GUTTING THE DUCK:

A CAM ANALYSIS OF ENERGY STORAGE TECHNOLOGIES FOR CALIFORNIA'S GRID

A Thesis

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by

Charles Ross Branch

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Department of Public Policy and Administration

Abstract

of

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Charles Ross Branch

Since California began decarbonizing its energy supply nearly 20 years ago, the state has become a leader in the clean energy revolution. Backed mostly by a rapid expansion of solar energy, California now generates more renewable energy than any other state in the nation. Although California's growth in solar energy is impressive, it does not come without challenges. Most concerning of these challenges is grid imbalance between energy supply and energy demand over the course of a day. Referred to as the "duck curve," the imbalance raises concerns about the grid's ability to integrate more solar energy as California moves to a 100 percent carbon free energy supply.

This thesis explores energy storage as one approach to address California's duck curve and meet the state's energy policy goals. More specifically, I look at four energy storage technologies and perform a criteria-alternative matrix (CAM) analysis to determine which storage technology best mitigates the duck curve while helping California achieve its energy goals. The thesis concludes that policymakers and regulators should implement the four following recommendations:

Recommendation #1: Adopt an “all of the above” strategy in terms of storage technologies.

Recommendation #2: Pursue underground CAES as a priority for utility-scale energy storage.

Recommendation #3: Expand the use hydrogen fuel cells for increased grid flexibility.

Recommendation #4: Reduce reliance on solar energy by classifying large hydro as “renewable” energy.

_______________________, Committee Chair
Su Jin Jez, Ph.D.

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Date

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Chapter 1: Introduction

In 2013, the California Independent System Operator (CAISO), the entity responsible for managing the state’s electric grid, developed a graph depicting the grid’s net energy load, on a typical spring day, as it integrates solar energy. The graph, later dubbed the “duck curve,” shows how California’s abundance of solar energy production creates grid instability. In particular, during the middle of the day, when solar energy generation is at its peak, the net load of traditional energy sources (e.g. natural gas) drops significantly. Then, in the early evening when demand is at its peak, and there is no solar energy production because the sun has set, there is a substantial ramp up of traditional energy sources to meet electricity needs. As midnight approaches, the net load levels off bringing energy supply and demand back into balance. The duck curve “raises concerns that the conventional power system will be unable to accommodate the ramp rate and range needed to fully utilize solar energy, particularly on days characterized by the duck curve, which could result in overgeneration and curtailed renewable energy, increasing its costs and reducing its environmental benefits” (Denholm, O’Connell, Brinkman, Jorgenson, 2015, p. 4). Figure 1 depicts the duck curve.

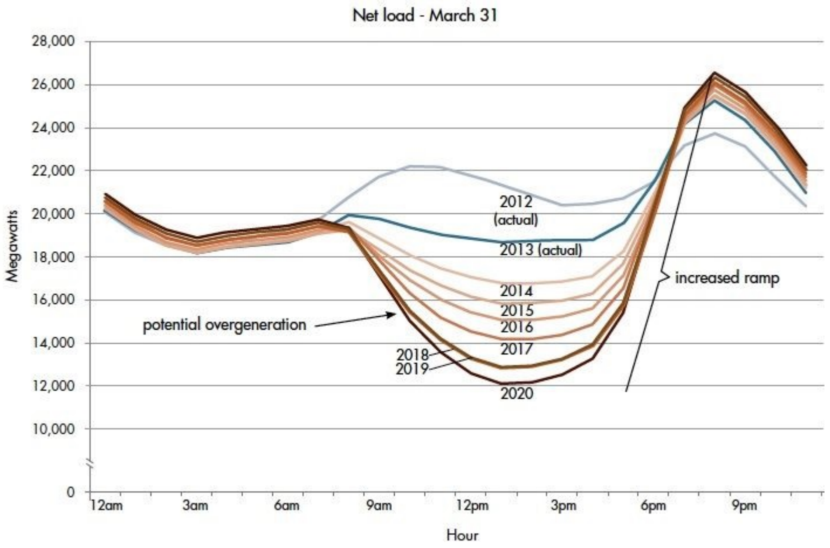


Figure 1. The duck curve. Adopted from CAISO

Because CAISO only regulates large utility-scale solar plants, the rapid growth of rooftop solar across California complicates matters. As solar installation and generation grows, the belly of the duck gets deeper. In fact, in 2018, CAISO reported that under-forecasting of rooftop solar growth has actually moved the belly of the duck, and consequential ramp, four years ahead of CAISO's original estimate (Loutan, 2018). As Figure 2 shows, the net load on February 18, 2018, reached 7,149 megawatts (MW), and the actual three-hour ramp of March 4, 2018 reached 14,777 MW, both exceeding estimates for the year 2020.

