis tracking PV Solar thermal trough plant Small hydropower Geothermal Biomass/biogas
Dispatchable Load Module	Load Following Fuel Cells Stationary Energy Storage Electric Vehicle Charging
Balancing Generation Module	Nuclear Geothermal Baseload Fuel Cells Simple-cycle gas turbines Combined cycle plants

These three technical modules, along with the economic module, are described as follows.

4.3.1 Renewable Energy Module

The renewable energy module was developed as part of Brian Tarroja's thesis work [107] and is detailed in Tarroja (2011) [108]. This module utilizes renewable resource data and technical models to calculate the temporal profile of renewable generation for an input renewable mix. Wind and solar generation profiles are determined from spatially resolved wind speed and solar insolation data from the National Renewable Energy Laboratory Wind and Solar Integration Project (NREL-WWSI) [109]. Wind power profiles are calculated using the following assumptions: total wind potential of 30.9 GW is determined from the combined works of the Renewable Energy Transmission Initiative (May 2010) [110] and the WWSIS study [109]; wind turbine density is assumed to be ten Vestas V90 3 MW turbines for 4 km square blocks; power curves for each wind block is calculated based on temporally and spatially resolved wind speed data; total hourly power output for the state is calculated by aggregating the power outputs of each wind block [106].

Two types of solar power are used in this work: solar photovoltaics (PV) and concentrated solar power (CSP). Total technical solar power potential is over 17,000 GW for PV and over 1,000 GW for CSP, according to the California Energy Commission. In HiGRID, the solar intensity and distribution is calculated from NREL's National Solar Radiation Database (NSRDB) radiation data [111] and the Renewable Energy Transmission Initiative (May 2010) [110]. PV power curves were developed based on solar cell power equations that consider cloud cover, direct and indirect solar radiation, and temperature impacts on power output [106]. Concentrated solar power curves were developed from power models of the Solar Energy Generation Systems (SEGS) VIII plant, which generates electricity from parabolic solar troughs and whose power output is supplemented by natural gas combustion. A description of the complete methodology is provided in [106].

The other renewable resources considered in HiGRID are geothermal, biopower, and small hydropower. Geothermal potential is determined to be 4.8 GW, which is based on estimates from the California Energy Commission [112], [113]. Geothermal plants are assumed to operate as baseload power with planned outages for maintenance determined from FERC data [114]. Biopower potential, which includes both biomass and biogas resources, is determined from UC Davis "biomass facilities database" [115] and the EPA Landfill Gas Emissions Model (LandGEM) [116]. Biopower is assumed to offset natural gas use in load following, combined cycle plants. Renewable small hydropower plant capacity is determined from historic capacity as well as future estimates and limitations as defined by the CEC and Senate Bill 1078. While the output renewable penetration includes small hydropower, the power profile of small hydropower is determined in the dispatchable load module, as it is a component of the larger hydropower system.

4.3.2 Dispatchable Load Module

The dispatchable load module considers the electricity demand profile and subtracts renewable generation calculated from the renewable energy module to determine the remaining electricity demand, or the net load profile, which needs to be met with other dispatchable resources. This module dispatches generation technologies from an input capacity of grid resources that can include load-following combined cycle power plants, hydropower (large and small renewable), load-following fuel cells, stationary energy storage, and electric vehicles. Dispatch of these resources within this model is determined through an iterative process, considering both physical and regulatory constraints to ensure realistic operational behavior. Specific technology parameters used for this work are described below.

4.3.2.1 Fuel Cells

The fuel cell model is based on the concept of locating fuel cells at distribution networks as Transmission Grid Energy Resource (TIGER) stations, as discussed in Section 2.1.2. The model has two modes of operation for the fuel cell systems:

Baseload. Baseload operation of the fuel cell consists of level, continuous power output with minimal ability to ramp up and down. Baseload fuel cells have a high minimum load point, meaning that the lowest power output they can provide is 75-90% of full power capacity. Operational behavior reflects current high temperature fuel cells (HTFC) performance and is similar to geothermal and nuclear power. Note: while described in this section, baseload fuel cells are dispatched by balancing generation module along with the other baseload generation technologies.

Load following. Fuel cells acting as load followers have faster ramping rates and a lower operational minimum load point than baseload fuel cells. This performance behavior imitates phosphoric acid fuel cells (PAFC) in operation today.

Parameters may be altered for each of these modes to test the impact of improvements in efficiency and dispatchability.

4.3.2.2 Stationary Energy Storage

The SES model was developed as a part of Josh Eichman's dissertation work [117]. SES is modeled as a state-level, grid connected system that charges and discharges to smooth the net load profile, ie. peak shaving and valley-filling. To provide this grid service, SES uses renewable generation to charge, and when no renewable energy is available, it may rely on non-renewable resources. Parameters of the SES model can be set to represent different energy storage technologies by varying the energy and power capacities of the system, ramp rate, charge/discharge power rating, and round-trip efficiency. Specific SES technologies used in this study are pumped hydro, compressed air energy storage (CAES), and vanadium redox flow batteries. The parameters used in this work to represent each technology are listed in Table 4 [48], [55].

Table 4. Stationary Energy Storage Parameters

Technology	Round Trip Efficiency	Maximum Dispatch Time
Pumped Hydro	75-85%	72 Hours
CAES	55-75%	24 Hours
Flow Batteries	65-85%	10-24 Hours

4.3.2.3 Electric Vehicle Charging

The electric vehicle model was developed as a part of the dissertation work of Zhang Li and is detailed in Zhang (2013) [77]. This model uses vehicle travel patterns derived from the 2009 NHTS to determine charging demands for an input fleet size of plug-in electric vehicles based on defined vehicle and infrastructure constraints. Parameters include: charging strategy, charging efficiency, maximum charger power, vehicle efficiency, charging locations, and vehicle range.

4.3.3 Balancing Generation Module

The balancing generation module receives the output of the dispatchable load module, adds baseload power, then calculates the additional capacity of load followers and peaker plants required to satisfy any remaining load and ensures that ancillary service requirements are met. Input baseload technologies include nuclear, coal, geothermal, and baseload fuel cells. Each of these technologies is considered to provide constant power output with a determined monthly capacity factor [106]. The load followers and peakers considered in this module are combined cycle and simple-cycle gas turbines, respectively. Operational constraints for these technologies include ramp rate, minimum load point, minimum run time, and generator size. Where generation does not line up with load due to physical and regulatory constraints, the portfolio derived in the balancing generation module can be reevaluated by the dispatchable load module to resolve the discrepancy. If constraints continue to result in excess generation, the balancing generation module will enforce renewable curtailment.

4.3.4 Economic Module

The levelized cost of electricity (LCOE) is calculated based on the final energy mix. The cost contribution of each technology is determined from the fleet capacity and total generation of each, as well as additional factors including capital costs, operational and maintenance costs, timing of generation, and tax incentives. The cost of generation module was designed in part based on the California Energy Commission's Cost of Generation Model [118] and a summary of the cost parameters used in this work can be found in Appendix A.

5.0 Results

5.1 The Deployment of Stationary Energy Storage versus Fuel Cells in the Near Term

This section focuses on the effectiveness of SES technologies to reduce grid GHG emissions and meet renewable targets if deployed on the grid today. Three SES technologies: pumped hydro, CAES, and flow batteries were selected due to their common ability to scale power and energy capacity independently (see Section 2.1.3), as well as their differences in dispatch times and round trip efficiencies. This provides an opportunity to observe how different power to energy ratios may affect SES performance.

SES is not the only technology being considered to help reduce CO_2 emissions and improve grid performance. The deployment of fuel cells has been proposed as an alternative approach to decrease electricity-related emissions. In this analysis, the relative effectiveness of stationary fuel cells operating as TIGER stations versus SES to decrease grid CO_2e emissions is compared to evaluate the potential role of a state-level SES system in the near term. A fleet capacity of 5 GW was selected to reflect the new power capacity that the California Air Resources Board predicts California will need by 2020 to address the reliability concerns associated with the closure of SONGS and other power plants due to environmental issues (AB 1318).

5.1.1 Metrics

The effectiveness of SES versus fuel cells to meet sustainability goals in the near term will be evaluated by the following metrics:

Renewable Penetration. This refers to the percentage of load that is met by renewable generation. California has two approaching renewable energy targets: 33% renewables (by 2020) and 50% renewables (by 2030). The type and scale of renewable technologies employed affect state-level grid dynamics. Therefore, the impact of deploying an advanced, complementary technology on the grid, either SES or fuel cells, may change in response to increased renewable penetration. The level of renewable capacity installed is scaled to meet these targets, considering present-day grid load dynamics and taking into account 0.5% curtailment in the 33% renewables base case and 2% curtailment in the 50% renewables base case.

Table 5. Renewable Fleet Capacity for 33% and 50% RE

% RE	Solar PV	Solar CSP	Wind	Geothermal	Small Hydro	Biopower
33	2.6	6.2	10.8	3.6	1.1	1.3
50	8.6	10.5	20.9	4.3	1.1	1.4

GHG Emissions. This refers to the grid-wide annual emission of greenhouse gases or carbon dioxide equivalent (CO_2e) emissions. CO_2e emissions are produced from various electricity generation resources. The amount of CO_2e emitted by each technology is dependent on how often each generator is used, how often it is turned on/off, and its efficiency during operation. In order to meet California's sustainability targets, the grid must reduce its GHG emissions.

Levelized Cost of Electricity (LCOE): This refers to the grid-average cost of electricity per MWh. A lower LCOE is preferred, as a high LCOE may serve as an economic barrier to technology adoption and CO_2e emission reduction.

CO_2e Reduction Cost per Ton: This refers to the incremental increase in the price of electricity per ton of CO_2e reduced compared to the base case—either 33% renewables or 50% renewables. This metric is used to provide a cost comparison between technologies and strategies in common units of cost/ton CO2e reduced. This cost is calculated from the following equation:

$$\frac{\$}{ton\ CO_2e\ reduced} = \frac{E_{annual}\left(LCOE_{Case\ X} - LCOE_{base}\right)}{\left(CO_2e_{base} - CO_2e_{Case\ X}\right)}$$

5.1.2 Scenarios for Analysis

This analysis examines the relative effectiveness of a defined power capacity of SES (5 GW) versus the same power capacity of fuel cells. For the selected SES technologies, however, a given rated power capacity can have a range of energy capacity values such that:

$$energy\ capacity\ (GWh) = rated\ power\ capacity\ (GW)\ x\ maximum\ dispatch\ time\ (h)$$

Therefore, before SES and fuel cells can be compared, the effect of energy capacity for the input power capacity of the SES fleet must be evaluated. To that end, several energy storage spanning cases were run and are summarized in Table 6. Although CAES and flow batteries currently have shorter dispatch times than pumped hydro, the full range is tested for each technology in order to draw comparisons and glimpse potential benefits with technology improvements that can increase the maximum dispatch time.

Table 6. Energy Storage Spanning Cases

Technology	Renewable Penetration (%)	Rated Power Capacity (GW)	Spanning Energy Capacity (GWh)	Efficiency (%)
Pumped Hydro	33	5 GW	0-360 GWh	75%
CAES	33	5 GW	0-360 GWh	65%
Flow Batteries	33	5 GW	0-360 GWh	75%
Pumped Hydro	50	5 GW	0-360 GWh	75%
CAES	50	5 GW	0-360GWh	65%
Flow Batteries	50	5 GW	0-360 GWh	75%

Fuel cells operating as TIGER stations can perform either as baseload or load following (LF) power plants. Two sensitivities are considered: improved dispatchability of baseload fuel cells and improved efficiency of load following fuel cells. They are as follows:

Baseload—high dispatchability. Baseload fuel cells with higher dispatchability have a greater ramping capacity than traditional baseload fuel cells. A lower minimum load point allows for greater turndown to help integrate renewable generation and avoid renewable curtailment. The minimum load points used in this study reflects values found in experimental and modeling studies [55], [119].

Load following-high efficiency. In the case that HTFC are operated as load followers, they may achieve higher efficiencies than load following PAFC, but less capacity to turn down power output.

A summary of the fuel cell scenarios with the specific parameters used in this study are summarized in Table 7.

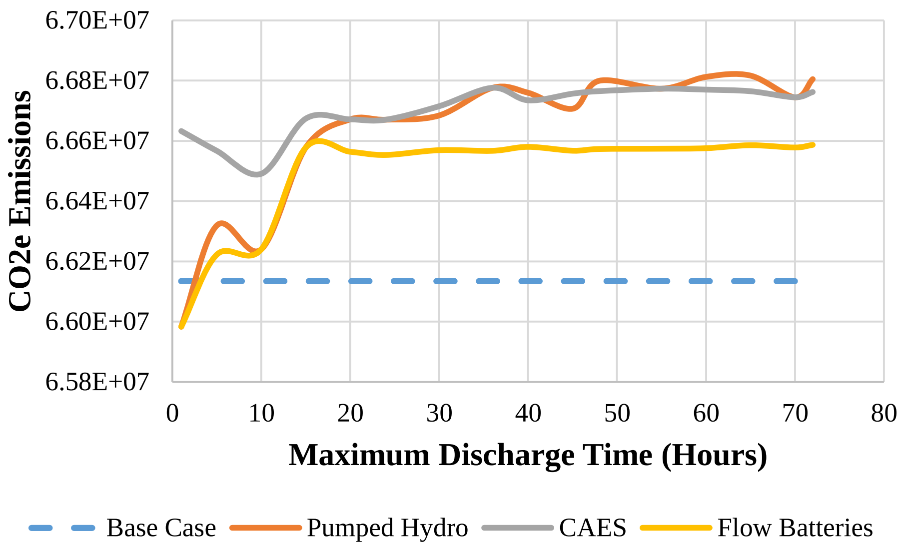
Table 7. Summary of Fuel Cell Scenarios

Fuel Cell Type	Renewable Penetration (%)	Rated Power Capacity (GW)	Minimum Load Point (%)	Generator Rated Efficiency (%)
Baseload	33	5 GW	90	52
Baseload—Higher Dispatchability	33	5 GW	80	52
Load Following	33	5 GW	55	38
Load Following—High Efficiency	33	5 GW	75	52
Baseload	50	5 GW	90	52
Baseload—Higher Dispatchability	50	5 GW	80	52
Load Following	50	5 GW	55	38
Load Following—High Efficiency	50	5 GW	75	52

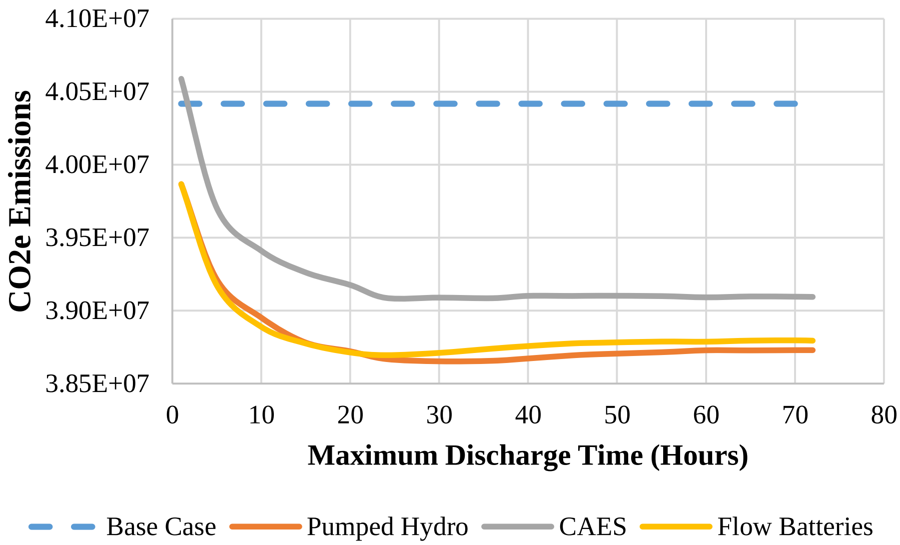
5.1.3 Stationary Energy Storage Spanning Cases

The target renewable penetrations of 33% and 50% were achieved at all levels of energy storage. At 33% renewables, all SES cases showed little to no improvement in GHG emissions compared to the base case (Figure 19a). Installing pumped hydro and flow battery systems with maximum dispatch times of less than five hours (equivalent to 25 GWh fleet energy capacity) resulted in minimal grid emission reductions. The greatest CO_2e reduction (<0.5% below the base case) was observed at one hour of dispatch for both pumped hydro and flow batteries (ie energy capacity of 5 GWh). (At this point, 100% of renewable curtailment is recovered and increasing SES capacity no longer contributes to higher renewable utilization.) All CAES cases for 33% renewables result in higher emissions than the base case, with the lowest emissions produced at 10 hours of dispatch (50 GWh). This is due in part to the use of natural gas in the gas expansion ("discharge") process of the CAES air compression-expansion cycle in order to increase power output.

When the energy capacity of the SES fleet is higher than the level of curtailment, there is not enough renewable generation to completely charge the SES fleet. The SES fleet can either be scaled back in order to ensure that only renewable generation is used. If the SES is allowed to be charged using non-renewable generation, it can still provide grid services, such as peak shaving, and may decrease grid reliance on low efficiency peaker plants. At the same time, this operation of the SES fleet will increase the grid's reliance on conventional load following plants that have higher efficiencies than peaker plants but still emit GHG. Replacing peaker generation with load following generation can either yield a net positive or negative impact on overall grid GHG emissions, depending on the level of inefficient generation offset versus the amount of new generation required to charge the SES fleet. For the 33% renewable case, peaker generation offset by SES operations was outpaced by the increase in load-follower generation needed to meet the new load associated with charging the SES system at SES energy capacities above 5 GWh (one hour dispatch). However, increasing the SES energy capacity beyond 15 hours had little to no impact on further increasing grid emissions.



(a)



(b)

Figure 19. Grid GHG Emissions for SES Dispatch Ranges for (a) 33% RE and (b) 50% RE

For 50% renewables, the addition of SES capacity in each scenario helped to recover curtailed renewable generation and reduce grid GHG emissions at all energy capacities examined (Figure 19b). For each marginal increase in energy storage capacity, the magnitude of GHG reduction decreased. A minimum was reached around 24-30 hours, depending on the technology, after which point increasing energy capacity had little to no impact on grid emissions. Renewable penetration showed a similar trend (ie. As SES energy capacity was increased, renewable penetration increased, but with diminishing benefits.) The maximum achievable renewable penetration level was reached at 24-30 hours. At this point, energy capacity stopped being a limiting factor in grid GHG/renewable performance. The effect of varying *power* capacity of the SES system is explored in the following sections.

A summary of the dispatch times and equivalent energy capacities for each SES technology that result in the lowest grid CO_2e emissions is in Table 8. The key differences between CAES versus pumped hydro and flow batteries are: CAES have lower efficiencies and use natural gas. These differences yield higher emissions for the same power-energy capacities of CAES versus pumped hydro and flow batteries. Increasing the round-trip efficiency decreases the amount of energy lost in transferring energy into and out of the energy storage fleet. Therefore, for the same power-energy capacity, the SES fleet is able to offset more generation and by extension more CO_2e emissions.

Table 8. Energy Capacity Resulting in Lowest GHG Emissions for 5 GW Power Capacity

Technology	**33% RE**		**50% RE**	
	Dispatch Time	**Energy Capacity**	**Dispatch Time**	**Energy Capacity**
Pumped hydro	1 hour	5 GWh	30 hours	150 GWh
CAES	10 hours	50 GWh	24 hours	120 GWh
Flow batteries	1 hour	5 GWh	24 hours	120 GWh

5.1.4 A Comparison of Grid GHG Emission Reductions

For both 33% and 50% renewables, the deployment of fuel cells results in the greatest reduction of grid GHG emissions compared to both the base case and all SES cases (Figures 20 and 21).

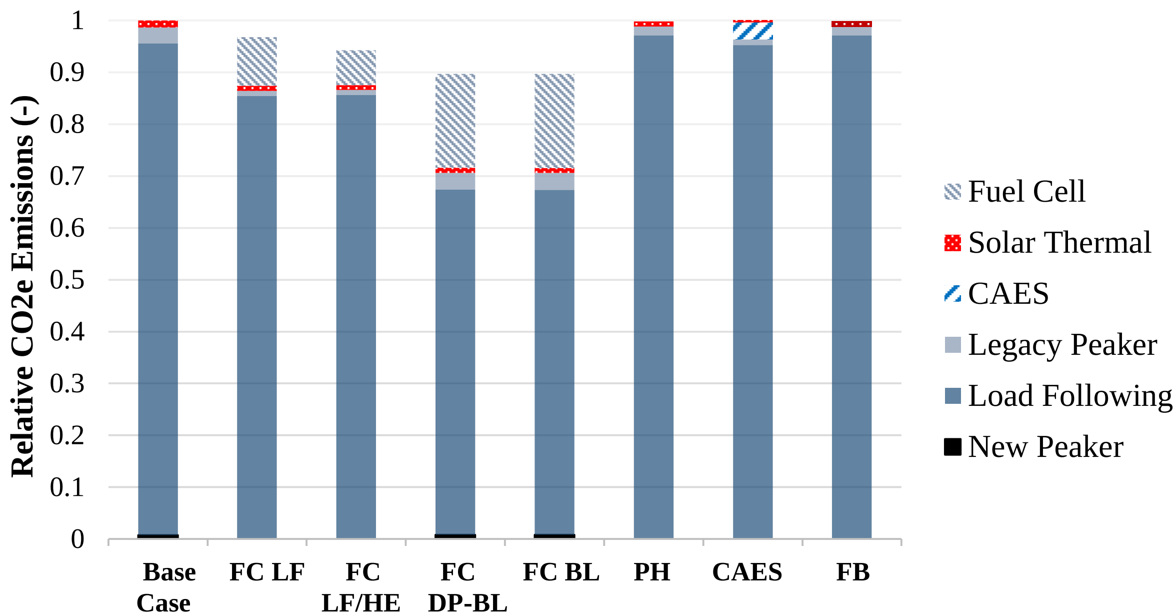


Figure 20. 33% RE: Change in CO_2e by Generation Source Compared to 33% Base

At a renewable penetration of 33%, baseload fuel cell deployment shows the greatest reduction in grid CO_2e emissions at 11% below the base case, followed by high efficiency, LF fuel cells which achieve about a 6% reduction. The lower total grid GHG emissions for the baseload fuel cell cases can be attributed to fuel cells offsetting generation from conventional load following power plants. Lowering the minimum load point of the baseload fuel cell fleet from 90% to 80% had a minimal impact on grid GHG emissions. Both cases produced relatively the same amount of generation throughout the year and required the same amount of new peaker capacity. The baseload fuel cell scenarios retained the new peaker capacity shown in the base case due to the increased need for dispatchable generation to support the increased ramping associated with higher solar generation.

For the LF fuel cell scenarios, fuel cells are called on less often to produce electricity compared to the baseload scenarios, resulting in less conventional generation being offset and higher overall grid GHG emissions compared to the baseload fuel cell cases. However, both LF fuel cell cases are able to offset peaker generation and do not require new peaker capacity, unlike the baseload cases. Both LF fuel cells with a minimum load point of 55% and those with a higher minimum load point of 75% offset the same level of generation from conventional load followers. However, the improved efficiency resulted in decreased emissions coming from the fuel cell fleet in the higher efficiency cases.

For the energy storage scenarios, pumped hydro and flow batteries both achieved minimal GHG reductions (CAES increased emissions), especially compared to baseload fuel cells. However, all three SES technologies were able to decrease peaker generation compared to the base case, showing similar peaker reliance to the LF fuel cell scenarios. SES technologies also increased conventional load following generation, whereas the LF fuel cells were able to offset both peakers and conventional load followers.

Increasing renewables from 33% to 50% results in a 38% decrease in GHG emissions without the addition of an advanced technology. Comparing the two base cases, there is 100% increase in reliance on peaker generation and 40% decrease in load follower generation for the 50% renewable generation. At 50% renewables, the high efficiency, LF fuel cell scenario results in the lowest GHG emissions about 6.6% below the 50% RE base case (Figure 21).

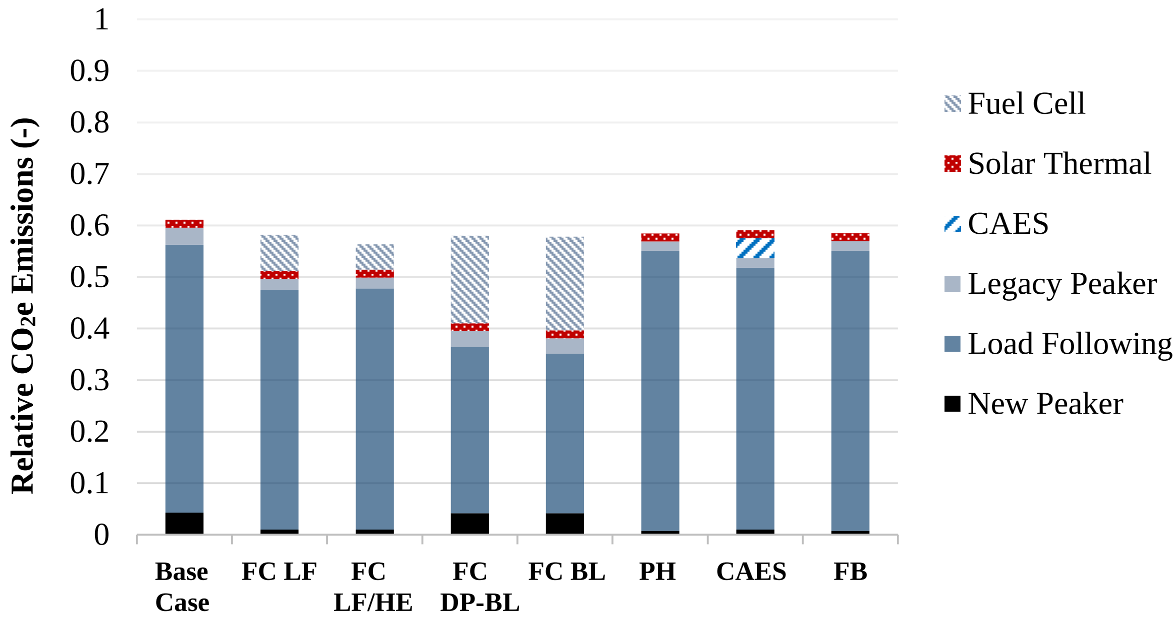


Figure 21. 50% RE: Change in CO_2e by Generation Source Compared to 33% Base

At 50% renewables, baseload fuel cells are able to offset load follower generation. However, new peaker generation is still required. While SES technologies have minimal GHG reductions compared to the fuel cell scenarios and increase conventional load follower generation, they are able to offset peaker generation even more effectively than the LF fuel cell scenarios.

5.1.5 Levelized Cost of Electricity

There is a common trend that the LCOE increases as renewable penetration increases independent of complementary technologies (Figure 22). From 33% to 50% renewables, the cost for the base case increases from \$0.11/kWh to \$0.165/kWh which is equivalent to a 50% increase in cost. The addition of advanced technologies causes an additional price increase for most cases. The exception is pumped hydro at 50% renewables.

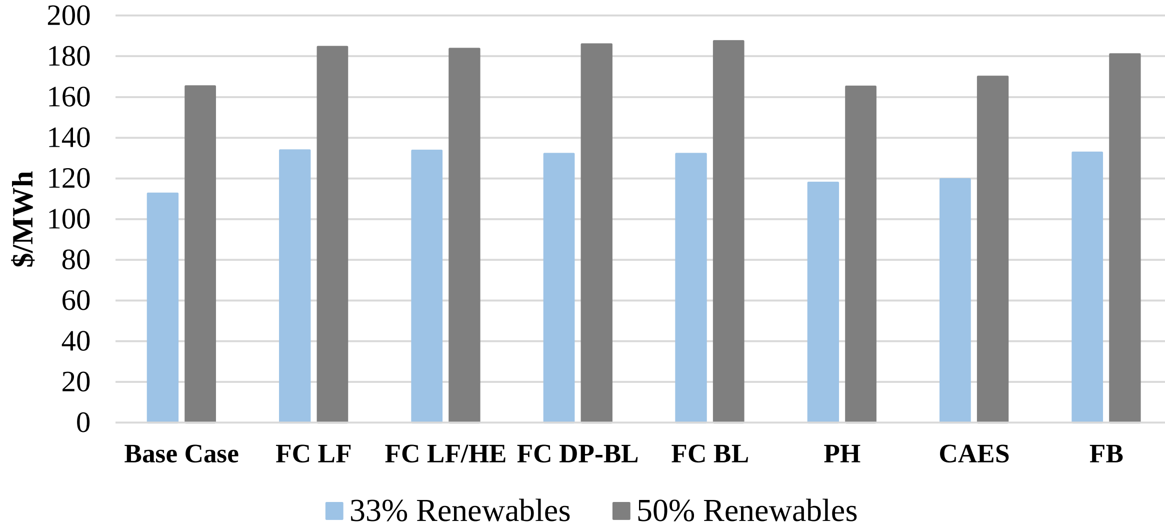


Figure 22. Levelized Cost of Electricity for 33% and 50% Renewables

At 33% renewables, all fuel cell scenarios as well as the flow battery scenario experience the highest LCOE at $0.02/kWh above the base case ($0.11/kWh) (Figure 22). The cost difference between fuel cell cases was minimal (< ±$0.005/kWh). Of the SES technologies examined, installing pumped hydro energy storage has the smallest increase in LCOE at + $0.005/kWh. CAES has the second lowest cost; however, this cost increase does not yield a GHG reduction benefit. Also, note that the LCOE for each SES technology is based on varying energy capacities. For the same energy capacity of 5 GWh, pumped hydro has a lower LCOE than flow batteries. CAES has a higher energy capacity (50 GWh) than both flow batteries and pumped hydro and is priced between the two.

At 50% renewables, the fuel cell cases have the greatest LCOE, with baseload fuel cells (minimum load point of 90%) having the highest cost at $0.188/kWh. Of the fuel cell scenarios examined, high efficiency, LF fuel cells have the smallest cost increase from the base case at $0.184/kWh. All three SES scenarios show lower LCOE than the fuel cell cases. Installing pumped hydro actually results in a very slight reduction in LCOE compared to the base case (less than $0.001/kWh). This modest reduction is reflected in a negative cost per ton CO_2e reduced.

5.1.6 Cost per Ton CO_2e reduced

The cost of reduction is both a function of total GHG emissions reduced and the LCOE. At 33% renewables, despite having the highest LCOE costs, the fuel cell scenarios also provide the largest GHG reduction. Subsequently, the relative cost per ton CO_2e reduced is the lowest of the technologies examined (Figure 23). Of the fuel cell scenarios, baseload fuel cells show the lowest cost of reduction at $811-812/ton CO_2e due to their higher overall GHG reduction potential and their minimally lower LCOE compared to the LF fuel cell scenarios. In comparison, at 33% renewables, SES increases LCOE with a minimal impact on grid GHG emissions. Therefore, the cost per ton CO_2e reduced is high for pumped hydro and especially so for the flow battery scenario. For the case of CAES, grid emissions actually increase and therefore a reduction cost cannot be calculated.

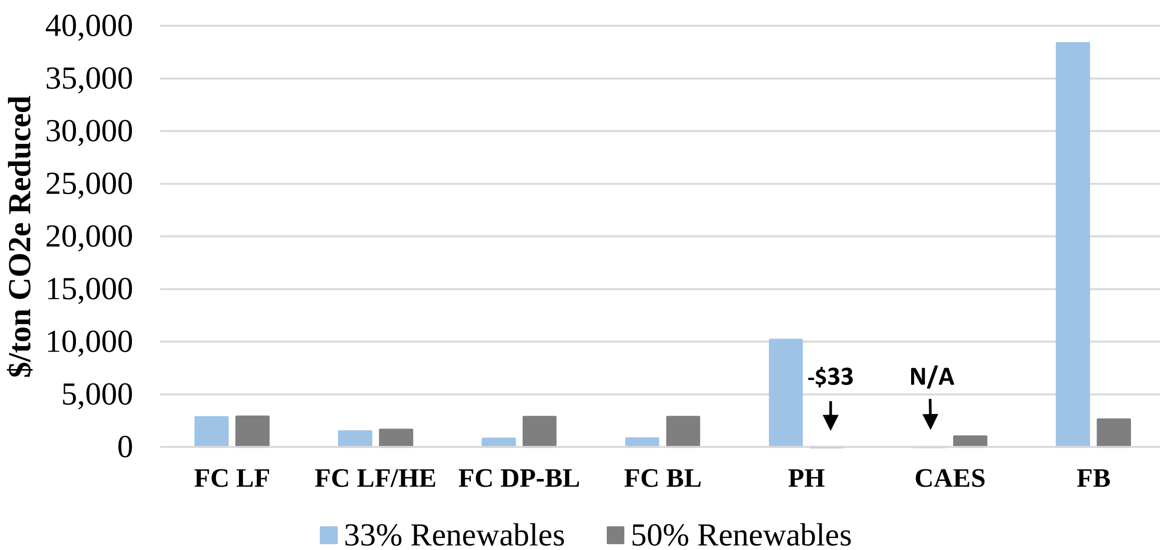


Figure 23. CO_2e Reduction Cost per Ton Reduced

At 50% renewables, fuel cell CO_2e reduction costs increase compared to the 33% case. In particular, baseload fuel cell reduction costs significantly increase. This is in part due to lower reduction potential compared to the base case and increased LCOE. In contrast, while LF fuel cells also increase LCOE, they show improvements in reduction potential, keeping reduction costs relatively steady. Therefore, whereas baseload fuel cells had the lowest reduction cost at 33% renewables, at 50% renewables, LF fuel cells become more cost effective than baseload operation. Highly efficient, LF fuel cells have the lowest cost of the fuel cells scenarios at \$1660/ton CO_2e reduced. SES technologies, on the other hand, become more cost competitive in terms of cost per ton CO_2e reduced. Because pumped hydro slightly decreases the LCOE, the cost for reducing is negative; not only does installing this SES technology decrease grid emissions, it also does not increase the cost of electricity. CAES is the second cheapest option at \$1000/ton CO_2e reduced. The remaining fuel cell scenarios (LF fuel cells and both baseload fuel cell cases) and the flow battery scenario had comparable reduction costs, ranging from \$2600-2900/ton CO_2e reduced.

5.1.7 Summary

At 33% renewables, technologies that are able to offset load follower generation are the most effective at reducing grid GHG emissions. As renewable penetration increases, so does new peaker capacity as well as overall peaker generation. Therefore, technologies that are able to offset peaker generation without increasing other non-renewable generation are the most effective in reducing emissions. Of the scenarios examined for 50% renewables, LF fuel cell scenarios are able to offset both peaker and load follower generation compared to the base case and therefore show the greatest CO_2e emissions reductions. In comparison, baseload fuel cells do not offset any new peaker generation or capacity compared to the base case at 50% renewables and require higher peaker capacity compared to both the SES and the LF fuel cell scenarios. While increased reliance on peaker generation offsets some emission reduction gains, baseload fuel cell deployment still provides a greater net reduction in grid GHG emissions compared to SES technologies.

Fuel cells were more effective in reducing grid GHG emissions compared to SES at both 33% and 50% renewables. Baseload fuel cells showed greater emissions reductions than LF fuel cells at 33% renewable penetration; however, at the higher renewable level of 50%, LF fuel cells showed greater relative emissions improvements. The key advantage of LF fuel cells over the other 50% renewable scenarios is their ability to provide dynamic low-carbon generation, offsetting both conventional load followers and peaker power plants. For their part, baseload fuel cells are not as capable as load followers to respond to increased renewable variability. SES are also able to respond dynamically and demonstrate the same benefit as LF fuel cells in that they can offset inefficient peaker plants. In the cases that new generation was required and there was a limited amount of peaker generation to offset, SES had little to no net benefit in reducing grid GHG emissions.

Examining costs, adding fuel cells operating as either load followers or baseload power increased the LCOE compared to the base case by \$0.02/kWh at both 33% and 50% renewables. On the other hand, installing SES increased LCOE from between \$0.00/kWh to \$0.02/kWh depending on the technology and renewable level. Costs between different technology scenarios were therefore comparable, with the greatest cost difference existing between the two base cases for 33% and 50% renewables associated with increased installed renewable capacity. The only scenario that shows a minimal reduction in LCOE is pumped hydro at 50% renewables, demonstrating that of the SES technologies, it is the most cost competitive for providing the same grid services.

Looking at the relative cost of CO_2e emissions reduction, all fuel cell scenarios at 33% had lower reduction costs per ton CO_2e reduced compared to each SES scenario. This is due in part to higher absolute emissions reductions and comparable increases in LCOE. Looking at the transition from 33% to 50% renewables, while fuel cells are more expensive to utilize at 50% renewables, fuel cell technologies remained cost competitive in terms of cost per ton CO_2e reduced especially compared to flow batteries. In particular, LF fuel cells maintain a relatively constant cost of reduction. Of the SES technologies examined, pumped hydro was most cost competitive, especially at 50% renewables. This is due in part to lower costs and higher round-trip efficiencies. This suggests that improving SES fleet efficiencies and lowering SES costs may increase emissions reduction potential and decrease the associated LCOE.

5.1.8 Discussion

The SES fleet's ability to reduce overall grid GHG emissions is strongly dependent on the availability of otherwise curtailed renewable generation and the degree to which they can offset inefficient, carbon-intensive peaker generation. Comparing the scenarios for 33% and 50% renewables, minimal curtailment (about 0.5%) existed for the 33% renewable scenarios and about 2% curtailment existed for the 50% renewable scenarios. At the higher renewable penetration, the SES fleet was able to peak shave and balance the net load and therefore was able to provide a net reduction in GHG reduction by offsetting peaker plants with both renewable and load following generation, despite the low curtailment level. This shows that when charged with non-renewable resources, there is a marginal opportunity to reduce grid GHG emissions by offsetting peaker generation. However, it is important to note that SES technologies are *not* generation resources, but rather storage systems that can respond dynamically. SES only provides zero emission power when they are charging using 100% renewable energy, preferably energy that would have otherwise been curtailed. This means that their contribution to grid GHG emissions is highly dependent on the resources used to charge them. SES technologies may be more beneficial in reducing grid GHG emissions at higher renewable capacities when there are increased opportunities to utilize otherwise curtailed renewable energy. The potential role of SES at higher renewables are explored in the following sections.