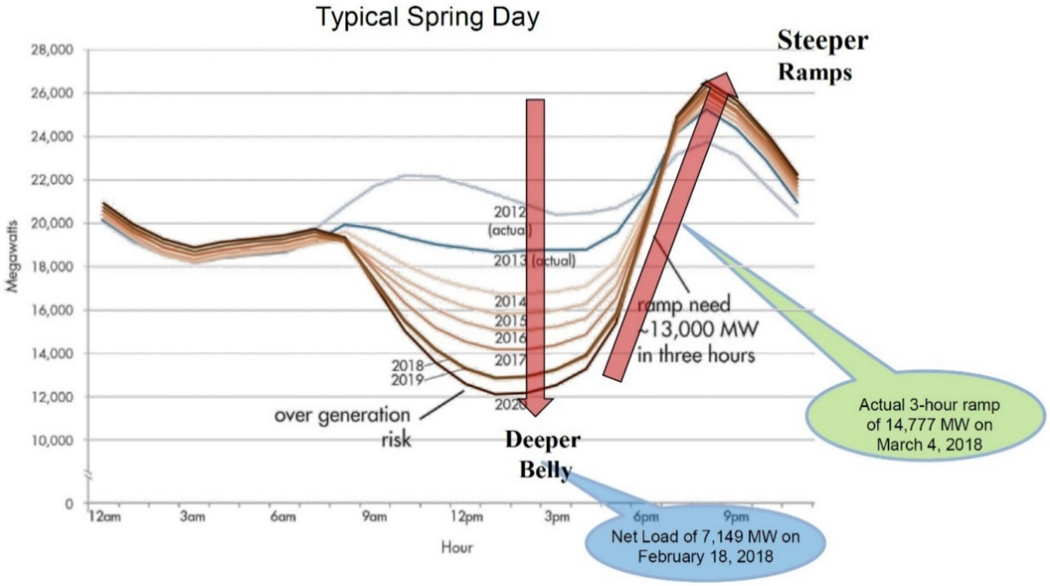


Figure 2. The duck curve 5 years later. Adopted from CAISO

The glut in the state's solar energy production and subsequent grid instability is largely the result of California energy policy. Therefore, it is useful to consider the policy alternatives available to address the duck curve on California's electric grid within the context of state law and regulatory requirements. Put another way, the purpose of this thesis, is to answer the following two questions: What alternatives are available for policymakers to invest in to address the duck curve; and then, which alternative best balances grid load while fulfilling California's energy goals? To answer the first question, I will review the available literature related to addressing the duck curve. After settling on alternatives to assess, I will answer the second question by conducting a criteria-alternative matrix (CAM) analysis.

The remainder of Chapter 1 is divided into four parts. The first part explores the larger context of the state's energy challenge, including a legislative and regulatory history explaining how California got to where it is today. This will provide important background of the political, legal, economic, and social factors discussed in subsequent chapters. The second part reviews the experience of other states and municipalities facing renewable energy phenomena similar to California's duck curve. The third part consists of a brief literature review specifically related to the duck curve, including possible solutions. I conclude Chapter 1 by outlining the remainder of this thesis, including a discussion of how each succeeding chapter fits into the framework of policy analysis.

California Energy Policy: A Background

California's move to decarbonize its energy supply coincided with a larger move to deregulate its energy market in 1996. That year, the legislature passed and the governor signed Assembly (AB) 1890, which among other things, established a public goods charge to support research and development of renewable energy programs. In 2002, the state enacted seminal renewable energy legislation with Senate Bill (SB) 1078, which established California's Renewable Portfolio Standard (RPS) program requiring investor-owned utilities (IOU), publicly owned utilities (POU), electric service providers, and community choice aggregates to increase procurement of eligible renewable resources. Under the RPS program, the California Public Utilities Commission (CPUC) develops and governs compliance rules for all energy suppliers, while the California Energy Commission (CEC), the state's primary energy policy and planning agency, certifies the eligibility of electrical generation facilities and enforces RPS procurement requirements for POUs. SB 1078 set a 20 percent renewable energy target by 2017.

Around the time the state established its RPS program, public awareness about global warming was on the rise. Sensing an open policy window, the California Legislature passed AB 32, the Global Warming Solutions Act, in 2006. While AB 32 did not directly speak to renewable energy, the state's investment in the technology combined with the apprehension of global warming seized the public conscious and the two issues became synonymous with each other. In 2006, the desire for more renewable energy seemed to transform into a crusade to stop global warming. The same year that California enacted AB 32, the state approved at least five other initiatives aimed at increasing the pace and scale of renewable energy development. SB 107, for example, accelerated California's RPS goal of 20 percent renewable energy from the year 2017 to 2010. Also passed in 2006 was SB 1, which established the California Solar Initiative (CSI). The CSI was important because it served as the foundation of California's subsidization policy for solar energy. Between 2007 and 2016, the CSI had a budget of more than $2.1 billion for a range of purposes and the "goal to install approximately 1,940 Megawatts (MW) of new solar generation capacity" (https://www.gosolarcalifornia.ca.gov/about/csi.php, para 3). To understand how solar capacity has exploded in the years since SB 1, consider that California had an installed solar capacity of over 23,000 MW by mid-2018, according to the U.S. Energy information Administration (U.S. Energy Information Administration, "California Profile Analysis," 2018).

Although the state has demonstrated success at incentivizing solar generation capacity across California, it has not come without some consequences, not the least of which is the duck curve. The subsidies provided under the CSI were paid by all of California's electrical utility users in the form of a surcharge on electric bills, which resulted in higher energy prices for everyone. Moreover, when CSI and other direct incentive programs wound down, the CPUC voted to permit a policy, known as net metering, which acts as indirect incentive. Funded it to the tune of over $111 million, net metering allows energy customers who own solar panels to distribute excess energy to the grid and receive a payment for it in the form of a rebate on their energy bill. However, as the Wall Street Journal points out, the rebate paid is eight times the wholesale price, and if the subsidies were removed, “solar adopters would be in the red” (Sexton, 2018, para 4).

Another way California has been the victim of its own solar success is in the real world consequences of the duck curve’s belly. As discussed earlier, the belly represents an overgeneration of solar power. Occasionally, that overgeneration can force energy prices negative and, because you cannot simply destroy energy, regulators in California have to pay neighboring states, like Arizona, to take the state’s excess energy (Penn, 2017). As solar production continues to increase, the duration and frequency of negative pricing will increase as well. Unsurprisingly, while neighbors benefit, California ratepayers bear the costs associated with interstate energy transfers.

Despite the challenges associated with California’s solar energy glut, in the waning hours of the 2017-18 California legislative session, the legislature passed SB 100, which establishes a statewide target of 100 percent carbon-free energy by the end of year 2045. SB 100 requires that 60 percent of energy generated be renewable, while the other 40 percent can be a zero-carbon source or renewable. To provide some perspective, according to the CEC, renewable power supplied roughly 32 percent of retail electricity sales in 2017.

Ducks, Monsters, and Emus

Although the duck curve, and all its particulars, are specific to California, the state is not alone with its solar energy challenges. A few other states, along with locations across the world face energy challenges due to a heavy reliance on solar energy. While scientific research does not afford the depth of interest to the energy problems of other regions, their experiences can provide insight to the way California addresses the duck curve.