This study assumed the same load profile as present day California. However, electricity demand may increase in the future due to population growth as well as the planned electrification of light-duty transportation. The impact of these changes on the role of SES will be explored in the following sections. For the near term analysis, fuel cells show greater effectiveness compared to SES technologies in reducing grid GHG emissions. As renewable generation increases, dynamic operation of fuel cells are more effective in reducing CO_2e emissions and decreasing reliance on peaker generation compared to the base case. SES, characteristically dynamic with quick response times, were also able to decrease new peaker capacity and overall peaker generation at 50% renewables. Together this highlights the opportunity to utilize clean dispatchable resources and dynamic control measures to decrease reliance on conventional simple-cycle peaker plants that have high emission profiles, thereby decreasing grid GHG emissions. Transitioning to more dynamic fuel cells in the near term can help meet carbon reduction goals. The net benefit of introducing SES capacity on grid GHG emissions at the higher renewable case alludes to the potential role of SES at high renewable penetrations. The potential for SES technologies to support renewable integration and GHG reduction goals at higher renewable levels in the future is examined in the following sections.

5.2 Deployment of SES without PEVs at Moderate to High Renewable Penetration

This section examines the role of SES technologies in the future to meet high renewable targets without the deployment of plug-in electric vehicles. While the previous section discussed the role of SES within present-day grid dynamics at intermediate renewable levels looking specifically at GHG reduction potential, this section discusses the potential role of SES to help achieve moderate to high renewable penetration, taking into consideration the future increase in electricity demand associated with population growth.

5.2.1 Metrics

Renewable Penetration. As in the analysis presented in Section 5.1, this refers to the degree to which renewable resources supply electricity. However, in this analysis, the renewable capacity is scaled to meet a load profile reflecting California's population growth to (a) 2030 and (b) 2050 with a target renewable penetration of (a) 50% and (b) 80%, respectively. In order to ensure that each year's renewable target is met, the theoretical potential for the year 2030 is 51.5% and for the year 2050, 87%. Potential causes for lower realized versus theoretical renewable penetration include renewable curtailment, transmission losses, and round trip efficiency losses (in the case that energy storage technologies are employed). Two additional scenarios for 2050 were run to examine the impact of increasing renewable capacity on the energy storage requirements to achieve a target renewable penetration. In 2050, solar power will be the only renewable resource that has not reached its maximum potential capacity. Therefore, when the renewable capacity is scaled up, it is PV and CSP capacity that increases (Table 9).

Table 9. Installed Renewable Capacity for Years 2030 and 2050

Year	%RE	Theoretical %RE	Solar PV	Solar CSP	Wind	Geothermal	Small Hydro	Biopower
2030	50	51.5	9.2	10.9	30.39	4.8	1.29	4.65
2050	80	87	45	45	30.39	6	1.29	4.65
2050	80	100	60.25	60.25	30.39	6	1.29	4.65
2050	80	125	88.25	88.25	30.39	6	1.29	4.65

Stationary Energy Storage Capacity. This refers to the rated power and energy capacity of the SES fleet deployed. Vanadium redox flow batteries (VFB) are used here as the deployed SES technology. This technology selection allows for both power and energy capacity to be independently spanned. Also, flow batteries are not geographically limited like pumped hydro or traditional forms of CAES whose deployment in California may be limited by site availability. The specific VFB parameters used in this study are in Table 10. For the year 2030, select power and energy capacities for a SES fleet are examined: 1% and 10% renewable capacity and average daily renewable generation.

For the year 2050, the target renewable penetration cannot be achieved without SES. Therefore, a full range of SES power and energy capacities is tested. The power capacity of the SES fleet is spanned up to 50% of the renewable power capacity (61 GW) and the SES energy capacity is spanned up to 2% of annual renewable generation (6 TWh) in order to observe the full range of impacts on renewable penetration for different power to energy ratios.

Table 10. Stationary Energy Storage Parameters

Storage Type	Maximum Individual Unit Power	Round-trip Efficiency	Charge to Discharge Power Ratio	Spanning Power Capacity	Spanning Energy Capacity
Vanadium Redox Flow Batteries (VFB)	10 MW	75%	0.8	0-61 GW	0-6 TWh

5.2.2 Scenarios

The deployment of SES technologies to achieve 50% renewables in 2030 and 80% in 2050 is examined. The 50% renewable target is based on SB 350, while the future target of 80% is a hypothetical goal based on a continued growth of renewable deployment in response to climate change policies. The electric load profiles used for each year are extrapolated from the current California profile, assuming constant per capita energy use. A summary of the scenarios for the deployment of SES without plug-in vehicle charging is in Table 11. These consist of two base cases without energy storage deployment for the years 2030 and 2050, select energy storage cases for 2030, and three spanning cases for the deployment of energy storage for three different installed renewable capacities for the year 2050.

Table 11. Scenarios for Years 2030 and 2050, No EVs

Year	Target % RE	Theoretical % RE	SES Power Capacity	SES Energy Capacity
2030	50	51.5	—	—
2050	50	87	—	—
2050	50	100	—	—
2050	50	125	—	—
2050	80	87	Spanning (0-132 GW)	Spanning (0-18 TWh)
2050	80	100	Spanning (0-132 GW)	Spanning (0-18 TWh)
2050	80	125	Spanning (0-132 GW)	Spanning (0-18 TWh)

5.2.3 Results

5.2.3.1 Year 2030, 50% Renewables

A 50% renewable penetration was achieved for the year 2030 without the need for SES capacity. A time series of the 2030 base case is presented in Figure 24. (Note “STA Load” for stationary load is used here to distinguish between stationary load and the vehicle load examined in the following analyses.) Electricity demand has grown in proportion to California population growth. As the figure shows, renewable generation was below demand for nearly all time periods, leading to a curtailment of less than 0.3% of available renewable energy.

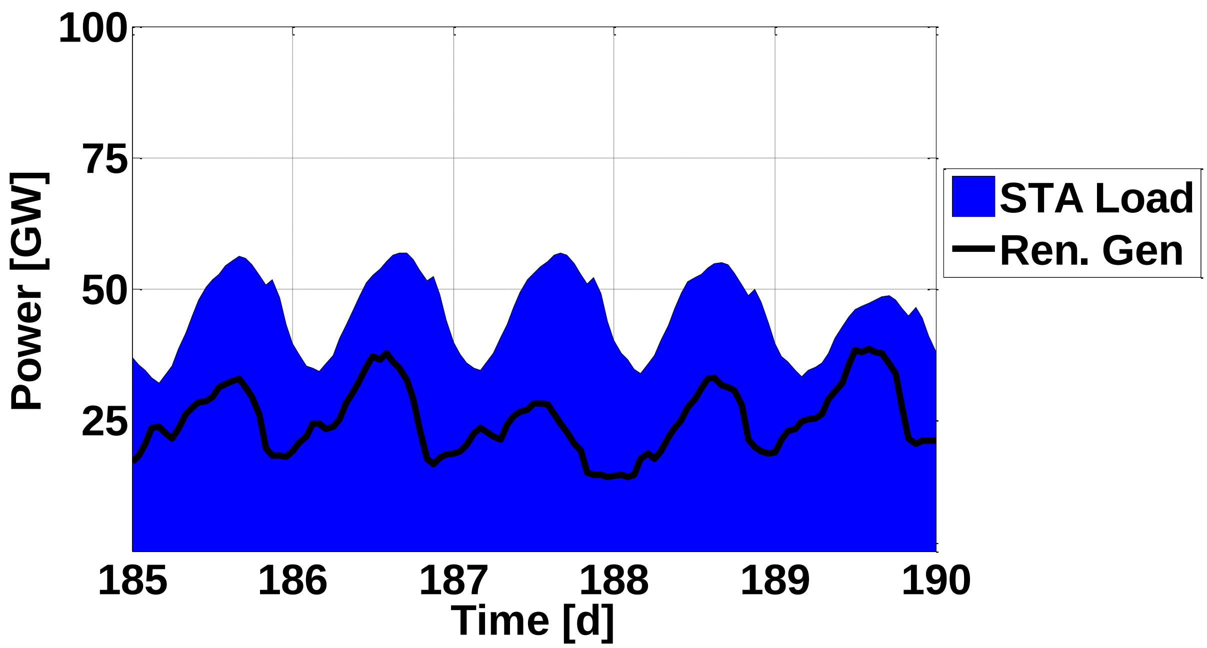


Figure 24. Year 2030 Time Series—Load Profile and Renewable Generation

Because renewable curtailment fell below 1%, no SES scenarios were run for the year 2030. The maximum retrievable renewable energy would have been 75% of 0.3% of total renewable generation (taking into consideration round-trip efficiency losses). The target renewable penetration was achieved without the need for installing energy storage technologies.

5.2.3.2 Year 2050, 80% Renewables

Without the addition of SES capacity, 80% renewables was not reached for any of the three renewable capacities examined in this study. For the scenario with a theoretical renewable penetration of 87%, only 71% renewables was realized. The target renewable level was not met due to the misalignment of renewable generation and electricity demand, as seen in Figure 25. Renewable generation during midday—peak solar production—is in excess of demand at that time and is, therefore, curtailed. On the other hand, in the late afternoon, renewable generation drops off while electricity demand remains high. The varied timing of generation and demand leads to an under-utilization of available renewable energy.

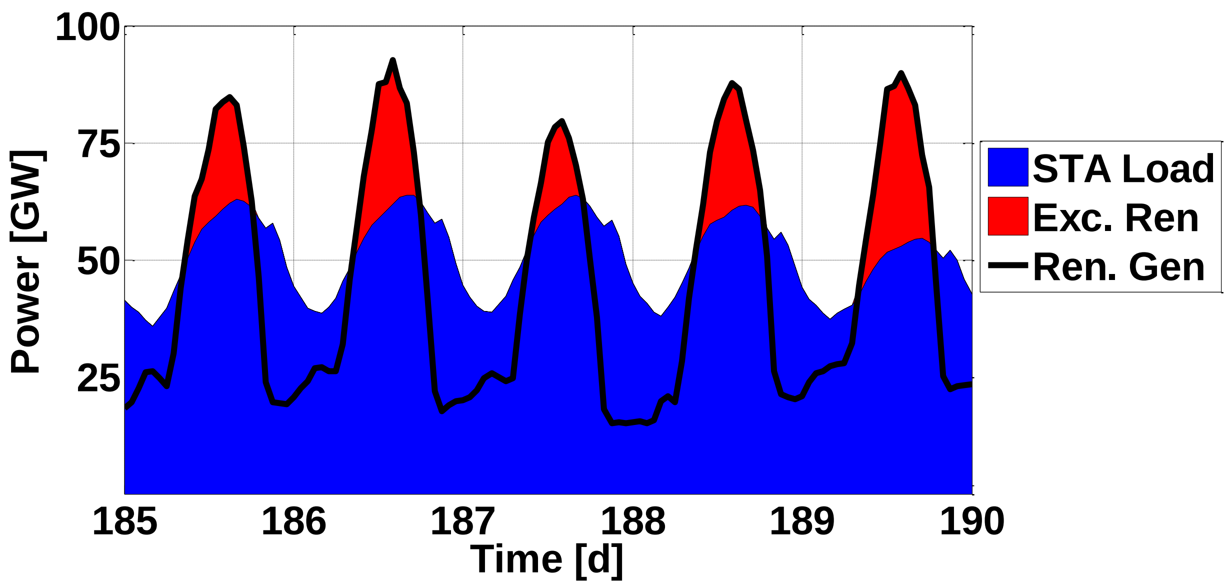


Figure 25. Time Series for 80% Renewables, Year 2050 No EVs

Increasing the installed renewable capacity from a theoretical renewable penetration of 87% up to 100% increases renewable penetration by only 1.4%; further increasing installed renewable capacity up to 120% increases the realized penetration by another 1.2%, for an overall renewable penetration of 73.6%. The effect of increasing renewable capacity on the renewable generation profile is represented in Figure 26. Increasing "renewable capacity" in 2050 implies increasing installed solar PV and CSP as the rest of the renewable technologies are assumed to have already reached their full potential capacity. Increasing solar generation increases the renewable peak midday, given the solar profile previously shown in Figures 6 and 11. This peak is already being curtailed, so increasing solar primarily contributes to an increase in curtailed energy.

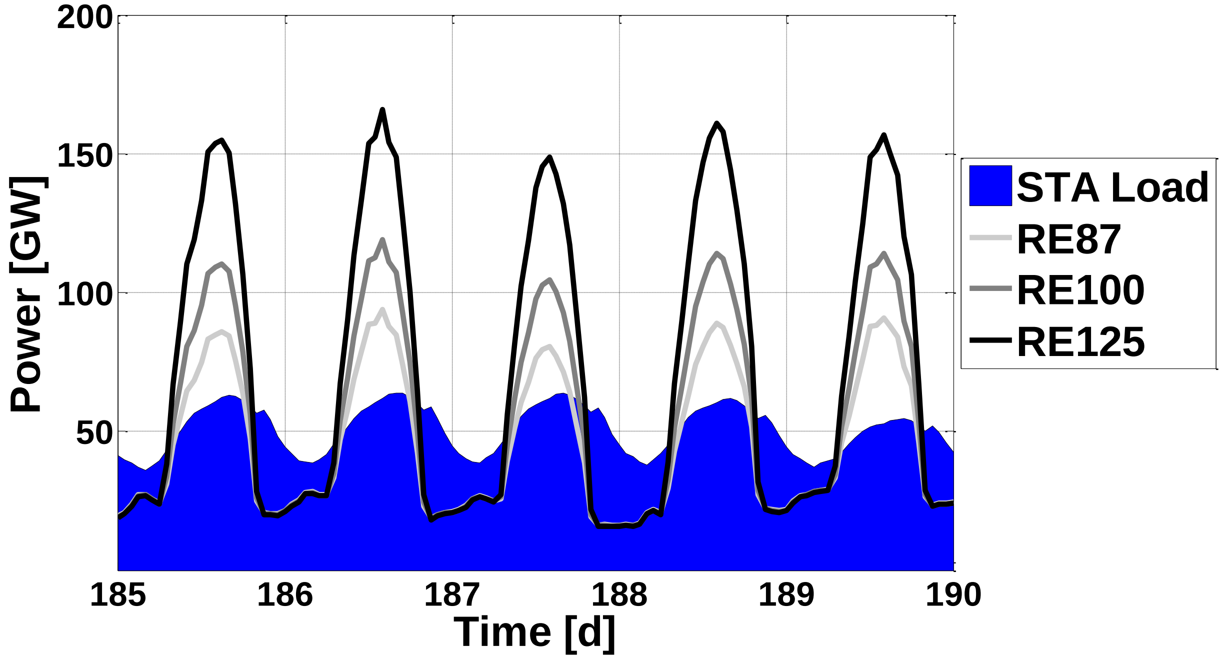


Figure 26. Renewable Generation Profile for Increased Installed Renewable Capacity

Examining the deployment of SES capacity, it was observed that renewable penetration increased with increased SES capacity, dependent on both power and energy capacity of the SES fleet (Figure 27). For a given power capacity, increasing energy capacity increased renewable penetration up to a point. After that point, power capacity needs to be increased in order to increase renewable penetration. With a theoretical renewable level of 87%, the minimum SES capacity to achieve 80% renewables was 35 GW and 2400 GWh, equivalent to 26% of renewable power capacity and 0.8% of annual renewable generation. The energy capacity required could supply 2.5 days of average load.

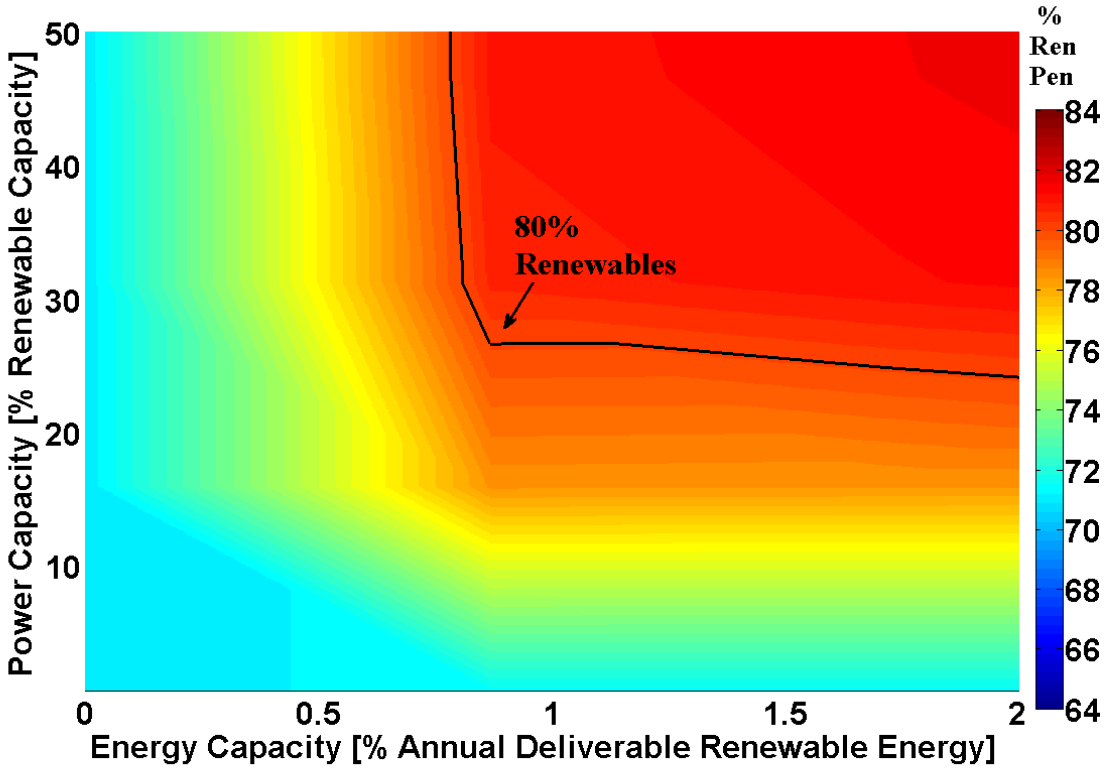


Figure 27. Renewable Penetration vs. Energy Storage Capacity for No EVs—80% RPS

Scaling of the SES capacity for the 100% and 125% renewable scenarios showed the same trend as for the 87% scenario: renewable penetration is dependent on both power and energy capacity. Increasing one will increase renewable penetration until a point where the other becomes limiting.

Figure 28 examines a time series plot of one scenario with SES capacity that meets the 80% renewable target (87% theoretical), showing that the SES charges during the day, coinciding with peak renewable generation that was previously curtailed in the base case scenario. The SES then discharges during the late afternoon and evening to partially satisfy electricity load demand when renewable generation is low.

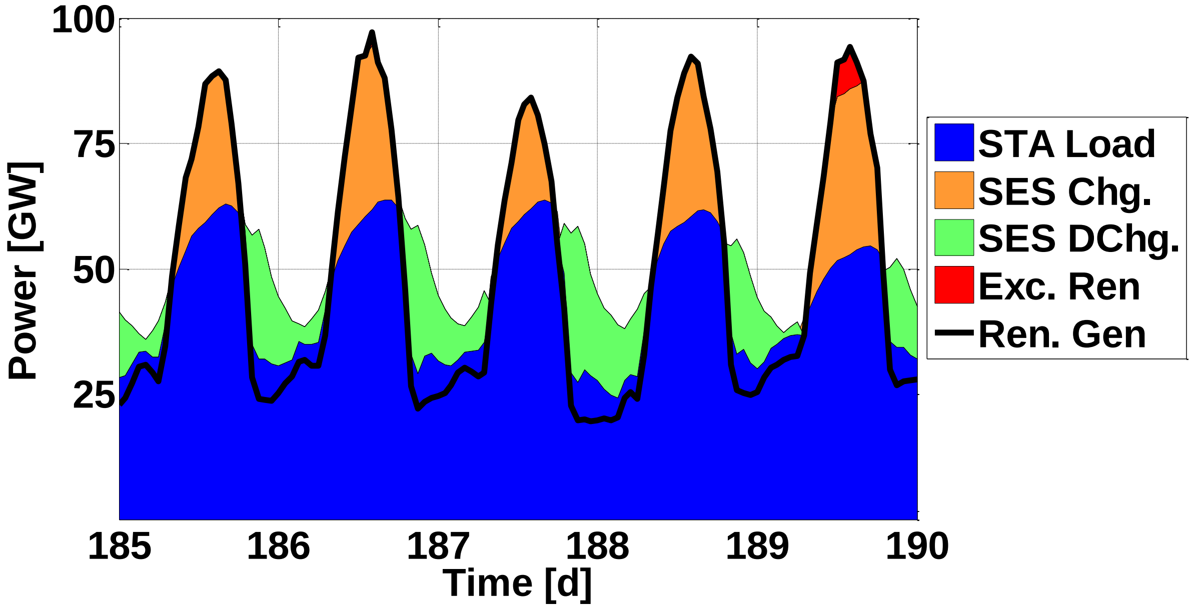


Figure 28. Year 2050 Time Series with SES Capacity—80% RPS

As renewable capacity was increased, minimum SES capacity to reach 80% renewable decreased. The minimum SES capacities for each case are summarized in Table 12.

Table 12. Minimum SES Capacity at Different Theoretical Renewable Penetrations

Theoretical RE (%)	Base RE (%)	Minimum Power Capacity at 80% RE (GW)	Minimum Energy Capacity at 80% RE (GWh)
87	71.0	35	2,400
100	72.4	16	1,200
125	73.6	12	300

Increasing the theoretical renewable penetration from 87% to 100% not only increases base renewable penetration but also decreases the minimum SES power and energy capacities by about 50%. Increasing the potential renewable penetration from 100% to 125% decreases both the minimum SES power and energy capacities by 25% and 75%, respectively. The new SES energy capacity for the 100% theoretical case can store up to 1.25 days of average electricity load demand and the 125% can store up to 0.3 days. There is a general trend that as installed renewable capacity increases, the maximum amount of energy needed to be stored by the SES fleet to reach the target renewable penetration decreases. However, for each marginal increase in installed renewable capacity, the marginal change in both renewable penetration and the minimum SES capacity required to reach 80% renewables decreases, such that a maximum for renewable penetration and a minimum for SES capacity required will eventually be reached (Figure 29).

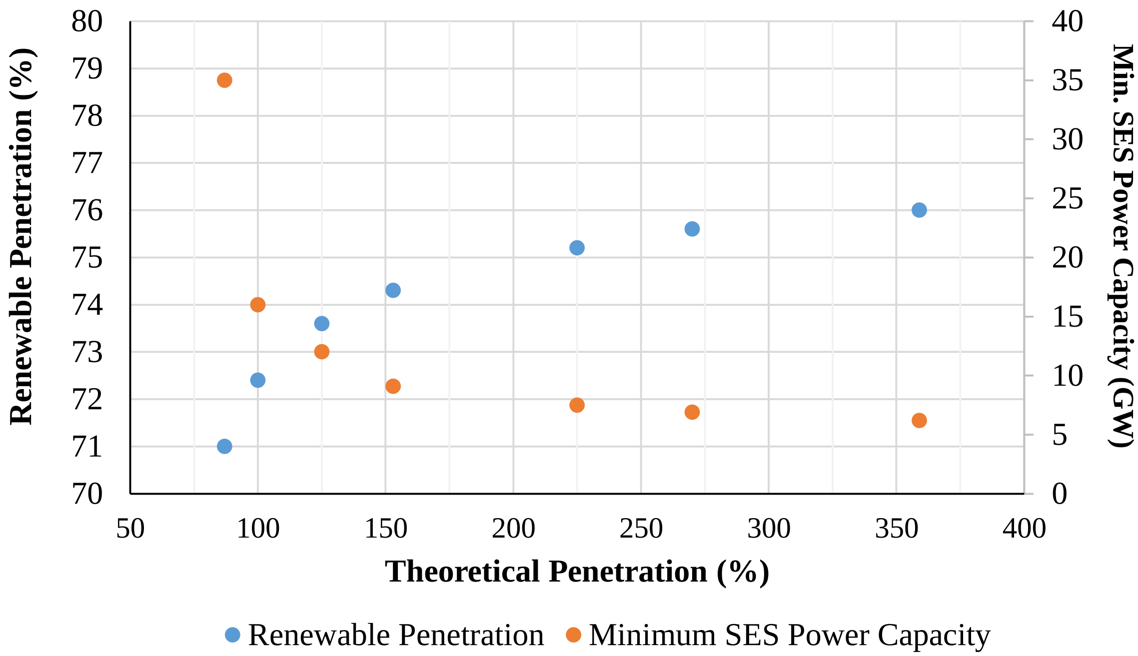


Figure 29. Impact of Increasing Renewable Capacity on Renewable Penetration

As Figure 29 shows, increasing the annual renewable generation (ie. theoretical renewable penetration) to over 400% of annual electricity demand still yields a renewable penetration below the 80% target. At this level of installed renewable capacity (over 800 GW), an SES capacity on the scale of 5 GW, 150 GWh is still required to achieve 80% renewables.

5.2.3.3 Summary

For the year 2030, 50% renewables was reached without the addition of SES capacity. In comparison, for the year 2050, the target renewable penetration of 80% could not be reached by solely scaling up renewable capacity, but rather, required the deployment of SES capacity. SES was generally deployed to charge during the day to capture otherwise curtailed renewable generation, and to discharge during the evening to offset non-renewable generation. The ability of SES to shift energy across this timescale contributed to increased renewable utilization and the target renewable penetration of 80% was achieved.

Over-installing renewable capacity, such that annual renewable generation far exceeded 80% of total electricity demand, minimally increased realized renewable penetration, and primarily contributed to curtailed energy. Nevertheless, increasing installed renewable capacity significantly decreased the scale of SES capacity required to reach the target renewable penetration. At higher renewable capacities, annual renewable generation increased and more days experienced curtailment at midday. This increased the number of days that could support evening demand with daytime renewable generation and reduced the amount of energy that needed to be shifted across multiple days.

5.2.3.4 Discussion

For the 2050 scenario with a theoretical renewable penetration of 87%, the scale of SES capacity provides enough energy to support over two days of load. This indicates there is enough energy stored to provide grid support for extended periods when renewable generation is extremely limited or wholly unavailable, either due to weather conditions or a seasonal drop in solar or wind availability. Increasing the theoretical renewable penetration not only decreased the power capacity but also the maximum storable energy of the SES fleet. This indicates that there is a decreased need for shifting renewable generation between long time periods. Instead, the function of the SES fleet changes to shifting energy at shorter time periods. At higher installed renewable capacities, on average, there is enough peak renewable generation available each day that can be captured and discharged that same evening. The SES fleet, therefore, does not need to store energy across multiple days in order to support days that do not have enough renewable generation to meet electric load demand.

This study assumed the load characteristics and renewable potential of the California grid system. (The load profiles used are quite similar to those in other countries, such as Germany. However, the potential for each renewable technology and by extension the ultimate mix of renewable resources can vary greatly between grid systems. Germany has a greater potential for wind power and lower potential for solar power, but still must manage the variability of both renewable resources.) A mix of renewables with higher wind versus solar generation may yield reduced diurnal variability but greater seasonal variability and therefore the need for energy storage is not necessarily reduced. Instead, this mix of renewables may require a combination of different SES technologies in order to meet both daily variability and the increased need for seasonal shifting of renewable generation.

Increasing renewable capacity successfully decreased the scale of SES capacity required to reach the target renewable penetration. However, even high renewable capacities did not remove the need for energy storage technologies and over-installing renewable capacity may have additional disadvantages that may make this strategy unfeasible. In particular, high curtailment levels lead to the underutilization of the renewable fleet and renewable plant operators may not be able to sell enough of their generation to the grid to overcome the cost of generation. Over-installing renewable capacity may also negatively impact water resources, because at high renewable utilization, a large fraction of new generation may come from CSP plants. The impact of CSP capacity on water resources in explored in Section 5.4.2.

This analysis highlights the need to appropriately size the SES fleet in order to achieve the desired level of renewable integration. Oversizing of SES at moderate renewable levels can lead to an increase in grid GHG emissions and decreased renewable penetration if allowed to charge with non-renewable, carbon-intensive generation. Under-sizing of the SES capacity will limit the degree to which renewable generation will be utilized, especially at high renewable levels. Over-installing renewable capacity will in part decrease the need for SES capacity. Though, in this study the marginal benefits decreased with increased renewable capacity. This is due largely to the type of renewable resources (solar PV and CSP) being installed. For another grid system, where the mix of renewable resources is different, the impact of over-installing renewable capacity may vary. Energy shifting may still be required but the capacity and the timescale (day versus seasonal) of shifting may change. However, one trend will hold: if increasing installed renewable capacity increases already curtailed energy, renewable penetration will not increase but the amount of SES capacity required to reach a target renewable penetration may decrease.

5.3 Deployment of SES with PEVs at Moderate to High Renewable Penetration

This section examines the impact of the electrification of the LDV fleet on the scale of SES required to reach high renewables. This study builds on the methodology developed in the analysis presented in the preceding section, now taking into consideration plug-in electric vehicle charging on the grid and how this additional load and its associated dynamics can either hinder or aid the advancement of grid GHG reduction goals. It considers the additional influence of charging intelligence on renewable integration and the associated demand for additional technologies to provide load shifting services in order to achieve a target renewable penetration.

5.3.1 Metrics

Renewable Penetration. As in the previous analysis, the target renewable penetration for year 2030 and 2050 are 50% and 80%, respectively. However, the renewable portfolio capacity is increased compared to the previous study to compensate for the additional electricity demand associated with BEV charging. Again, for the year 2030, the theoretical renewable potential is 51.5% and for 2050, 87%. Energy losses include the reasons listed in Section 5.2.1, with the addition of efficiency losses associated with charging the BEV fleet.

Table 13. Renewable Fleet Capacity for 50% and 80% RE

Year	Target RE (%)	Solar PV	Solar CSP	Wind	Geothermal	Small Hydro	Biopower
2030	50	12.8	12.8	27.5	4.80	1.29	4.65
2050	80	88.25	88.25	30.39	6	1.29	4.65

Stationary Energy Storage Capacity. The methodology from Section 5.2 is used for this analysis. Again, VFBs serve as the SES technology deployed. For the year 2030, select SES cases are examined: 10%, and 50% RE capacity/average daily renewable generation. For the year 2050, the SES power capacity is spanned up to 100% of the renewable power capacity, now 218 GW, and the associated energy capacity is spanned up to 6% of *annual* renewable generation, now 26 TWh.

Charging Intelligence. This refers to the level of communication that the charging vehicle fleet has with the grid. The three charging intelligences considered in this study are immediate, smart, and V2G. An overview of each of these charging strategies is in Section 2.3.1.

5.3.2 Scenarios

The dual deployment of SES and plug-in electric vehicles on the grid to achieve 50% and 80% renewable penetration is examined for the years 2030 and 2050, respectively. The deployment of plug-in electric vehicles was modeled using parameters that correspond to the performance of battery electric vehicles (BEVs) on the road today. Specific parameters are listed in Table 14. EVSE was assumed to be universally available at both home and work.

Table 14. Plug-in Electric Vehicle Parameters

Parameter	Description or Value
Vehicle Type	Battery electric vehicle
Vehicle Efficiency	0.423 kWh/mi
Vehicle Range	200 mi
Charging Efficiency	85%
Maximum Charger Power	10 kW
Charging Infrastructure Available	Home and Work
Charging Strategies	Immediate Smart V2G

*weighted average of passenger, light SUV and truck (0.344-0.462 kWh/mi)

The California BEV fleet is assumed to grow from current levels to moderate levels (about 28.88% of the LDV fleet) by 2030 and high penetration (80%) by 2050 in line with the California Air Resources Board projections for ZEV adoption required to meet the 2050 air pollution and GHG emission reduction goals [120]. The impact of charging intelligence was also examined, exploring the potential role of increased network communication in increasing renewable utilization and thereby lowering SES capacity requirements. A sensitivity analysis was conducted to examine the effect of BEV fleet size on SES capacity required to meet the 2050 renewable target. A summary of the scenarios for this analysis is in Table 15.

Table 15. Summary of SES and BEV Scenarios

Year	Target RE (%)	BEV Pen (% of LDV Fleet)	Charging Strategy
2030	50	28.88	Immediate
2030	50	28.88	Smart
2050	80	80	Immediate
2050	80	80	Smart
2050	80	80	V2G
2050	80	50	Immediate
2050	80	50	Smart
2050	80	50	V2G

5.3.3 Results

5.3.3.1 Year 2030, 50% Renewables

For the year 2030, stationary load and vehicle miles traveled were scaled to reflect a population growth to 44.1 million people for the state of California. The charging of BEVs (28.88% of the LDV fleet) was added as a new load to the expanded stationary load, making up 12% of total electricity demand.

5.3.3.1.1 Immediate Charging

Additional storage provided by SES was unnecessary to achieve 50% renewables with immediate charging of the BEV fleet. Renewable generation was lower than electricity demand for almost all time periods (curtailment less than 1.5%). This is illustrated in a time series plot of a five-day period (Figure 30). Stationary load alone exceeded renewable generation, with charging being an additional load above that. Vehicle charging occurred primarily in the late afternoon with some charging occurring outside that time range.

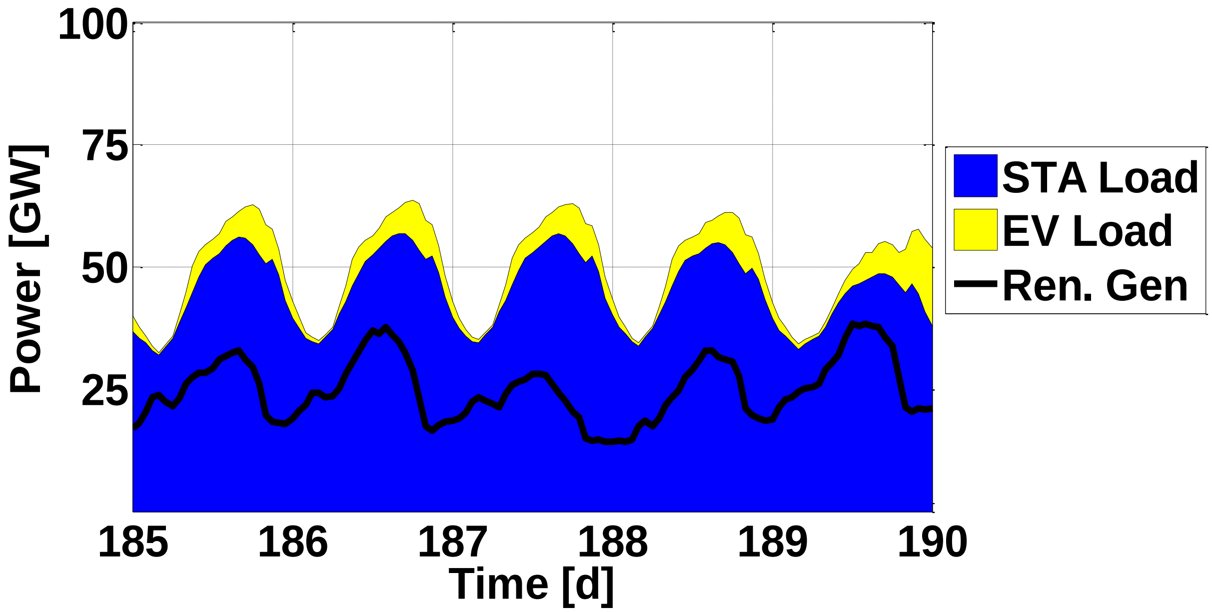


Figure 30. Year 2030 Time Series with Immediate Charging—Load

The misalignment of renewable generation and electricity load demand results in low load follower operation during the morning and midday. In the early evening into the night, load followers and peakers ramp up in order to support demand as renewable generation quickly decreases (Figure 31).

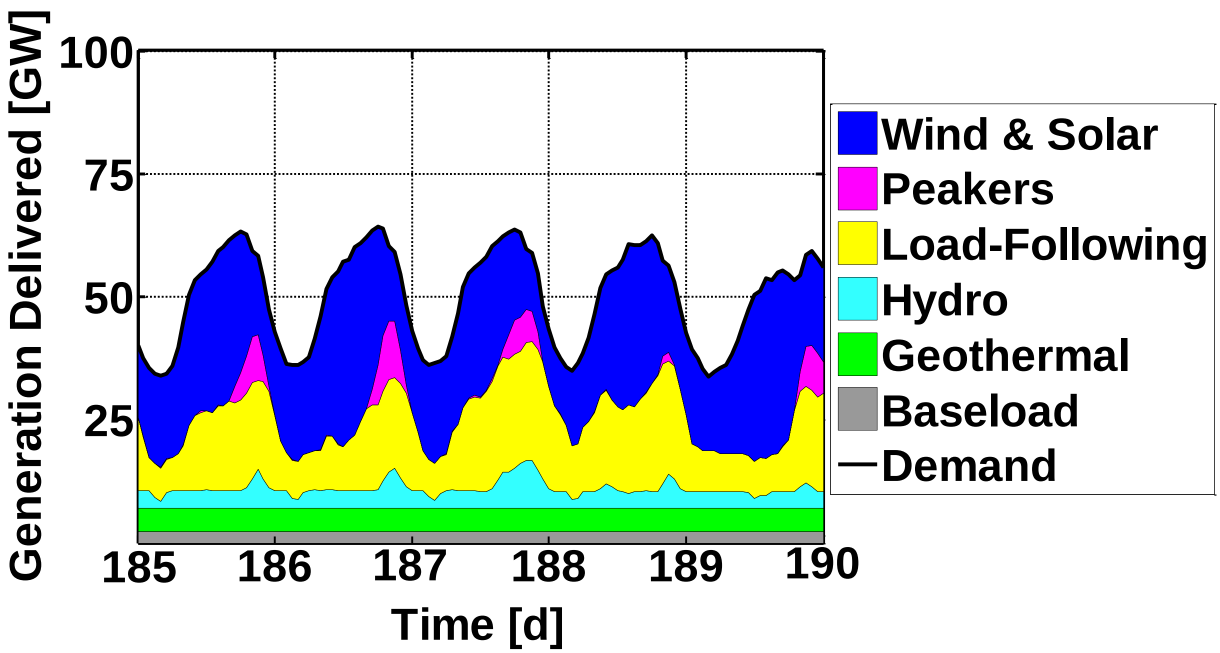


Figure 31. Year 2030 Times Series with Immediate Charging—Generation

The addition of SES capacity slightly increased renewable penetration, with diminishing returns as SES capacity increased (Table 16). A SES capacity equivalent to 50% of renewable capacity (about 32 GW) and 50% average daily renewable generation (about 255 GWh) had a minimal impact on increasing renewable penetration (0.3%). This is only 0.1% up from an SES capacity one-fifth the size.