New England

Much like California, New England is starting to experience the effects of small-scale solar energy growth (rooftop solar) in recent years. According to the New England Independent System Operator (ISO), the grid operator for Massachusetts and five adjacent states, “The telltale shape of the duck is appearing in the daily energy charts” (Spector, 2018, para 5). Currently, the New England ISO manages about 2,400 MW of solar energy; for comparison, California generates nearly 23,000 MW of solar energy. Nonetheless, that 2,400 MW of solar energy produced in New England forces system load down during the middle of the day resulting in a ramp up of system load when demand peaks. ISO New England estimates in 2019, the penetration of solar energy during the day will reach 3 Gigawatts, or 3000 MW, forcing an equal draw down in system load. The challenges of New England’s duck curve, however, do not end there. Because much of the region uses natural gas for heating, the New England duck curve, unlike the California duck, appears in winter, further constraining “the natural gas available to meet New England’s increasingly steep evening ramps” (Spector, 2018, para 14).

Massachusetts, a state known for its progressive politics, accounts for a large portion of New England’s solar generation and represents nearly half of the overall load managed by the New England ISO (Spector, 2018). Despite its apparent contribution to the development of the New England duck curve, Massachusetts plans to double its solar generation capacity over the next few years. Indeed, “The duck is about to have a growth spurt” (Spector, 2018, para 11).

Hawaii

To understand the energy challenges California may face in the future due to the saturation of solar energy, look no further than its neighbor to the west, the Hawaiian island of Oahu. There, solar energy is so pervasive that it occasionally causes backfeed, where energy flows backwards re-energizing the lines it just came through (St. John, 2014). Put another way, solar energy supply is exceeding demand to such a degree that demand from traditional sources drops below zero. The subsequent spike produced when the sun goes down, and demand peaks, is so steep the Hawaii Electric Company (HECO) has dubbed its duck curve the Nessie Curve, the name given to the mythical lake-dwelling dinosaur in Scotland, the Loch Ness Monster. Figure 3 depicts Oahu’s Nessie Curve.

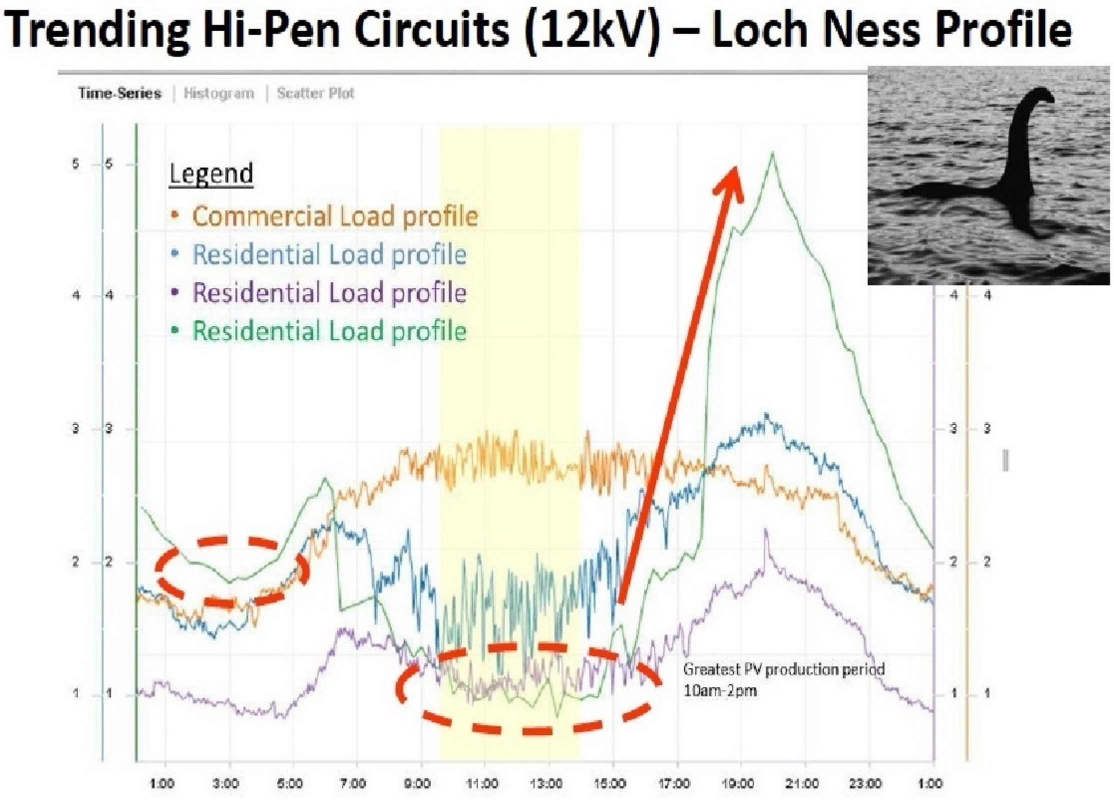


Figure 3. Nessie curve. Adopted from HECO

Similar to California, lucrative incentives generated much of the increase in Oahu’s solar energy, mostly in the form of rooftop solar. In the early part of the last decade, Hawaii offered a 35 percent state tax credit for the installation of photovoltaic systems, the second largest credit in the county at the time. In 2014, because of the Nessie Curve, HECO instituted “new interconnection requirements…for even small-scale rooftop solar photovoltaic systems, which has slammed the brakes on new projects and drawn the ire of the solar industry” (St. John, 2014, para 8). Also like California, Hawaii has a RPS target; 40 percent of the state's electricity be generated by renewable resources by the year 2030.

The Hawaiian Islands have the additional challenge of being water-locked. With few sources of traditional energy generation and not a lot of land to build more gas-fired plants, accounting for the glut of solar energy the raises costs of grid operations.