Table 16. The Effect of SES Capacity for 2030 Immediate Charging Scenario

SES Capacity (% RE Power Capacity, % Average Daily Renewable Generation)	Renewable Penetration (%)
0	50.3
10	50.5
50	50.6

5.3.3.1.2 Smart Charging

Shifting from immediate to smart charging increased renewable penetration, recovering the 1.4% renewable curtailment experienced in the immediate charging scenario. Comparing the two scenarios, smart charging showed increased daytime charging with peak charging occurring midday charging. This resulted in better alignment with the variation in renewable generation (Figure 32).

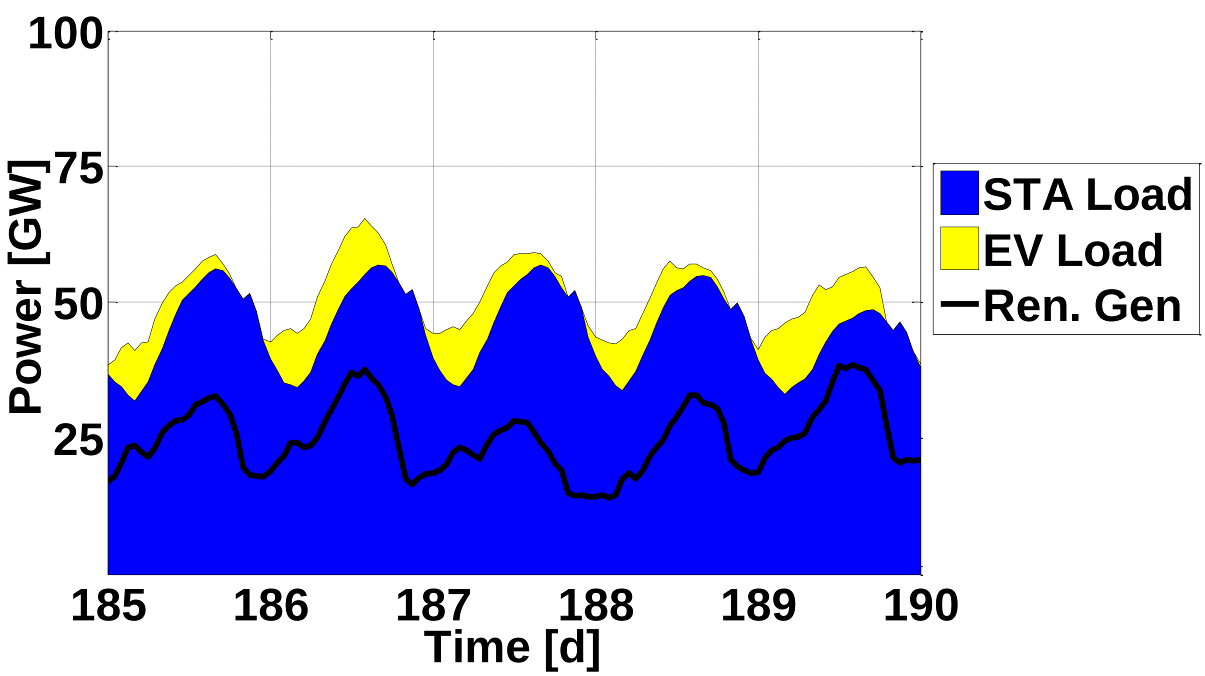


Figure 32. Year 2030 Time Series with Smart Charging—Load

The improved alignment of renewable generation and electric load demand can be further illustrated by examining the dispatch of other generation resources to support the net load. As the time series in Figure 33 shows, there is relatively steady output from load followers, with a slight peak in the late afternoon corresponding to the drop in solar availability. Peakers are called upon on some days to further support this transition period. Comparing the immediate charging and smart charging scenarios, there is less ramping of load followers, leading to higher overall load following generation, and there is decreased reliance on peaker plants (down by 90%).

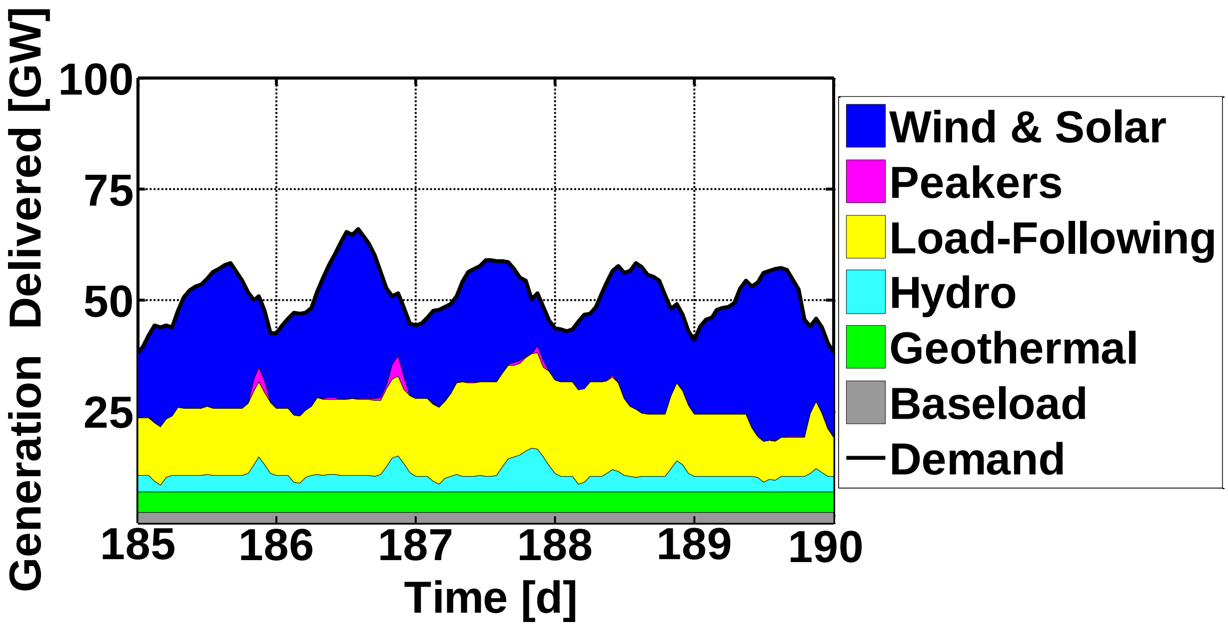


Figure 33. Year 2030 Time Series with Smart Charging—Generation

5.3.3.2 Year 2050, 80% Renewables

For the year 2050, both stationary load and VMT were scaled to reflect a population of 49.1 million people. A BEV fleet equivalent to 80% of VMT was added as a new load, now making up about 30% of total demand. The total electric load demand increased by 75% compared to current levels.

5.3.3.2.1 Immediate Charging

For the year 2050, despite having a theoretical renewable penetration of 87%, the immediate charging of the BEV fleet resulted in high levels of curtailment and a realized renewable penetration of only 56.7%. Employing a strategy of immediate charging led to a charging peak in the late afternoon, higher than the 2030 scenario due to the increase in BEV penetration. At the same time, in 2050, a majority of renewable generation occurs midday due to the high installed capacity of solar power. This misalignment of demand and generation, more significant than in the 2030 case, led to significant curtailment of renewable generation (Figure 34).

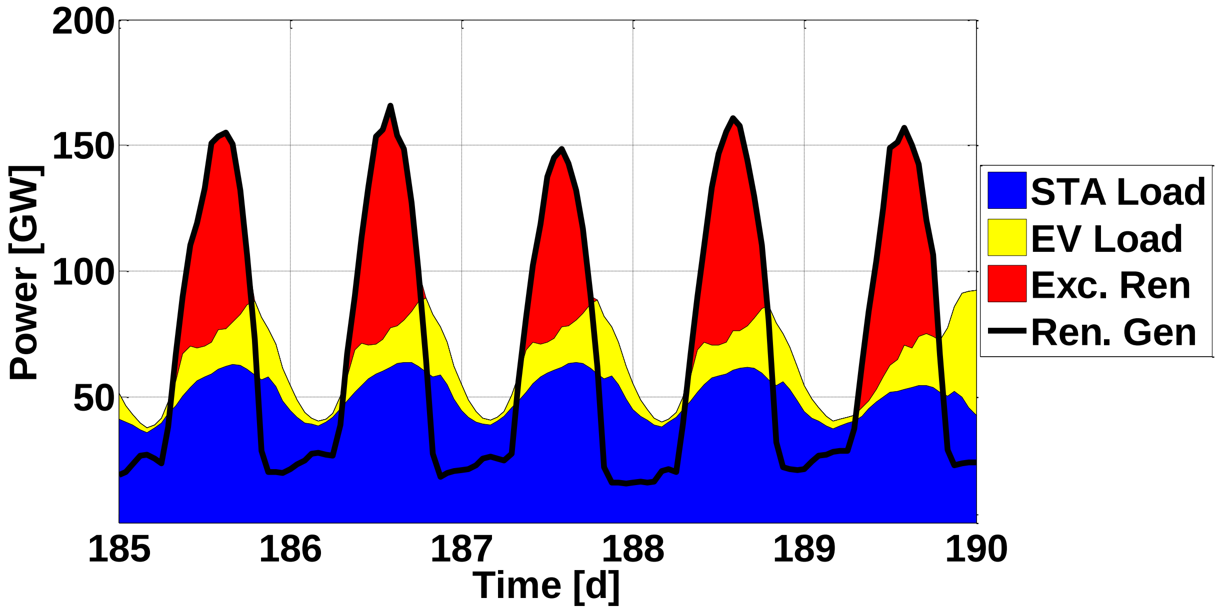


Figure 34. Year 2050 Time Series with Immediate Charging

Installing SES was successful in increasing renewable penetration. The effect of spanning SES power and energy capacities are represented in Figure 34. The contour line denotes the power and energy combinations that result in 80% renewables. For a constant power capacity, increasing the energy capacity increases renewable integration up to the point that power capacity becomes the limiting factor. The same pattern holds when spanning power capacity with a constant energy capacity. The minimum SES capacity required to support a LDV of 80% BEVs and achieve 80% renewables in 2050 was found to be 135 GW and 10,000 GWh. This equates to a SES system that can charge/discharge at 61.5% of the rated power capacity of the renewable fleet and store at any given time about 7.9 days of average demand (about 2.3% of the total annual renewable generation).

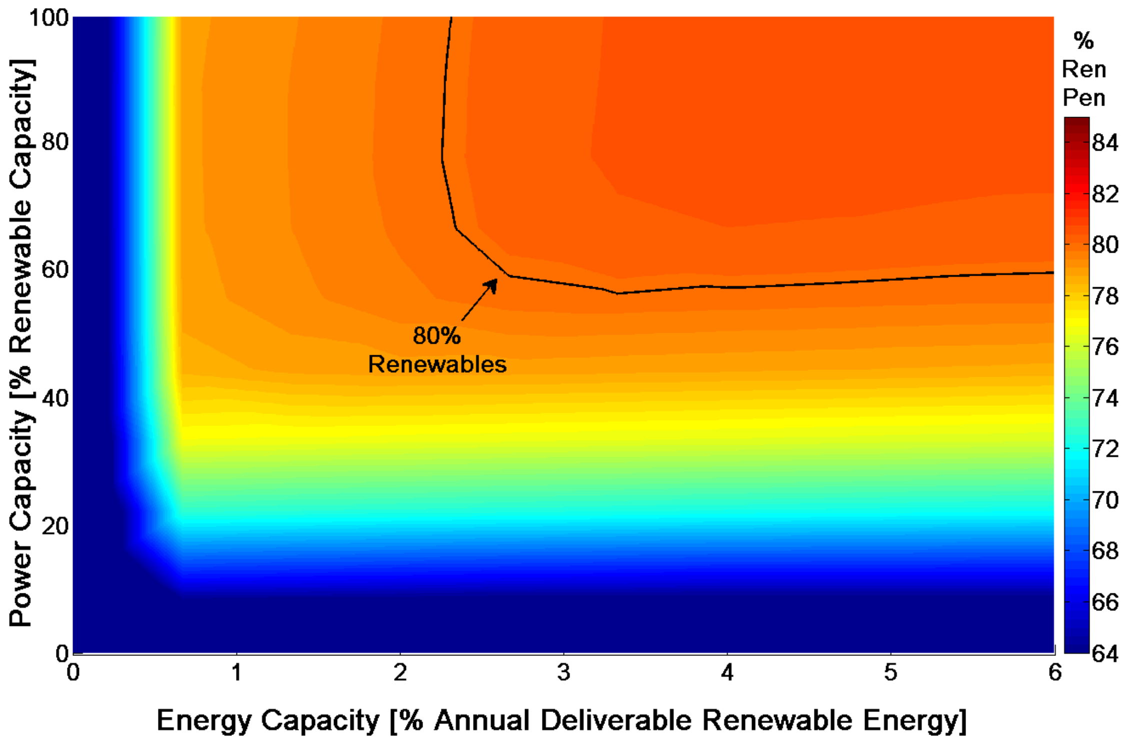


Figure 35. Renewable Pen. vs. SES Capacity with Immediate Charging - 80% RPS Target

A five-day time series for one 80% renewable penetration case is represented in Figure 35. This graph illustrates a few ways in which the installed SES capacity helps increase renewable penetration and improve grid performance. The SES system charges during the day, capturing otherwise curtailed renewable energy, and discharges in the afternoon in line with the drop in solar power and the peak of BEV charging. Effectively, the SES system is able to shift generation from midday to late afternoon. The SES system is also able to decrease the need for other generation resources by sharply ramping up and down in response to the diurnal variation in solar generation. It provides quick dispatch, either charging or discharging, effectively smoothing the net load to which the other grid resources must respond to.

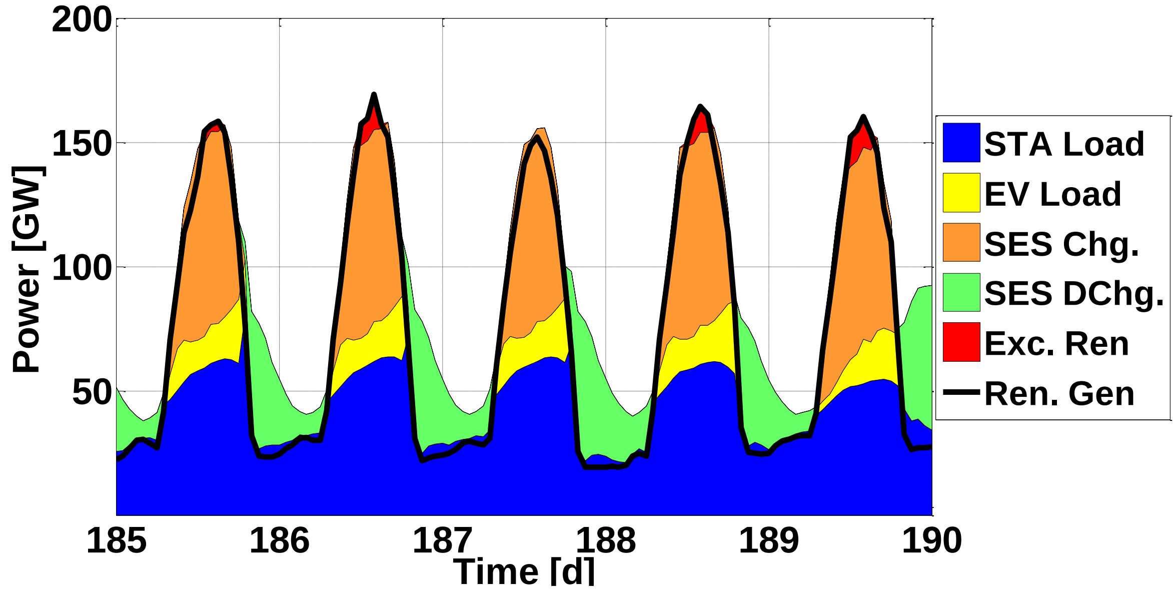


Figure 36. Year 2050 Time Series with Immediate Charging and SES Capacity

Same-day load shifting does not account for the large energy capacity (roughly 7.9 days average load) required to reach 80% renewables. Rather, the large energy capacity indicates that while most load shifting occurs within the day range, there are events in which renewable generation needs to be shifted and discharged over longer, potentially week-long periods. At smaller energy capacities, the SES system is able to capture and later discharge enough energy to shift renewable generation across single-day periods. As the energy storage capacity is increased, however, the system increases its capacity to reserve additional renewable generation for these longer periods when renewable generation is insufficient to meet electricity demand.

Power capacity of the SES system corresponds to its maximum power output and, therefore, directly correlates to the capability of the SES fleet to respond up and down to match renewable dynamics. A given SES fleet can ramp up and down quickly (almost instantaneously for some technologies). However, the minimum and maximum rates of charging/discharging are time-dependent, constrained by the SES's SOC. Depending on the amount of energy stored, a nearly empty battery may not have the capability of discharging enough power over the necessary time period to fully compensate for a sudden drop in renewable generation. On the other hand, a low SOC right before a peak in renewable generation would be beneficial in maximizing the capture of excess renewable energy. An SES fleet with a low power to energy ratio may not be able to take in or discharge energy quickly enough to reach the target renewable penetration. Increasing power capacity will increase the amount of peak curtailment the SES can capture, up to the point that energy capacity becomes limiting.

5.3.3.2.2 Smart Charging of BEVs

Increasing charging intelligence from immediate to smart increased the renewable penetration from 56.7% to 73% (potential 87%). Smart charging of the BEV fleet allowed for the planned charging of vehicles during the day to coincide with available renewable generation (Figure 37).