South Australia

Starting in 2006, South Australia undertook a massive effort to decarbonize its electrical grid. In concert with the installation of new wind and solar generation, South Australia began shutting down coal-based generation. According to the Melbourne Energy Institute, by August of 2016, the country has installed over 1500 MW of wind capacity and 680 MW of solar capacity (Parkinson, 2017). Within the same time, South Australia mothballed 770 MW of coal generation. Despite the closure of a number of coal plants, the penetration of renewables is forcing demand for grid electricity to fall and then rise sharply when renewable sources stop generating. The result is South Australia's duck curve, or as the Australian Energy Market Operator (AEMO) calls it, the "emu curve." Figure 4 illustrates South Australia's emerging problem.

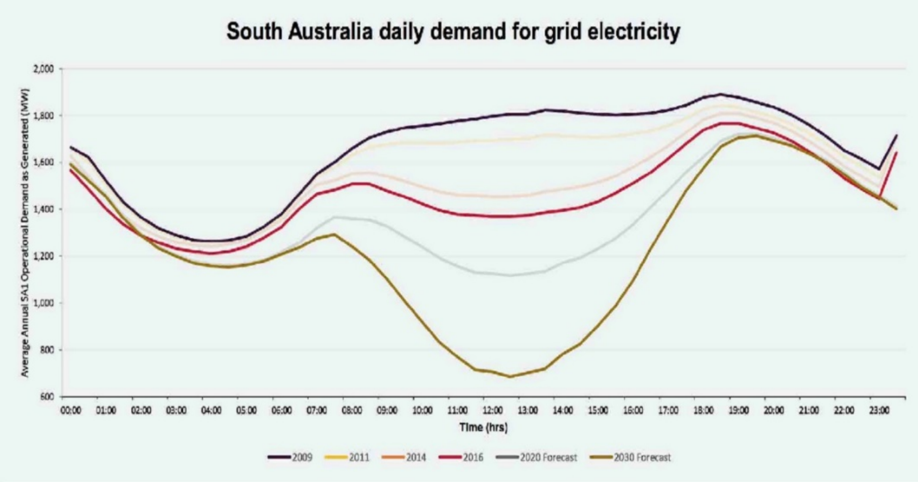


Figure 4. The Emu Curve. Adopted from AMEO

According to the AMEO, and as shown in the emu curve, “midday demand will more than halve [by] 2030, from around 1800 MW in 2009 to below 700 MW by 2030, all due to the huge uptake in solar” (Parkinson, 2017, para 8). For South Australia, the loss of coal and gas generation, that would normally feed the ramp, has had reduced supply security. For example, in September of 2016, South Australia experienced a widespread power outage after a “one in 50-yeas storm” damaged electricity transmission infrastructure. Although the weather caused the blackout, “the sheer volume of renewables in the system that day did contribute to the lack of stability which might have saved the power grid” (Harmsen, 2017, para 27).

Audrey Zibleman, of the AMEO, believes flexibility is the first line of defense for coping with South Australia’s emu curve. To help handle summer peak loads, the AMEO marshalled a number of energy generation sources, including previously closed gas capacity; but, even then, there is guarantee there will not be more outages in the future (Parkinson, 2017).

To Fatten or Flatten the Duck? A Literature Review

As noted in the previous section, despite an emu, a Nessie, and other emerging ducks, the California duck curve receives the lion’s share of scientific analysis. Most of the literature related to the duck curve focuses on ways to accommodate more solar power on the grid; researchers categorize their approaches as either fattening or flattening the duck (Denholm et. al., 2015). Fattening the duck refers to changing grid operations to allow for more penetration of variable/renewable generation. While this approach could reduce or eliminate curtailment of renewable energy, it means there would be less traditional load on the grid for the evening ramp. Flattening the duck refers to shifting the supply of solar energy to later in the day, which would shrink, or flatten, the belly of the duck. Changing supply and demand patterns to get the most out of solar energy, however, requires a way to store energy created during the day for use in the evening. To that end, a number of federal research facilities, associated with the U.S Department of Energy, have commissioned studies to look at energy storage technologies. Argonne National Laboratory in Illinois studied the benefits advanced pumped hydro storage in relation to grid reliability and integration of renewables (Botterud, Levine, & Koritarov, 2014), while Lawrence Livermore National Laboratory, in California, evaluated multiple different storage options and demand response (Edmunds et al., 2014). The National Renewable Energy Laboratory looked at the economics of hydrogen storage in California (Eichman, Townsend, & Melaina, 2016). On a state level, the CEC's *2020 Strategic Analysis of Energy Storage in California* is one among many reports produced by regulatory agencies looking at storage options.

Recognizing the promise that energy storage holds for addressing the duck curve, the California Legislature has taken steps to ramp up California's deployment of storage technologies. In 2010, the state enacted AB 2514 (Skinner), which required the PUC to set targets for a load serving entities to procure energy storage systems by 2015 and 2020. AB 2514 also required POUs to set their own energy storage targets and meet those targets by 2016 ad 2021. Lastly, the bill required IOUs to integrate energy storage as part of their energy procurement plans. Between 2013 and 2016, California enacted a handful of other laws aimed to support the state's storage policy with improved procedures for conflict resolution and interconnection disputes; another handful boosted requirements for more energy storage. Today, the cumulative energy storage procurement target for California's IOUs totals 1,325 MW "to be completed by the end of 2020 and implemented by 2024" (CAISO, 2014, p 2).

Similar to the financial incentives available for renewable energy procurement, California also provides incentives for the research, development, and installation of energy storage technologies. The Electric Program Investment Charge (EPIC) provides approximately $162 million annually, through 2020, to partly "fund the development of storage valuation methodologies and tools with the purpose of making such tools and methodologies transparent and publicly available" (CAISO, 2014, p 7). On the consumer-side, the Permanent Load Shifting and Self Generation Incentive Program (SGIP) pays individuals, state and local governments, and businesses for distributed energy storage. At the end of the 2017-18 legislative session, the Legislature voted to extend the SGIP through 2026. As with California Solar Initiative program mentioned earlier, EPIC and SGIP are utility ratepayer-funded programs. Through the end 2019, authorized incentive collections under SGIP total over $500 million ("Self-Generation Incentive Program Handbook," 2017).

Given California's large investment in renewable energy technologies and supportive energy policy, storage seems certain to play a pivotal role in the state's energy future. Therefore, the focus of this thesis is to examine different types of storage technologies to determine which alternative best balances grid load while fulfilling California's energy goals.

Thesis Outline

The remainder of this thesis is organized into five more chapters. Chapter 2 explores the social, political, and economic environments that exert influence on state energy policy. The context provided in Chapter 2 is important as it contributes to the choice of storage alternatives examined and the methodology used in the analysis. Chapter 3 introduces the storage alternatives used in this analysis. It order to determine the appropriate storage alternatives for analysis, Chapter 3 also reexamines the cause of the duck curve and defines the variables inherent in storage technology options. Chapter 4 is devoted to the selection and justification of criteria for the CAM analysis. Crucial to the selection of criteria is assigning weight to each criterion. As Munger (2000) explains the weights "give the relative importance of the criteria in the decision process" (p 11). Chapter 4 also includes a discussion of my methodology. Chapter 5 provides the results of my CAM analysis, both qualitatively and quantitatively. Worked into the discussion are projected outcomes of each storage alternative. The thesis concludes with Chapter 6, which contains my recommendations for policymakers and an examination of short and long-term issues of implementation.

Summary

This introductory chapter discusses the focus of the thesis as addressing California's duck curve. It begins the discussion with background on California Energy policy, followed by a discussion about similar energy challenges in other localities. I, then, covered some approaches to address the duck curve in the literature and identified energy storage as a pivotal player. Accordingly, the focus of this thesis is to examine different types of storage technologies to determine which alternative best balances grid load while fulfilling California's energy goals.

Chapter 2: California Energy Policy in Context

Any chosen policy alternative to address California's duck curve must take into account the environment in which renewable energy policy and energy storage technology operates. If, for example, a proposed alternative has little government support or is economically unfeasible, it unlikely to progress forward or produce the desired outcomes. Keeping this in mind, in this chapter I examine the social, political, and economic constraints that shape state policy related to renewable energy, energy storage, and the duck curve. The constraints and environment identified here contribute to the methodology used for analysis in subsequent chapters.

The first section of this chapter discusses the public perception of energy policy in California and the factors that influence that perception. There is also a brief description of impending changes to retail energy markets and the possible effects of those changes on energy consumers in the state. Next, I look at California's political framework and the role that framework plays in implementation state policy; this includes a discussion on different pressures placed upon the political process. In the last section, I examine the economic environment. Because much of the growth of renewable energy over last decade is due to government intervention, the economics are extremely important.

Social factors

Despite the fact that solar energy and other renewable sources have been staples of California's energy landscape for the better part of two decades, public awareness of the duck curve remains limited. Interest in the duck curve and its effect on the state's electric grid is relegated to academic journals, energy utilities, "green" venture capitalists, and the regulatory agencies tasked with managing energy policy.

Conversely, public awareness and interest in renewable energy technology is pervasive in California. The state is home to some of the biggest names in renewable energy technology, and

California leads the nation in photovoltaic energy generation. Contributing factors to public awareness include California's sunny weather, substantial government intervention, and the public perception of renewable energy benefits on climate change. As noted in Chapter 1, the two topics are synonymous with each other, and climate change, in particular, is a salient issue for California residents. A July 2018 poll conducted by the Public Policy Institute of California, for example, found that 62 percent of California adults say climate change is extremely or very important to them, with 65 percent favoring the state government making its own policies to address climate change (Baldassare, Bonner, Dykman, & Lopes, 2018). A follow up question in the poll asks California residents if they favor or oppose "a proposed state law that would require 100 percent of the state's electricity to come from renewable energy sources by the year 2045" (Baldassare et al., 2018, p. 19). By margin of 72 to 21 percent, adults in the poll favored the law, now known as SB 100. The poll does not inquire about the need or preferences for energy storage.

The societal disconnect between the benefits and challenges of renewable energy, described above, represents a quasi-market failure called asymmetric information. In economics, the term refers to transaction where one party has more, or better, information than the other party, creating a disadvantage for the party with less information. In such instances, the government can intervene to reduce or eliminate the negative effects of asymmetric information; but this has not been the case with renewable energy, particularly in regards to solar energy. Instead, the government and regulatory agencies continue to enact policies that exacerbate the state's overgeneration problem. A prime example is the CPUC's net metering program discussed in Chapter 1 – when consumers can get paid back eight times the wholesale price for energy produced via rooftop solar. Why would consumers not be interested in installing solar panels? While it seems the government is on the losing side the net metering transaction, coming changes to energy markets might prove otherwise. In an effort to flatten the duck curve, California's electricity providers are implementing the practice of "Time of Use" pricing, which essentially charges different energy prices depending on demand; the higher overall demand on the grid, the higher price consumers pay and vice-versa. Because solar owners can only generate energy during the day, when demand and prices are low, there is a real risk that energy rebates will diminish precipitously under Time of Use pricing. Furthermore, as has been experienced recently, what happens to solar owners when prices turn negative? The need for home energy storage for solar owners could prove paramount in the near future.

Because the duck curve affects the stability of California's electric grid, the presence of asymmetric information in the renewable energy market could cause fallout beyond private solar energy owners. The inability to meet demand, due to drops in net load, or the failure to store solar overgeneration could cause blackouts. The loss of economic and social productivity due to power outages take a toll on the society as a whole. The same goes for curtailing solar energy in an attempt to address overgeneration. Because ratepayers have financed much of the growth in solar energy, stranding solar assets produces losses of capital beyond the initial costs to bring solar facilities online and threatens public support of solar energy programs.