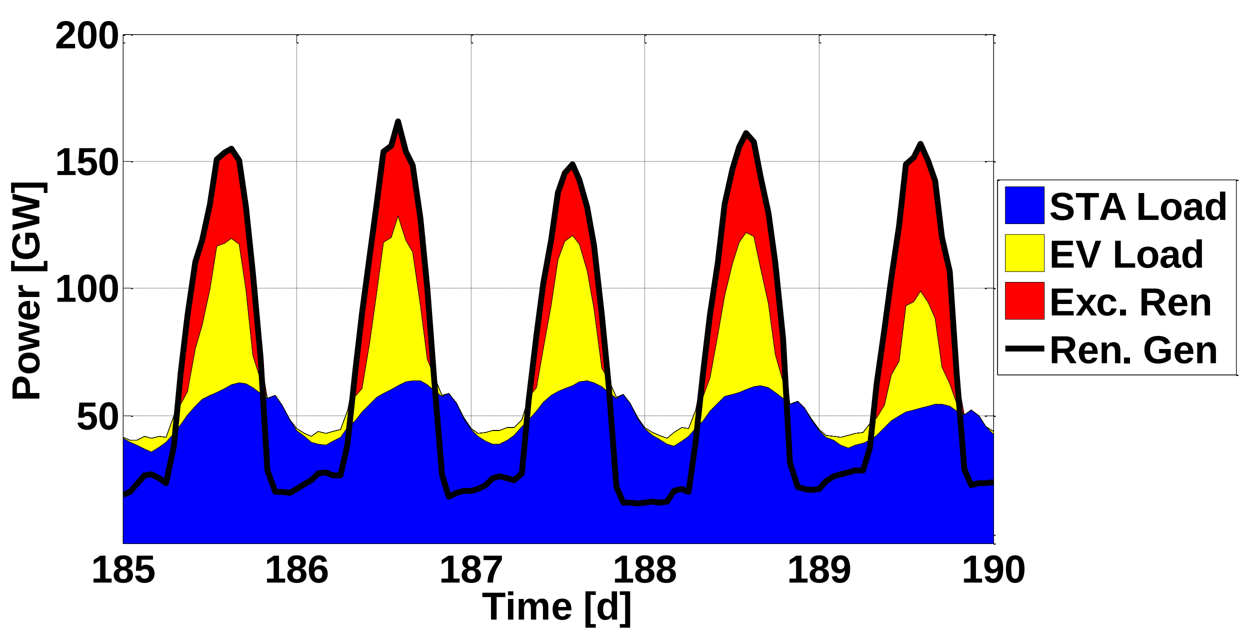


Figure 37. Year 2050 Time Series with Smart Charging

Overall, fleet charging better aligned with renewable generation, decreasing renewable curtailment. A significant amount of curtailment (about 14%) remained due to travel and fleet battery capacity constraints, which (1) forced a portion of the fleet to charge during the evening when renewable generation was unavailable and (2) limited renewable capture during peak generation as the BEV batteries retained a high state-of-charge (SOC) throughout the day. For the first case, a majority of the BEV fleet is charging during the day (predominantly at work). Trips, such as when car owners drive home from work, however, partially deplete the BEV battery in the evening and result in nighttime charging. In the second instance, the ability of the BEV fleet to capture renewable generation is dependent on the available space in the vehicles' batteries. The average distance traveled per day is roughly 40 miles while each BEV battery has the capacity to travel up to 200 miles. This means that if the fleet's batteries are fully charged at the start of the day, after morning driving demands are met (on average <40 miles traveled/vehicle), the car maintains a high state-of-charge and has a limited available capacity to capture that day's excess renewable generation.

Smart charging increased renewable integration; however, the renewable target of 80% was not met. Adding additional SES capacity increased renewable penetration to the target level. Figure 38 shows the effect of spanning SES power and energy capacity on renewable penetration for this case. Like the SES spanning case with immediate charging, for a given power capacity, increasing the SES energy capacity increases renewable penetration up to the point that power capacity becomes limiting. Conversely, for a given energy capacity, increasing the power capacity of the SES system increases renewable penetration up to the point that energy capacity becomes limiting.

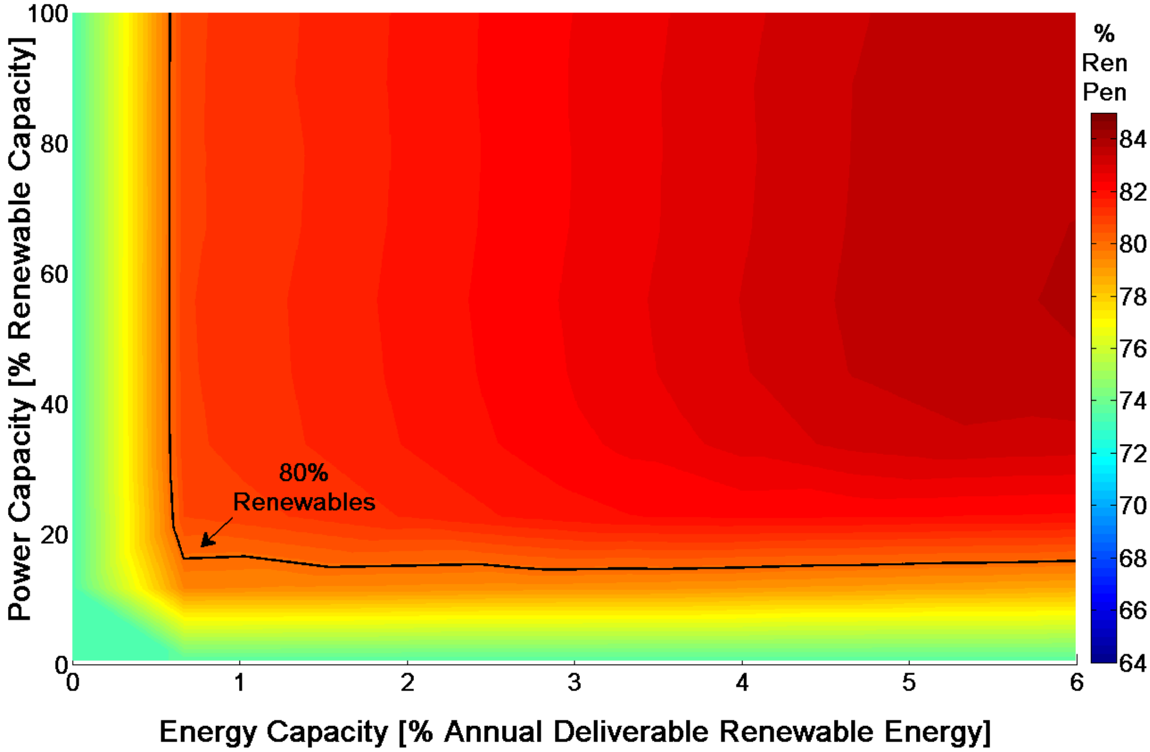


Figure 38. Renewable Pen. vs. SES Capacity using Smart Charging - 80% RPS Target

The improved alignment of renewable generation and electric load demand with smart charging versus immediate charging decreases the amount of overall energy that needs to be shifted to achieve 80% renewables. Smart charging of the BEV fleet significantly reduces both the power and energy capacity of the SES system required to reach 80% renewables. The minimal SES capacity that achieves 80% renewables is about 35 GW (16% of renewable power capacity) and 2530 GWh (0.6% of annual renewable generation). This is an approximately 74% reduction in both SES power and energy capacity compared with immediate charging.

Again, SES predominately provides load shifting in the day range as well as ramping assistance for the diurnal rise and decline of solar generation (Figure 39). Despite improved charging intelligence yielding a better overlap of renewable generation and electricity load demand, there continues to be a pattern of excess storage being retained over a few days to address multi-day events, where renewable generation is insufficient, in order to achieve a renewable penetration of 80%. Smart charging increases the ability of the grid to plan charging events and better utilize the large energy capacity of the BEV fleet, thereby decreasing the size of SES energy storage required.

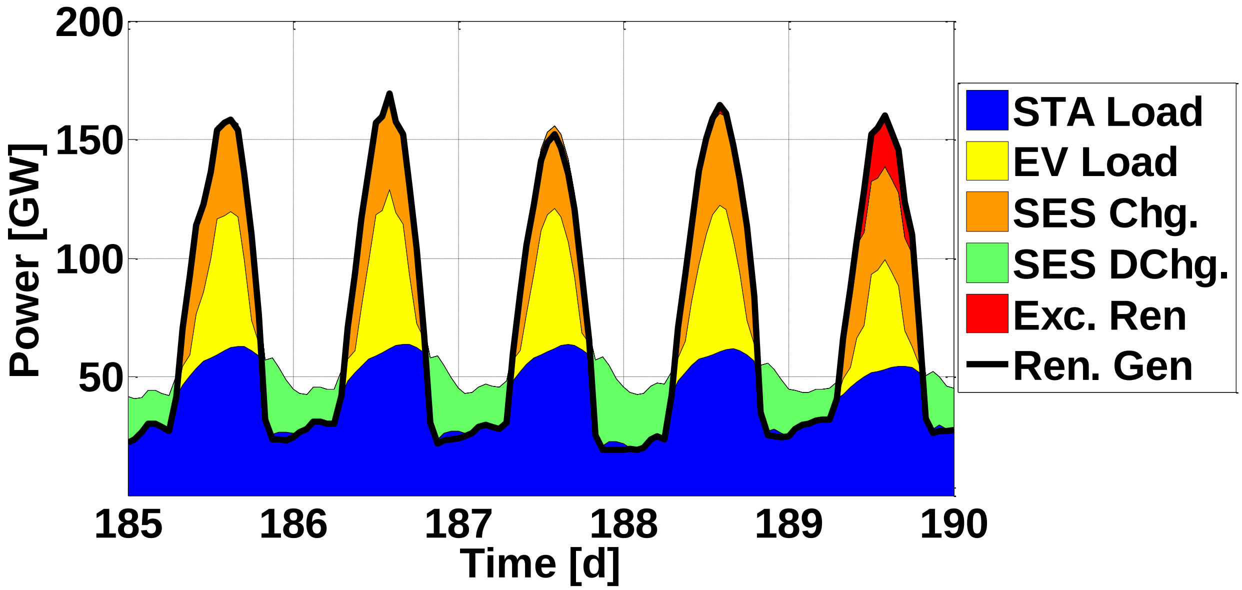


Figure 39. Year 2050 Time Series with Smart Charging and SES Capacity

5.3.3.2.3 Vehicle-to-Grid (V2G) Charging

Switching from smart charging to a vehicle-to-grid (V2G) charging significantly increases the renewable penetration. The 80% BEV scenario with V2G charging exceeds the renewable target of 80%, achieving an 84% renewable penetration without the addition of SES capacity. This is roughly 27% above the immediate charging scenario and 11% above the smart charging scenario. Figure 40 illustrates a time series plot of the system when V2G charging is employed. The BEV fleet charges primarily during the day, aligning with solar renewable generation, and it discharges in the early evening into the night, offsetting non-renewable generation.

Because the BEV fleet is able to discharge under a V2G charging strategy, the batteries' SOC at the start of the day is lower than the smart charging case. This means that when vehicles are plugged in during the day, they have an increased ability to capture otherwise curtailed renewable energy, which in turn leads to higher renewable utilization and decreased curtailment.

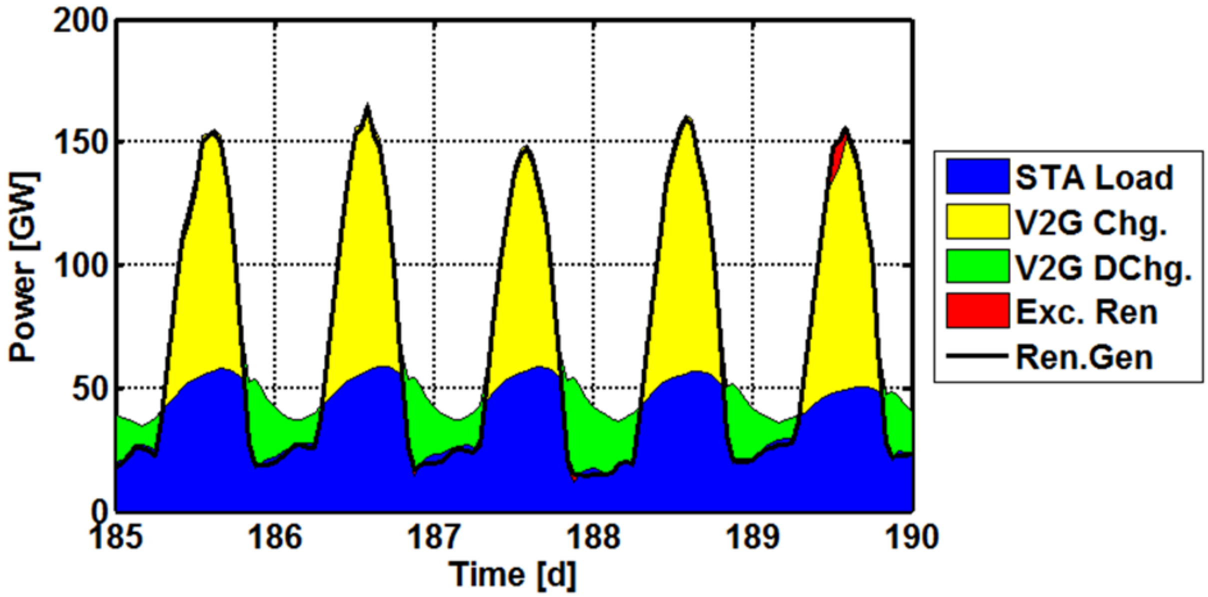


Figure 40. Year 2050 Time Series with V2G Charging

Adding SES capacity to the deployment of BEVs with V2G charging results in a relatively small impact on recovering additional curtailed renewable energy, increasing renewable penetration by roughly 1% for an SES capacity of 218 GW and 26 TWh. This is equivalent to 100% renewable capacity and 6% of annual renewable generation (Figure 41). The maximum theoretical potential of 87% is not reached due to round-trip efficiency losses of the SES network (75% efficient) and the large timescale that energy needs to be shifted in order to recover the last portion of curtailed energy.

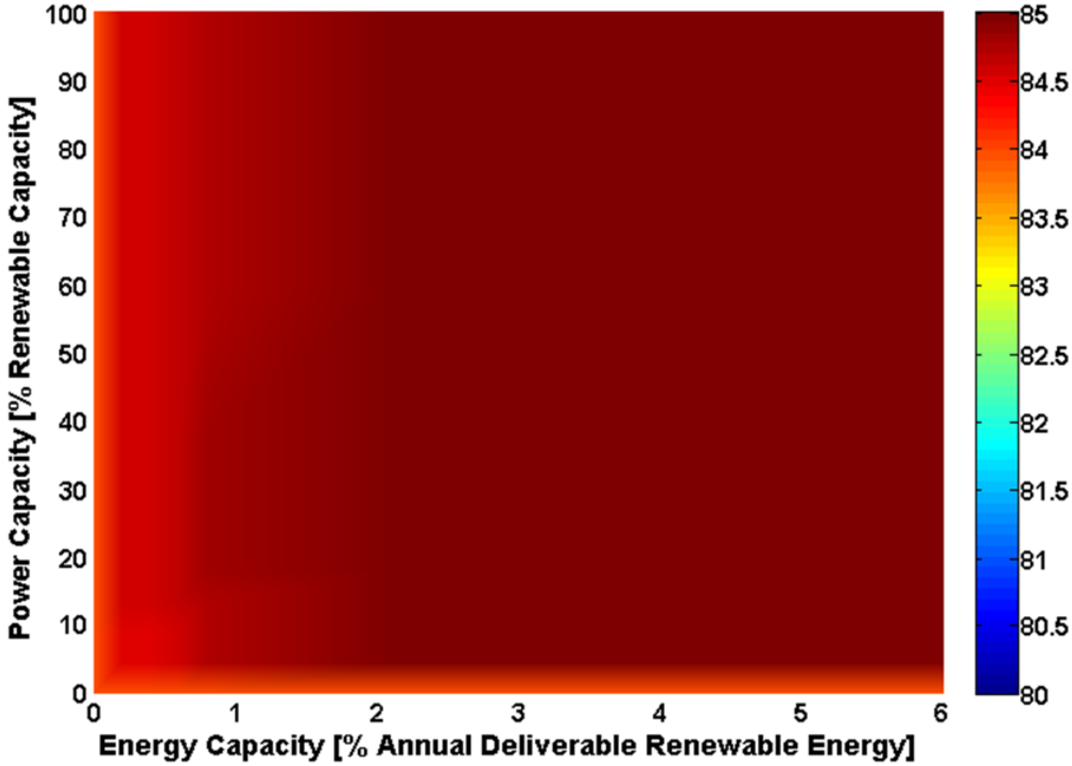
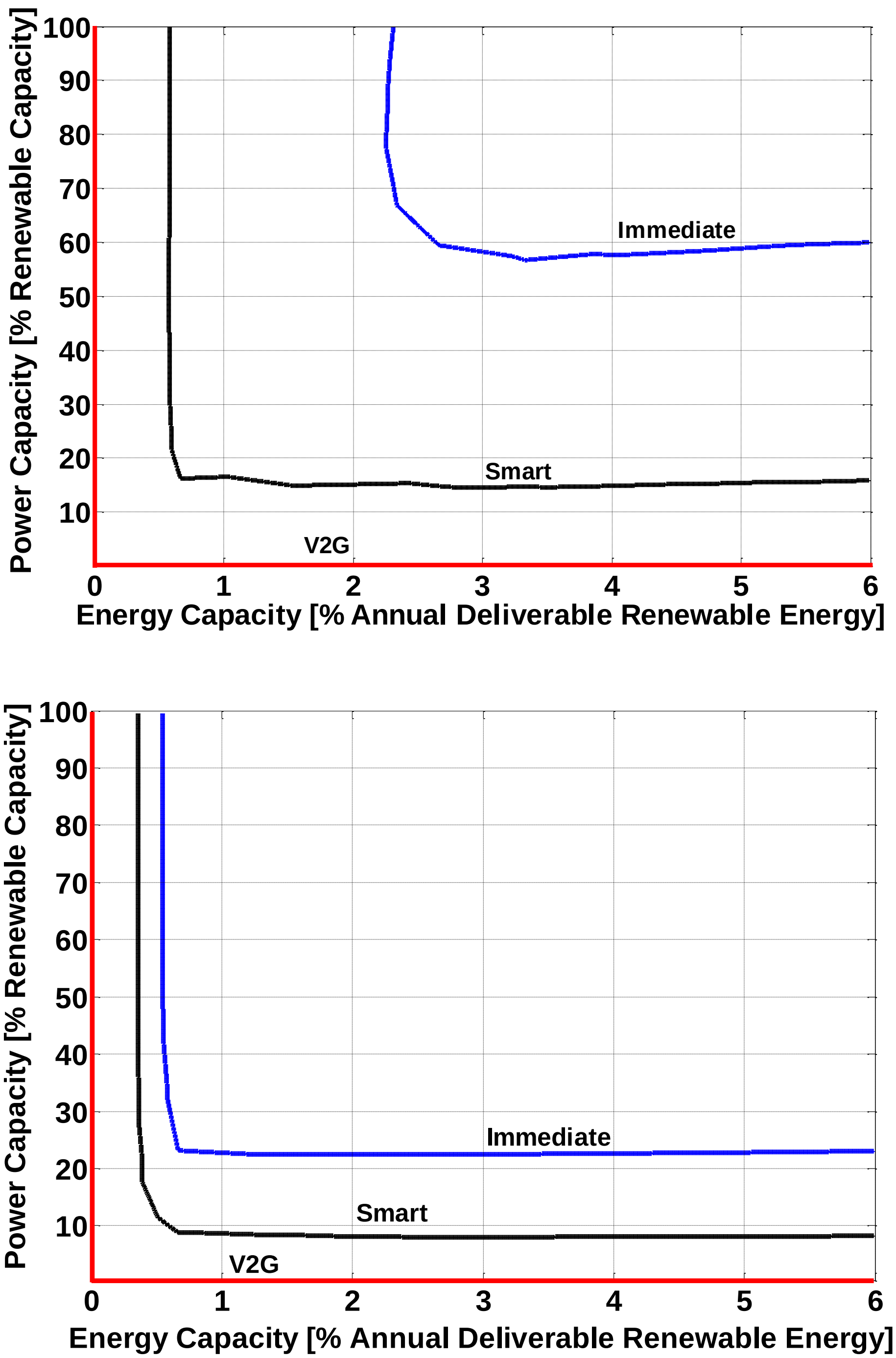


Figure 41. Renewable Pen. vs. SES Capacity for V2G Charging—80% RPS

5.3.3.3 Sensitivity to BEV Penetration

The scale of SES required to reach 80% renewables is dependent on BEV fleet size. BEV charging under immediate, smart, or V2G strategies affects the total system load as well as the load demand profile. Reducing BEV charging demand decreases the overall demand for electricity, thereby decreasing the amount of renewable energy needed to supply 80% of total electricity generation. Decreasing the BEV fleet capacity under smart and V2G strategies also reduces the scale of flexible load that can be shifted to support renewable integration.