What is clear from the social factors discussed is that the popularity of renewable energy, especially solar, has never been higher in California. Moreover, there is an expectation among the public that the state is actively moving toward a more sustainable energy future. Unless there is a change in the public conscious, whether it be from more-complete information or another factor, the trajectory for more renewable energy advances forward. As the demand for renewable energy grows, the need for energy storage grows as well.

Political factors

In addition to the social factors described above, energy policy in California operates within complex political parameters. These parameters are important because they define the extent to which the government can intervene and guide policies related to energy and energy storage. Beyond the obvious entity responsible for energy policy, the California Legislature, the two agencies mostly responsible for policy implementation are the CPUC and the CEC.

The CPUC "regulates services and utilities, protects consumers, safeguards the environment, and assures Californians' access to safe and reliable utility infrastructure and services" (CPUC, n.d. "About,"). A five-member board governs the Commission, with each "commissioner" appointed by the governor and serving a six-year term; each commissioner requires approval from the California State Senate. Under California's RPS program, the CPUC develops and governs compliance rules for all energy suppliers.

Similar to the CPUC, a five-member board governs the CEC, with each "commissioner" appointed by the governor and approved by the California State Senate. Rather than a serving six-year term, CEC commissioners serve a five-year term with each member representing one of the following expertise areas: law, environment, economics, science/engineering, and the public at large. The CEC is the state's primary energy policy and planning agency; its core responsibilities include, but are not limited to, advancing the state's energy policy, achieving energy efficiency, investing in energy innovation, and developing renewable energy (CEC, n.d., "Commissioners at the California Energy Commission").

Because the governor appoints and the senate confirms commissioners to both the CPUC and CEC, political and social exigencies of the day can heavily influence the decisions and directives of either commission. Both commissions hold their meetings in public (as required by the Brown Act) and face consistent and, normally, divergent pressure from a number of stakeholders. Just as these stakeholders can influence the commissions, the decisions they make directly influence the behavior California consumers and producers. In 2018, for example, the CEC voted unanimously to change the state's building code to require that every new home and multi-family residence, of three-stories or fewer, be built with solar panels, starting in 2020. The heavily contested decision brought out activists on both sides of the issue, with opponents saying it would increase California's already high housing costs and proponents claiming consumers would save money on the long-run and it would better for the environment. Regardless of one's opinion on the decision, more solar power, absent efficient use or storage, will certainly exacerbate the duck curve.

In addition to the external pressures faced by the CEC and CPUC, there are internal pressures as well. For one, governors will most assuredly appoint people who closely align with their own political inclinations. If a governor desires to expand the use of renewable energy, as is the case with former Governors Brown and Schwarzenegger, his or her appointees will most likely share a similar view. Moreover, if an appointee wants senate confirmation, they may have to acquiesce to the wishes of the majority party.

Beyond the regulatory actions of the CPCU and CEC, both agencies also administer energy storage programs like SGIP and EPIC, respectively. Considering the large amount of funding provided to these agencies to carry out renewable energy programs, and the significance they play in policy implementation, any alternatives proposed here must recognize the current political dynamics of both commissions and the pressures exerted on them.

Economic factors

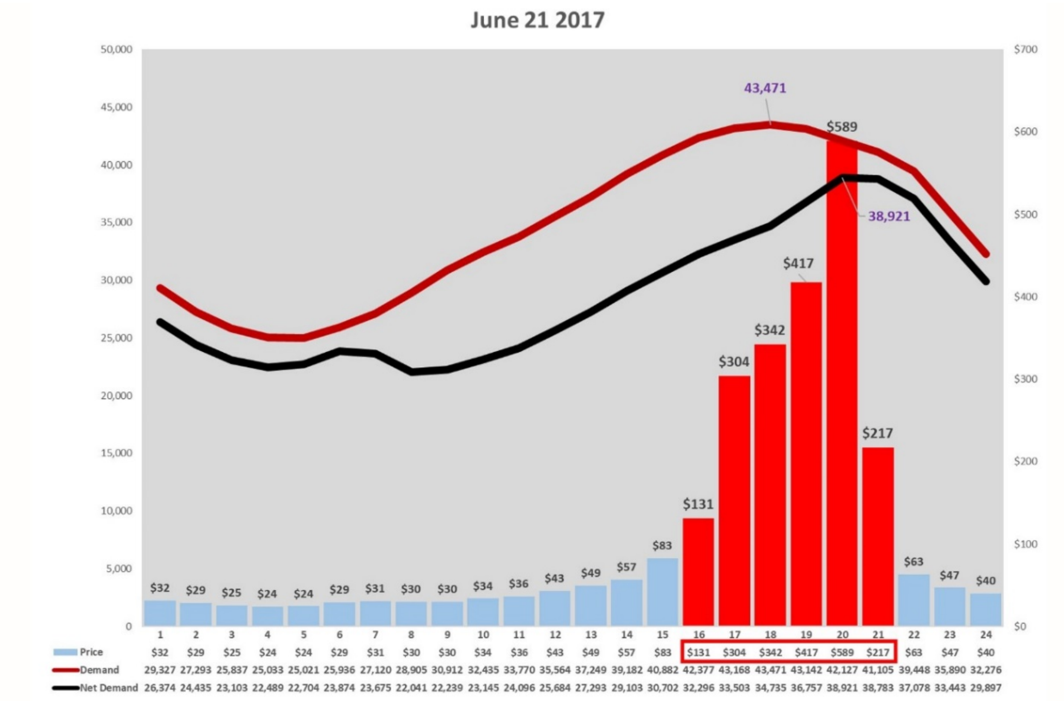
Perhaps the most consequential factor in renewable energy and energy storage policy is economics. Whether influencing consumer behavior through incentives or subsidizing the production of new storage technologies, economics is the mechanism that makes policy practical.

What is common through all the economic aspects of California's renewable energy policy is distortion of the supply and demand model.