When the BEV fleet is reduced, the additional SES capacity required to reach the target renewable penetration of 80% under immediate and smart charging strategies is also reduced. A V2G charging strategy is still able to meet 80% renewables without the need for SES capacity. The effect of decreasing the BEV penetration from 80% to 50% of the LDV fleet on SES capacity under both immediate and smart charging strategies is illustrated in Figure 42. The contour line for V2G charging is placed along the x-y axes to denote that 80% renewables was achieved without SES.



(a)

(b)

Figure 42. (a) 80% BEV Penetration and (b) 50% BEV Penetration

Reducing the BEV fleet decreases annual electricity demand by 10%. To reach 80% renewables with immediate charging, the minimum SES capacity for the 50% BEV scenario is roughly 65% smaller in terms of both power and energy capacity compared to the 80% BEV scenario. With smart charging, reducing the BEV fleet from 80% to 50% of the LDV fleet, reduces the minimum SES power capacity by 37.5% and the energy capacity by 16.7%.

5.3.3.4 Summary

Similar to the results of the previous section, SES capacity is not required to reach 50% renewables for the year 2030 when BEV vehicles are deployed. Comparing renewable penetration for the immediate charging case versus no BEVs, there is minimally higher curtailment with immediate charging (<1.5%) and, therefore, the additional deployment of SES capacity is able to recover a portion of the previously curtailed renewable generation. However, as SES capacity is increased, there are diminishing returns in terms of increased renewable penetration. Smart charging of the BEV fleet allows for improved alignment of load and renewable generation compared to the immediate charging scenario, leading to higher renewable penetration without the addition of SES capacity.

For the year 2050, all scenarios, except those with V2G charging, required additional SES capacity to reach 80% renewables due to the misalignment of load and generation. Immediate charging required the largest SES capacity to achieve the target renewable penetration. Immediate charging increased the total load without providing flexibility of shifting the load to align with excess generation. It was found that with a strategy of immediate charging, BEV charging peaked in the early evening, which did not align with peak renewable generation and instead required that a majority of the fleet be charged using non-renewable resources. This misalignment of total electricity demand and renewable generation resulted in significant renewable curtailment, increasing the scale of SES capacity required to reach 80% renewables compared to the no EV 2050 scenario.

Switching from immediate to smart charging increased renewable utilization by allowing for coordination between vehicle charging and renewable generation. Peak EV load shifted from early evening to midday in line with peak solar generation. By increasing charging intelligence, the scale of SES capacity required to reach the target renewable penetration also decreased but was not fully removed. While the smart charging scenario was able to coordinate charging of the BEV fleet to align with the renewable generation profile, travel constraints and the inability to discharge back to the grid limited the fleet's capacity to increase renewable utilization.

In comparison, the V2G charging scenarios were able to achieve the 80% renewable target by providing both a flexible load that could be scheduled to align with renewable generation and a large battery capacity that could discharge this renewable-based energy back to the grid during periods that would otherwise rely on non-renewable resources. Similar to the smart charging scenarios, V2G charging led to primarily daytime charging. However, V2G charging also provided energy back to the grid in the early evening, supporting the sharp decline in renewable generation associated with the setting of the sun and throughout the night, offsetting non-renewable generation. By discharging back to the grid, the BEV fleet's average state-of-charge (SOC) is decreased, and at the start of the next day, there is an increased capacity to capture peak renewable generation. This led to decreased renewable curtailment and higher overall renewable utilization.

Decreasing the BEV fleet from 80% to 50% decreased the capacity of SES required to reach 80% renewables. Reducing the fleet size decreased the grid load resulting in a higher renewable penetration. However, the percent decrease in required SES capacity was greater for the immediate charging scenarios compared to smart charging. This was due to the improved alignment of BEV charging load and renewable generation. Reducing the fleet size not only reduces load being served by non-renewable resources, it also decreases the portion being served by renewable generation. While the net impact is beneficial in terms of renewable penetration and SES requirements, the change is less significant than the immediate charging scenario where a larger portion of the BEV fleet is being charged with non-renewable resources.

5.3.3.5 Discussion

Overall, increasing charging intelligence decreased the scale of SES capacity required to reach high renewable penetration. Although the deployment of BEVs contributes a new load to the grid, the charging schedule of BEVs was flexible enough with smart charging that a majority of charging events could be planned to correspond with renewable availability. This resulted in improved renewable integration compared to the immediate charging scenarios.

Because charging demands of the BEV fleet must be met, vehicle load demand is not restricted to solely renewable generation, i.e. vehicles can be charged with either non-renewable or renewable resources, depending on the availability of renewable generation and the travel constraints of the BEV fleet. The timing of charging events is therefore key in coordinating charging with renewable generation. This allows vehicles to utilize renewable energy instead of increasing demand for carbon-intensive generation, as was the case for the immediate charging scenarios.

The future deployment of BEVs is dependent on consumer preference and the degree to which EVSE will be available. Intelligent charging EVSE, while being used in limited pilot projects, have not yet been applied in the mainstream market. Access to EVSE is currently limited due to several technical and logistical challenges still being addressed, including siting, construction, and grid-connectivity issues. One such problem is the need for upgraded distribution lines that are able to handle higher local load associated with vehicle charging [120], [121]. In order to meet the emission reductions targets set for the LDV fleet, California needs to expand access to EVSE and other ZEV infrastructure.

This study assumed that EVSE would be universally available to drivers at home and work. Real deployment of EVSE may fall short of this level of access. In that case, charging patterns may be affected and BEVs may be less available to provide grid services, increasing the need for additional technologies to achieve the target renewable penetration. Even with universal access to chargers during the day and night, immediate charging strategies showed a peak in charging demand during the early evening, indicating a general fleet-wide preference for at home charging. For the high renewable cases, the most significant change in charging behavior between immediate and smart charging cases was the shift to daytime charging, which was crucial for capturing peak renewable generation associated primarily with solar generation. This indicates that it is not enough to provide EVSE at locations visited during the day. Communication between the BEV fleet and the electric grid was required to capitalize on BEV battery capacity to capture otherwise curtailed renewable generation.

This study examined the scenarios for the entire BEV fleet using immediate charging or the fleet using smart charging, exclusively. However, the future BEV fleet may use a combination of immediate, smart, and V2G charging strategies depending on access or driver preference. Smart and V2G strategies are just emerging and may be deployed in the near term in a limited number of areas. Also, smart and V2G charging strategies assume that the driver is willing and able to pre-schedule their travel plans and defer charging. This may not be the case for all BEV drivers. There is a need to better understand the charging preference of potential

BEV drivers to better understand how BEV charging will affect the load profile and to better evaluate to what degree vehicles will be available to provide grid services. The potential impact of multiple charging strategies working in concert is a point of future research.

While this study assumed that all zero emission vehicles (ZEVs) deployed were BEVs, the future ZEV fleet may be a combination of plug-in electric vehicles (PEV), plug-in hybrid electric vehicles (PHEV), and fuel cell electric vehicles (FCEV). The future load associated with PEV charging is dependent on the degree to which PEVs are adopted compared to other competing vehicle types. Assuming that a portion of the ZEV fleet is FCEVs, the production of hydrogen from renewable energy may serve as a way to capture otherwise curtailed energy and, at the same time, fuel the LDV fleet. This is a topic for future work.

Decreasing the reliance on SES capacity may help reduce the cost of achieving renewable targets. As the first analysis showed, installing certain types of energy storage technologies can increase LCOE. Reducing SES capacity required to reach renewable targets may also decrease the material and energy costs of manufacturing storage technologies. The deployment of intelligent charging vehicles is one strategy for reducing the need for SES to adjust for the misalignment of generation and electricity demand. However, there exist several demand-side solutions, such as demand response, that could be considered in conjunction with BEVs in order to decrease the need for SES capacity. Additionally, other studies have considered the impact of removing baseload power in increasing renewable penetration [35]. This strategy is effective in reducing grid GHG emissions as long as the generation resources removed were high emitters, such as coal fire plants. For the California grid, the removal of in-state baseload plants would imply the removal of nuclear and/or hydropower plants, which are already net-zero. The removal of these plants may, therefore, actually increase grid emissions despite allowing for increased renewable integration, as was seen after the closure of the San Onofre Nuclear Generating Station (SONGS) [13].

5.4 Water Considerations in Renewable Deployment and Future SES Capacity

5.4.1 Future SES Capacity

Table 17 lists the minimum SES capacities required to reach the target renewable level in each scenario. The largest SES capacity required to reach 80% renewables— 135 GW, 10,000 GWh—was in the scenario considering the high deployment of BEVs with immediate charging. Switching to smart charging with the same BEV fleet reduced the SES capacity by 75%, resulting in a similar SES capacity as the 87% theoretical renewable penetration scenario with no EV deployment.

Table 17. Minimum SES Capacity Requirements for 80% Renewables in 2050

Scenario	Target RE (%)	Theoretical RE (%)	Minimum Power Capacity (GW)	Minimum Energy Capacity (GWh)
No BEVs	80	87	35	2,400
No BEVs	80	100	16	1,200
No BEVs	80	125	12	300
80% BEV Imm. Charging	80	87	135	10,000
80% BEV Smart Charging	80	87	35	2,500
50% BEV Imm. Charging	80	87	47	3,500
50% BEV Smart Charging	80	87	22	2,100

It is unclear whether this scale of SES capacity can be feasibly deployed in the time frame proposed in this study. As previously discussed, the target capacity for new SES installations for California is 1.325 GW by 2020. The scale of SES proposed in this work far exceeds this number and rivals the worldwide capacity for existing SES capacity. It may exceed the potential in California for a single given technology. In particular, it exceeds the pumped hydro potential as calculated by the U.S. Department of Energy. In the near term analysis performed, pumped hydro not only achieved the greatest CO_2e emissions reduction of the three

SES technologies examined, it also did so at the lowest cost. For these reasons, pumped hydro may be a preferred storage technology. On the other hand, since SES capacity demand at high renewables exceeded pumped hydro potential in all cases, except those with exceptionally high renewable capacity, reaching the target renewable penetrations with SES may require the application of multiple SES technologies simultaneously. Additional constraints on pumped hydro include large land requirements, permitting hurdles, and increased fluctuations in water availability due to climate change forcing. The impact of climate change on future water resource availability for hydropower and pumped hydro is a subject for future work.

The results of this work show that load shifting occurs at both the day scale and multi-day scale. This indicates that there may be an opportunity to utilize multiple SES technologies—some that at short time scales, such as pumped hydro, CAES, and flow batteries, and others that can serve as longer-term storage, such as power to gas (P2G) technologies. Utilizing a suite of technologies to achieve the appropriate scale of SES capacity has the potential to draw on the strengths of each to meet California's sustainability goals. Hydrogen production, for example, could serve as both a storage medium and fuel for FCVs. The potential of utilizing otherwise curtailed energy for hydrogen production to subsequently support a FCV fleet is a topic for future work.

5.4.2 Solar CSP Deployment and Water Demands

Over-installing renewable capacity may decrease the scale of SES capacity required to reach high renewable penetration. Even so, as demonstrated, this strategy has its limitations given the dominance of solar generation on the California grid at high renewables. Also, increasing solar CSP capacity to an extreme level may negatively impact water resources in the regions where CSP plants are installed. The CSP capacity used in each scenario is listed in Table 18. As previously stated, California's CSP potential is over 1,000 GW. The values used in this work are below this maximum capacity. The scenario with the largest CSP capacity would require 20% of California's potential capacity and the most frequent CSP capacity used (88.25 GW) would only require 8.8%.

Table 18. CSP Capacity and Generation for Different Scenarios

Year	Scenario	Theoretical RE (%)	CSP Capacity (GW)	CSP Generation (GWh)
2030	No BEVs	51.5	10.9	16,000
2030	28.88% BEVs	51.5	12.8	19,000
2050	No BEVs	87	45	69,000
2050	No BEVs	100	60.25	92,000
2050	No BEVs	125	88.25	136,000
2050	No BEVs	225	200	308,000
2050	80% BEVs	87	88.25	136,000
2050	50% BEVs	87	88.25	136,000

Despite there being adequate CSP potential across the state, the impact of CSP deployment on water availability at the regional level remains of significant concern, given its potentially high water demands in regions that are already water-limited. Although CSP capacity utilized in this work can be met at the state level, future regional water constraints associated with CSP operation may yield a lower sustainable capacity at the county level. The breakdown of CSP technical potential capacity by county, according to the CEC is provided in Table 19.

The CSP county potentials calculated by the CEC is generalized and does not specify a specific CSP technology. These estimates consider geographical areas that have average insolation levels greater than 6 kWh/day/m^2; slope of less than 1^o; and are not occupied by forests, water, or pre-existing built environment (such as roads and existing urban spaces), park lands, or sensitive habitat [28]. The CEC estimates listed above do not consider CSP water impacts. Water demands of a CSP plant are dependent on several factors: CSP technology, plant capacity, cooling system (wet, dry, or hybrid), air temperature, etc. Although water demands differ between CSP technologies, the values are all within the same order of magnitude. The main determinant of water use is the type of cooling system employed. For a wet recirculating cooling system, average water consumption is 500-900 gal/MWh; for a hybrid system, to achieve 99% of full performance, 250-450 gal/MWh is required; for dry cooling, 78-130 gal/MWh with a 1-5% performance penalty depending on CSP technology deployed [94], [98].

Table 19. California CSP Potential by County

County	Total GW	Total GWh
San Bernardino	381	988,017
Imperial	220	547,973
Riverside	127	318,998
Kern	127	330,489
Inyo	102	270,325
Los Angeles	74.2	189,442
Mono	12.1	30,997
San Diego	7.69	18,628
Lassen	7.38	16,377
Plumas	1.60	3,520
El Dorado	0.447	997
Santa Barbara	0.290	653
Sierra	0.194	438
Nevada	0.149	341
Placer	0.0980	226
Modoc	0.0560	123

5.4.2.1 Scenarios

As mentioned earlier, water consumption is the fraction of water withdrawal that is not returned back to its original source. Even though the United States Geological Survey (USGS) has water withdrawal data, it has incomplete/unavailable data concerning consumptive versus withdrawal water demand. Therefore, for this analysis, county withdrawal data is used in the place of consumptive data. In terms of water withdrawal versus water consumption for CSP plants, on average almost all water withdrawn is subsequently consumed. By examining the relative magnitude of CSP water consumption compared to current county water withdrawal levels, the impact of installing CSP capacity on county water resources is evaluated.

First, existing CSP capacity is determined and water demands are calculated based on available data for each plant. This existing CSP capacity and its associated water demands are removed from the water demand calculations in order to avoid double counting and ensure that new water demands are restricted to new CSP capacity. New required CSP capacity is then determined and the water demands are calculated assuming (a) wet-cooling, (b) hybrid cooling with a 1% performance penalty, and (c) air cooling with a 3% performance penalty. (Note that the performance penalty increases the nameplate capacity of the CSP fleet (GW) and plant size, but does not affect the total annual renewable generation (GWh) required to meet the target renewable penetration.) Median values for each cooling type are used to estimate annual water consumption demands: (a) 750 gal/MWh, (b) 375 gal/MWh, and (c) 90 gal/MWh, respectively. The relative impact of CSP deployment for different counties for each scenario is evaluated using the following formula:

$$Increase\ in\ water\ demand\ (\%) = \frac{CSP\ water\ consumption\ rate\ \left(\frac{gal}{MWh}\right) \times CSP\ generation\ (MWh)}{county\ annual\ water\ withdrawal\ (gal)}$$

5.4.2.2 Results

Existing CSP capacity and its associated generation as well as projects in development were determined from NREL, CEC, and EIA data (Table 20) [97], [122], [123]. Some values were estimated (labeled “est.”) based on known data. A majority of the CSP plants use parabolic troughs or power tower designs. Both of these systems rely on Rankine steam cycles to produce electricity. A combination of dry and wet cooling systems are employed. Total existing and in development CSP capacity is 2.736 GW, with the ability to deliver approximately 5,851 GWh of renewable energy annually. Total near term CSP generation by county is 1,928.5 GWh for San

Bernardino; 3,171 GWh for Riverside; 600 GWh for Kern; and 150.5 GWh for Los Angeles.

Table 20. Existing CSP Plants in California

Name	County	Type	Cooling System	Operation Date	Capacity (MW)	Generation (MWh) [EIA]	Annual Water Demands (Mgal)
Blythe Solar	Riverside	Parabolic Trough	Dry Cooling	Under Development	1,000	2,100,000	195.5
Ivanpah (I-III)	San Bernardino	Power Tower	Dry Cooling	2014	377	652,000	32.6
SEGS (I-IX)	San Bernardino	Parabolic Trough	Wet Cooling	Full operation 1990	353.8	623,000	436 (est.)
Mojave Solar	San Bernardino	Parabolic Trough	Wet Cooling	2014	250	503,500	350.9
Genesis Solar	Riverside	Parabolic Trough	Dry Cooling	2014	250	621,500	56.2
Beacon Solar	Kern	Parabolic Trough	Wet Cooling	Under Development	250	600,000	521
Rice Solar	Riverside	Power Tower	Dry Cooling	Under Development	150	450,000	59.7
Victorville 2 Hybrid	San Bernardino	Parabolic Trough/ Natural Gas	Wet Cooling	Under Development	50/513	150,000 (est.)	35 (est.)
Palmdale Hybrid	Los Angeles	Parabolic Trough/ Natural Gas	Wet Cooling	Under Development	50/520	150,000 (est.)	35 (est.)
Kimberlina Solar	Kern	Linear Fresnel reflector	NA	2008 (closed)	5	NA-pilot project ended	NA
Sierra Sun Tower	Los Angeles	Power Tower	Wet Cooling	2009	5	552 (frequently offline)	0.2 (est.)
				CA Total	2,736	5,850,552	1722.1

The 2010 county water demands listed in Table 21 include water withdrawal from installed CSP plants in operation before 2010. These water demands already include the water demands of SEGS, Kimberlina Solar Project, and Sierra Sun Tower Project. After adding the water demands of the known CSP projects under development/completed after 2010, it was determined that the committed CSP renewable generation currently accounts for less than 1% of total freshwater withdrawal for each county.

Table 21. Water Demands of Solar Thermal Potential by County, 2010 Water Use Data

County	Thermo-electric Freshwater Withdrawal (Mgal/yr)	Total Freshwater Withdrawal (Mgal/yr)	Total Saline Withdrawal (Mgal/yr)
San Bernardino	5,442	233,534	7,320 (ground water "gw" for mining, public supply)
Imperial	8,218	427,065	0
Riverside	2,429	386,818	14,687 (gw for public supply)
Kern	3,755	756,615	32284 (gw for mining)
Inyo	0	37,288	3463 (gw for thermoelectric)
Los Angeles	32.9	587,074	532,056 (97% once through cooling)
Mono	0	83,887	15
San Diego	3.65	244,038	785,306 (99.6% once through cooling)
Lassen	285	73,985	18
Plumas	0	43,341	26
El Dorado	0	20,344	11
Santa Barbara	0	94,457	2,060 (gw for mining)
Sierra	0	14,256	0
Nevada	0	17,715	69
Placer	0	69,828	15
Modoc	0	95,517	7
CA Total	23,873	11,361,503	2,504,183 (94.6% for once through cooling)

If the largest CSP capacity of 200 GW were to be installed with wet cooling systems, it would account for 2% of California's 11 trillion gallons of freshwater withdrawn annually. But, CSP water demand would not be evenly distributed across the state, rather it would be concentrated where CSP potential is the highest. The impact of increasing CSP generation on total freshwater withdrawal levels for counties with CSP potential above 50 GW is shown in Figure 43.