As with most markets, California energy demand largely drives energy supply. In 2017, the total in-state electric generating capacity was 79,825 MW; natural gas provided over 42,000 MW, and solar generated just under 10,000 MW (CEC, 2018, Tracking Progress). The state receives another 10 percent of generating capacity from out-of-state carbon sources. Simply put, the goal of California's decarburization policy is to retire the 40,000-plus MW of in-state natural gas fired power plants and replace them with carbon free sources.

Implementation if this goal, however, has effects that cannot be legislated or regulated away. The first is the supply and demand imbalance represented in the duck curve. What the belly of the duck represents, economically speaking, is an artificial increase in solar demand resulting in artificial scarcity of natural gas energy. Yet, this is only half of the equation. Because technologies to store and dispatch excess solar energy are not fully developed, gas-fired power plants, known as "peakers," must cover the ramp when actual demand increases in the early evening. Peaker plants are "less efficient and have higher operating costs and higher emissions" than natural gas-fired plants that provide base load energy (Franco, 2018). Furthermore, because natural gas demand drops during the day, the price does as well, increasing the costs to run peaker plants in and economic fashion. These increased costs first hit energy utilities who then pass the costs onto consumers. An examination of wholesale natural prices on a hot summer day clarifies the economics. In Figure 5 below, the numbers across x-axis of the graph (1-24) represent the hours of the day, while the numbers on the y-axis represent price per MW hour (MWh) (right-hand side) and MW generated (left-hand side). As gas-fired plants start to fire up at 4pm to cover the drop in solar energy generation, natural gas prices start to increase dramatically, peaking at

$589 per MWh from 8pm - 9pm. Speaking in economic terms, solar overgeneration intensifies the inelasticity of natural gas, raising its price.



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Price	$32	$29	$25	$24	$24	$29	$31	$30	$30	$34	$36	$43	$49	$57	$83	$131	$304	$342	$417	$589	$217	$63	$47	$40
Demand	29,327	27,293	25,837	25,033	25,021	25,936	27,120	28,905	30,912	32,435	33,770	35,564	37,249	39,182	40,882	42,377	43,168	43,471	43,142	42,127	41,105	39,448	35,890	32,276
Net Demand	26,374	24,435	23,103	22,489	22,704	23,874	23,675	22,041	22,239	23,145	24,096	25,684	27,293	29,103	30,702	32,296	33,503	34,735	36,757	38,921	38,783	37,078	33,443	29,897

Figure 5. Wholesale natural gas prices in California (June 21, 2017). From Placer County Water Agency, 2018

In addition to energy prices, there are costs to decarburize California’s electric generating infrastructure. Nearly half of the state’s power generation comes from gas-fired power plants, so replacing that infrastructure will require large amounts of capital. In 2016, for example, the average construction cost of a utility-scale battery power plant equaled $2,434 per kilowatt (kW) compared to $895 per kW for a natural gas power plant (U.S Energy Information Administration, “Electricity,” 2018). This cost does not take into consideration the costs of transmitting the energy from its source to the grid. Gas-fired power plant also have a much longer life span that most energy technologies, with the exception of hydroelectric facilities and nuclear plants.

Despite the supply and demand distortions created by solar subsidization and grid penetration, there are some positive economics. For one, the cost of utility-scale solar energy generation decreased from $359 per MWh in 2009 to $50 per MWh in 2017 (Lazard, 2017). Furthermore, experts anticipate the cost of solar energy will dip below that of natural gas by 2025. Energy storage technology tells a similar story. Since 2014, the cost of large-scale lithium-ion battery installations, for example, declined from $6,200 per kilowatt (kW) to an estimated $1,500 per kW, and costs are expected to decrease another 35 percent over the next years (Lazard, 2017). As the cost-efficiency of renewable energy and storage technology improves, private capital investment should increase. However, in the interim, government continues to play to a role. In a study, reviewing the installation of 124 grid-scale batteries projects across the United States between 2009 and 2014, Hart and Sarkissian (2016) identified public investment as an important enabler of battery storage growth.

Summary

In this chapter, I examined myriad of factors that have influenced, and will continue to influence, the development of renewable energy policy and the deployment of energy storage in California. Social factors include strong support among California's population for further investment in renewable energy technology, as a way to fight climate change. Because state policy already supports growth in renewables, the public's support will act an expediter of further public investment. Closely correlated to the social factors are the political factors, which include a complex and fragmented regulatory regime influenced by partisanship and patronage. Whether it be the CEC or CPUC, appointees to these powerful commissions will be partial to the political proclivities of the governor who appoints them and the legislators that approve their appointment. These commissions possess great authority to implement the will of the legislature through regulation and funding programs. Lastly, I examined the economic factors of the state's renewable energy policy and their affect the development of energy storage technology. I showed how the growth of solar energy in California has disrupted the supply and demand dynamics of energy markets. This disruption has a number of effects, mostly notably higher gas prices for consumers caused by an intensification natural gas' inelasticity. Combined, the social, political, and economic factors create an environment that will continue to be supportive of further investment in renewable energy, therefore increasing the need for more energy storage.

Chapter 3: Energy Storage Alternatives

Previous chapters of this thesis provide an overview of California’s duck curve conundrum in two distinct contexts. Chapter 1 defined the problem posed by California’s duck curve, its origin and development, and how past legislative and regulatory policies are largely responsible for its creation. I then reviewed the experiences of other states and municipalities facing similar challenges, paying special attention to the Nessie curve in Hawaii, the Emu curve in South Australia, and emerging problems in New England. Chapter 1 concluded with potential strategies to address California’s duck curve, with storage as a leading candidate. Chapter 2 examined the duck curve within California’s social, political, and economic environments, which inevitably influence policy decisions regarding renewable energy, generally, and solar energy, in particular.

This chapter introduces energy storage technologies utilized and in development to balance California’s electrical grid by flattening the duck curve. Energy storage technologies identified here constitute the alternatives used for CAM analysis in the Chapter 5. This chapter is organized into three sections. In the first section, I briefly re-analyze the causes of the duck curve to provide more context for the storage alternatives proposed. The second section discusses the variables that influence the development and utilization of energy storage technologies. The final section reduces and simplifies the different storage technologies that I analyze later.