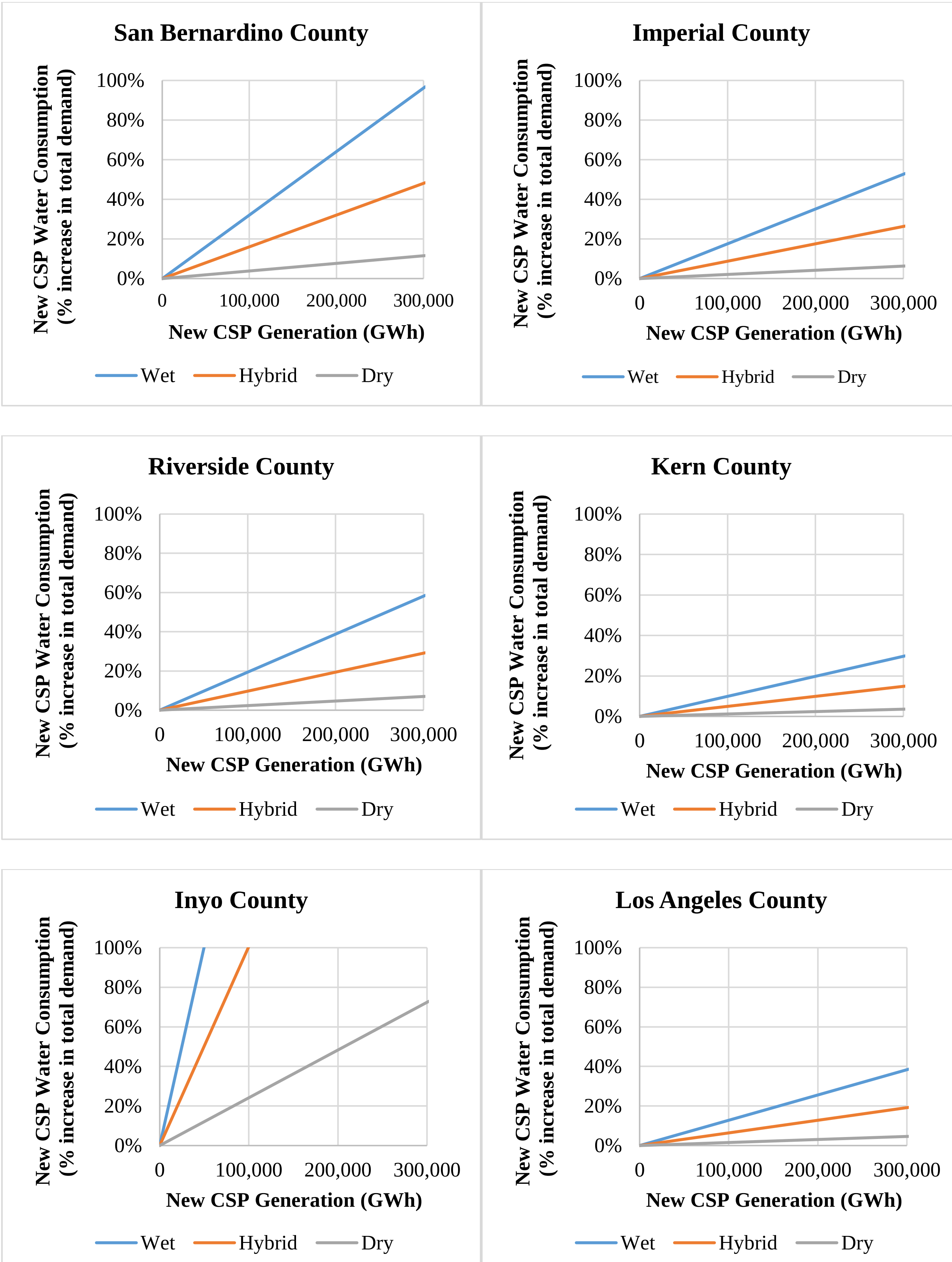


Figure 43. The Impact of New CSP Generation on County Water Demand

Water consumption increases linearly with increased CSP generation. The varying impacts of wet, hybrid, and dry cooling on county water resources are directly proportional to their different rates of water consumption per unit of generation. As expected, wet cooling shows the greatest increase in water consumption, with hybrid cooling required 50% less than wet cooling, and dry cooling requiring nearly 90% less.

For the 50% renewable scenarios, roughly 10,000-13,000 GWh of new CSP generation would be needed annually, requiring the installation of 7-11 GW of CSP capacity. If this generation was met using plants with wet cooling systems, 7500-9750 million gallons of water would be required each year. Assuming that the new generation was installed in a single county, this is equivalent to increasing water demand in San Bernardino by 4%, Imperial by 2%, Riverside by 2%, Kern by 1%, Inyo by 25%, or Los Angeles by 1.5%, depending on which county supported the CSP generating plants. Switching to hybrid cooling would cut these percentages in half, reducing the water impacts for all counties, except Inyo County, to a minimal growth in water demand equivalent to 0.5-2% above current demand. Dry cooling would reduce this demand even further, down to 0.2-0.5% above current withdrawal levels. For Inyo County, dry cooling for a CSP generation of 13,000 GWh (equivalent to an overall CSP capacity of 13 GW, when taking into consideration performance losses), would fall below 3.2% of current demand.

In comparison, 63,000-130,000 GWh of new CSP generation would be required to meet 80% renewables. (The lower bound is for no EV deployment and the upper bound is for EV deployment.) Installing 88.25 GW of CSP capacity in a single county, equivalent to 130,000 GWh annual generation—used most frequently in the 2050 cases—showed water demand for San Bernardino would increase by 42%; Imperial, 23%; Riverside, 25%; Kern, 13%; or Los

Angeles, 17%. Installing the capacity in Inyo had the greatest increase of 262% of current annual water withdrawal. While switching to dry cooling helped minimize new water demand for most counties, this reduction in demand still led to a significant increase in overall water use in Inyo County. Installing 88.25 GW of CSP capacity using dry cooling in Inyo would still increase water demand by over 20%. In comparison, this same capacity with dry cooling installed in the other five counties would result in a 3-5% increase in county water demand.

Over-installing renewable capacity has previously been discussed as a strategy to decrease SES capacity requirements. Increasing CSP capacity from 88.25 GW to 200 GW would result in a 127% increase in CSP water demand. For wet cooling, this means overall water demand for San Bernardino would increase by 97%; Imperial, 53%; Riverside, 59%; Kern, 30%; Inyo, 608%; or Los Angeles, 39%, compared to current withdrawal rates, depending on which county installed the new generation. Switching from wet cooling to dry cooling would result in a 73% increase in water demand for Inyo County or, for the other five counties, a 5-12% increase above present-day levels.

5.4.3 Summary

For five of the six counties with more than 50 GW of potential CSP capacity, moderate CSP deployment (10-12 GW) for 50% renewables can be achieved with minimal impacts on water demand (<5% increase) without needing to switch to hybrid or dry cooling. Inyo County is an outlier, as it has much lower annual water demand compared to San Bernardino, Imperial, Riverside, Kern, and Los Angeles. (In fact, historically a majority of Inyo County's local water resources have been exported to other counties.) Switching to dry cooling can reduce this demand even further.

As California moves to higher renewable levels and CSP generation becomes a larger portion of the renewable mix, the increase in water demand becomes more significant. Under wet and hybrid cooling scenarios for 80% renewables, counties with the highest CSP potential risk increasing their water demands from 6 to 262%. Dry cooling, on the other hand, minimizes the increase in water consumption for all cases.

Despite reduced demand with dry cooling, installing CSP capacity in Inyo County would still significantly increase demand for water resources compared to current levels. For this reason, of the counties with the highest CSP potential, Inyo County is the least suited to support the high water demands of largescale CSP installations.

5.4.4 Discussion

The installation of CSP capacity in any county will increase the water demands of that county, counter to water conservation measures. Cities in California are expected to decrease their water use between 8 to 36% in order to achieve a statewide cut of 25% [124]. Mandated reduction targets for the cities within San Bernardino, Imperial, Riverside, Kern, Inyo, and Los Angeles counties span the full range, from 8% for East Los Angeles to 36% for Bakersfield, with the majority of the cities within these counties having reduction targets at the higher end of the spectrum. These water conservation efforts are in direct conflict with water demand increases associated with CSP deployment. To avoid undue water stress in a single county, CSP capacity may be distributed across multiple counties, but switching to dry cooling provides the single greatest opportunity to reduce CSP deployment impacts on regional water demand. Dry cooling decreases CSP water consumption by approximately 90% compared to wet cooling systems for a given installed capacity, so that for most cases even at high deployment of CSP, water demand will climb less than 5%. Alternatively, large-scale solar PV may be deployed in place of CSP, requiring 95% less water per MWh than the CSP dry cooling scenario [94]. CSP may still remain attractive to investors, as they provide an opportunity to utilize both natural gas and TES, which can not only increase the capacity factor of the plant but also increase the dispatchability of plant generation.

One issue to consider beyond the scope of this analysis is the availability of freshwater versus saline water resources for cooling applications. For this analysis, only freshwater resources are considered. Once-through cooling accounts for 94.6% of current saline water withdrawals. California is currently moving away from ocean-sourced cooling systems, having recently passed measures to restrict once-through cooling [125]. CSP may still be able to utilize saline groundwater sources. The potential of this creating additional negative impacts on the environment such as increased particulate air pollution in areas already in noncompliance for air quality [126]. Supporting CSP deployment by exacerbating air pollution is counterproductive to the holistic nature of sustainability goals.

Another issue not covered in this analysis is the pairing of CSP generation with supplemental natural gas fuel and/or thermal energy storage (TES). Natural gas combustion is sometimes employed to increase the capacity factor of CSP plants and to improve profit margins due to the low cost of natural gas. This hybrid design also provides the additional benefit of increasing the dispatchability of the power plant, which can help manage variable renewable generation. But, by increasing generation from the CSP plant, water demand will also increase in proportion, putting even greater stress on water resources. The use of natural gas in conjunction with CSP may also undercut emissions savings from installing zero-GHG emission CSP capacity and dampen efforts to move to high renewable utilization by extending the lifetime of nonrenewable generation.

In terms of energy storage, the co-location of TES with CSP facilities could provide a storage medium not previously discussed in this analysis, partially satisfying the need for SES capacity to reach high renewable penetration. Similar to natural gas fuel use, the integration of TES with CSP generating plants would also increase the capacity factor of the CSP plants and, by extension, increase water demands. The impact of TES on CSP generation and water demands is a topic for future work.

This analysis is a cursory overview of water and CSP interactions aimed at identifying regions that are vulnerable to increased water consumption. A more in-depth analysis examining the impact of air temperatures, population growth, and climate change conditions is a topic for future research.

6.0 Summary of Overarching Results and Conclusions

6.1 GHG Reduction

In the near term, SES technologies have a limited effectiveness in reducing emissions due to low renewable curtailment levels. Deploying stationary fuel cells is more effective in reducing grid GHG emissions compared to SES, because the fuel cells are able to offset electricity production from conventional resources in addition to being able to reduce the overall carbon-intensity of generation. While baseload fuel cells are more effective than load following fuel cells at decreasing grid GHG emissions at 33% renewables, at higher renewables, load following fuel cells outperformed baseload fuel cells by managing to both offset conventional load followers and decreasing reliance on peaker generation. This indicates that dynamic, dispatchable resources may increase in importance for meeting GHG emission targets as the portion of renewable generation on the grid increases.

The effectiveness of SES to decrease grid GHG emissions is directly tied to the resources used to charge them. In order to contribute to the decrease in overall carbon-intensity of electricity generation, SES must be charged primarily from zero-emission resources. In other words, SES is limited in its capacity to decrease grid GHG emissions by the availability of excess renewable generation. There is a trend that as renewable capacity increases, curtailment also increases. Renewable curtailment increased between the 33% and 50% renewable scenarios, while the higher renewable scenarios showed significant curtailment before energy and load shifting strategies were applied. This demonstrates that there is an increased opportunity at high renewable penetrations to utilize SES to recover otherwise wasted renewable generation and offset inefficient conventional generation. The overall ability of SES to reduce grid GHG emissions is proportional to the amount of zero-emission, renewable generation it can recover and utilize, as illustrated by the near term scenarios. The large-scale deployment of SES capacity can successful recover and utilize renewable generation at high renewable levels to achieve renewable penetration targets in line with energy sustainability goals, as illustrated by the 2030 and 2050 scenarios.

6.2 High Renewable Utilization

As renewable capacity increases, so does renewable curtailment. Without the use of energy storage or other complementary management strategy, renewable utilization will reach a maximum below 80% of total electricity demand. In order to reach high renewable penetration, at or above 80% of demand, renewable generation and/or electric load must be shifted so that the two align.

Immediate charging of the BEV fleet contributes a new load to the grid that does not coincide with renewable generation. This exacerbates the misalignment of renewable generation and electricity load demand, thereby increasing renewable curtailment, which in turn results in higher SES capacity requirements than the no EV scenario. Switching to smart charging allows the new BEV load to be scheduled in line with renewable variability. In this case, the increase in load is counterbalanced by its flexible scheduling, and SES capacity requirements are reduced to the scale required for the no EV scenario. While smart charging provides a flexible load, it is still limited in its capacity to integrate renewable generation, because it cannot provide discharge back to the grid in order to provide support during periods of low renewable generation. In comparison, operating the BEV fleet batteries with V2G capability completely offsets the need for SES capacity.

6.3 Conclusions

The following overarching conclusions result from this work.

1. **Fuel cells are more effective than SES in reducing grid GHG emissions in the near term when there is limited to no curtailment of renewable energy.** Fuel cells can generate low-carbon electricity and offset higher polluting resources such as conventional load following power plants. SES technologies, on the other hand, may increase generation from these same resources when renewable energy is unavailable to charge the SES fleet. While SES technologies can decrease the reliance on peaker generation, the net impact on GHG emissions is less than those reductions achieved with fuel cells.
2. **The technologies and strategies that are the most effective in reducing grid GHG emissions will evolve as renewable capacity increases.** The near term analyses showed that when there is limited renewable curtailment, fuel cells are more effective than SES technologies in reducing grid GHG emissions. The important function of fuel cells on the grid at low to moderate renewable utilization is their ability to offset more carbon-

intensive generation. At 50% renewables, when the grid becomes more dynamic due to the increase in solar and wind generation, there is an increased need for dynamic, dispatchable resources, leading to load following fuel cells outperforming baseload fuel cells in terms of GHG reduction potential. At high renewable levels, the role of energy storage technologies to achieve target renewable penetration and meet GHG reduction goals increases. This increase can be attributed to its quick response times, near instantaneous ability to ramp up and down to follow renewable variability, and its capacity to shift renewable energy from time of generation to time of demand.

3. **The benefits of SES technologies for reducing grid GHG emissions and increasing renewable utilization are dependent on the availability of excess renewable generation.** In all the 50% RPS scenarios, both for the near term and year 2030 analyses, there was low renewable curtailment for energy storage capacity to recover. Energy storage can offset carbon-intensive generation and increase renewable utilization only when it is charged using renewable generation that would otherwise be curtailed. In comparison, the 2050 (80% RPS) scenarios showed significant misalignment of renewable generation and electricity demand, leading to high renewable curtailment for the immediate charging, smart charging, and no EV deployment scenarios. In these cases, SES was able to recover the excess renewable energy and offset conventional generation during periods of low renewable availability.
4. **The degree to which increasing installed renewable capacity can decrease reliance on energy storage is dependent on the net load profile characteristics.** Solar renewable generation dominates the California 2050 renewable mix. Increasing renewable capacity has a limited impact on increasing achieved renewable penetration, as

it contributes primarily to renewable curtailment. Not only does it increase total curtailment, it increases the number of days with curtailed energy. This results in SES shifting energy over shorter time periods, decreasing the overall energy capacity required to reach the target renewable penetration.

5. **Increasing the charging intelligence of the PEV fleet reduces the scale of SES capacity required to achieve high renewable utilization.** Intelligent charging of vehicles allowed for a majority of charging events to be scheduled to correspond with renewable availability. This led to increased renewable utilization and, by extension, decreased renewable curtailment compared to the immediate charging scenario. Switching from immediate to smart charging reduces the power and energy capacity of the SES system by roughly 75%, and switching to V2G charging removes the need for any SES capacity to reach the 80% renewable penetration target.
6. **The sizing of SES power and energy capacity is dependent on the scale and timing of excess renewable generation as well as the target renewable penetration level.** The installed SES power capacity determines the maximum power level of renewable generation it can capture. Increasing charging intelligence shifts load to better align with peak renewable generation, leading to a decreased difference in peak load and generation. The SES power capacity required to capture the peak renewable curtailment therefore decreases. The installed SES energy capacity determines the maximum amount of renewable energy that can be shifted from a period of over-generation to a period of low generation. As SES energy capacity increases, SES are able to shift energy across longer time periods.

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Appendix A

Cost Parameters

	Instant Cost ($/kW)	FOM ($/kW-yr)	VOM ($/MWh)	Eff. Degrad.	Cap. Degrad.	Debt Term (Yrs)	Econ. Life (Yrs)	Start-Up Fuel (MMBtu/MW)	Plant Losses	TX Losses	Transf. Losses	Distrib. Losses	TX Cost ($/MWh)
Flow Battery	3100	32	0	0	0	5	10	0	0	0.05	0.005	0.005	4.3
CAES	1250	24.6	65	0.0005	0	20	20	2.8	0	0.05	0.005	0.005	4.3
Pumped Hydro	2500	35	7	0	0	20	40	0	0	0.05	0.005	0.005	4.3
Fuel Cell	4000	150	0	0.008	0.008	12	20	0	0	0	0	0.005	0
89 MW Par Trough SEGS	3687	51	2	0.0005	0.005	15	20	0	0.224	0.05	0.005	0.005	11.62
Leg. PK	0	12.19	10.19	0.005	0.005	0	10	2.8	0.068	0.021	0.005	0.005	4.3
Leg. LF	0	17.78	4.21	0.002	0.002	0	20	2.8	0.058	0.021	0.005	0.005	4.3
Leg. Geo.	0	134.1	11.9	0	0.04	0	20	0	0.05	0.05	0.005	0.005	4.3
Leg. Hydro	0	16.94	3.02	0	0.02	0	20	0	0.05	0.021	0.005	0.005	4.3
Leg. Coal	0	36.64	5.25	0.002	0.001	0	20	2.8	0.1	0.021	0.005	0.005	4.3
Leg. Nuke	0	109.6	2.5	0.002	0.002	0	20	2.8	0.1	0.021	0.005	0.005	4.3
Wind	1975	13.7	5.5	0	0.01	20	30	0	0.01	0.05	0.005	0.005	5.64
Geo-Binary	4000	47.44	4.55	0	0.04	20	30	0	0.05	0.05	0.005	0.005	10.67
Fixed	6600	25	0	0	0.005	20	25	0	0	0	0	0.005	0
New PK/LF	827	16.33	3.67	0.0005	0.0005	12	20	2.8	0.034	0.0209	0.005	0.005	4.3