Causes of the Duck Curve

There are two main causes for California’s duck curve. The first cause is the intermittent nature of renewable energy. Because the sun does not always shine, and the wind does not always blow, energy provided by these sources is not stable like a gas-fired power plant. Moreover, intermittent sources do not have the peaking ability required to meet sharp rises in demand. Although the timing of solar energy and other renewables may be predictable, say from a weather report, the energy is only useable at that time. This is the main reason storage is such an attractive option.

The second cause of the duck curve is a public policy. I discussed much of this policy in detail previously, but it is useful to examine some of the effects. One of the most pronounced effects is the decentralization of power generation. Like most industrial societies, California historically produced energy by central station power plants that provide bulk power. However, with the advent of renewable energy technologies, energy generation transitioned away from the centralized model to a dispersed model, known as distributed generation. While this thesis does not intend to detail the merits, or demerits, of either model, the reality is California's energy infrastructure has not transitioned at the same pace as distributed generation. So, as California replaces large-scale generation far from consumption with small-scale generation close to consumption, the belly of the duck curve grows deeper and the ramp steeper.

Despite this challenge, policymakers and regulators continue to push for more renewable energy production. In the most recent legislative session, legislators introduced no fewer than 145 bills related to energy, with a large amount mandating more renewable energy production. Another example of supportive public policy comes in the form of monetary incentives. The problem with a majority of past incentive programs, such as the CSI discussed in Chapter 1, is they were geared toward residential or small-scale solar installation, which the CAISO cannot physically regulate. Home and small-scale solar generation is a prime example of distributed generation. When it comes to financial incentives for energy storage, most subsidies and rebates target small-scale operations, such as home battery systems.

From Chapter 2 we learned that there are circumstances that shape the renewable energy market and potential policy solutions to the duck curve. These circumstances include asymmetric information, fractured governance, and supply and demand imbalances. While there are tools available to government to address these realities, many are long-term solutions trying to solve an imminent problem. Information dissemination, for example, may provide the public with a greater understanding and familiarity with the duck curve, which, in turn, could change public perception and, therefore, policy decisions of regulatory agencies or elected representatives. However, this could take years, if not decades, and there is little to suggest it would have any effect on current trends. Other options like solar generation curtailment or grid regionalization provide more immediate solutions, but are fraught with their own challenges. AB 813, for example, which sought to regionalize CAISO with neighboring states in an effort to dilute excess energy through interstate transfers, failed to muster enough political support for passage in the closing days of the 2017-18 legislative session.

Considering the resources put towards energy storage, current storage mandates, and the promise storage technologies possess, it is appropriate to analyze different storage options as the solution to the duck curve. Prior to getting into specifics of different energy storage technologies, it is helpful to review some of the variables that could affect the selection of storage alternatives.

Variables in Storage Technologies

There are currently 32 types of energy storage technologies available for use in California. In most market economies, the prevalence of some technologies depend on the value, or utility, of one product versus another. I address this utility factor in my first variable of technology maturity.

Technology Maturity

Because there is an immediate need for storage capabilities, to address the rapid growth of intermittent energy sources in California, the maturity of specific storage technologies is important. I define “maturity” by the following terms: response time, discharge time, depth of discharge, and cycle life. Why these terms? Because for grid operators, like CAISO, these are the most important factors in energy storage. Response time is essentially the time it takes for an energy storage system to ramp from zero discharge to full discharge. Response times can range anywhere from seconds to hours, depending on the technology. Discharge time is the duration for which a storage system can maintain its energy output. Based on 2015 technology, discharge times range from seconds to ten-plus hours (CEC, 2018, Tracking Progress) and measured in terms of megawatts per hour. For example, a one MW battery with a discharge of three hours can provide three MWh of energy. Depth of discharge refers to the ratio of stored energy used in relation to the total capacity. Defined by its name, cycle life is the number of charge-discharge cycles before the storage system becomes inoperable. In addition to the above terms, current use is also a maturity factor. Current use can be measured by the number of facilities in service, or the aggregate amount of energy (MW) stored among the facilities. In this thesis, I use the latter definition, as the effectual amount of storage is what is important.

Considering all the terms above, and the capabilities required in order for CAISO to balance the grid, the most mature technology is one with a quick response time, a medium to long-term discharge time, a large depth of discharge, a long cycle life, and currently in use.

Regulatory and Legislative Policy

As evidenced by the efficacy of regulatory and legislative policy to spur production and deployment of renewable energy, regulatory and legislative policy can equally influence the development of energy storage technologies. The CEC notes, “California has the largest energy storage market in the United States” (2018, Tracking Progress, pg. 2) and first legislated storage mandates in 2010 with AB 2514. In the years that followed passage of AB 2514, the CPUC issued a number of decisions that drove further development of energy storage technologies by California’s three major IOUs. In 2016, the year after a massive natural gas leak at Aliso Canyon Natural Gas Storage Facility, the CPUC ordered Southern California Edison and San Diego Gas and Electric to accelerate procurement of electric storage to address a decline in natural gas reserves (CEC, 2018, Tracking Progress). Other legislation in 2016 and 2017 either directed regulatory agencies to implement investment programs in energy storage systems or directly allocated funding for storage projects in the state. In August of 2018, the CEC reported that California had 332 MW of energy storage online, out of the 1300 MW requirement set by AB 2514 (CEC, 2018, Tracking Progress).

Beyond the direct intervention of government to influence development of storage technology, policy decisions can also set parameters that impact energy storage. A good example is the renewability limit placed upon large hydroelectric facilities. Under AB 2514 and subsequent legislative action, hydro facilities with a generating capacity of more than 30 MW of energy qualify as carbon-free, but not renewable. In the coming years, as the legislature and regulators work to clarify what qualifies as “renewable” and “carbon free” under SB 100, those decisions are a variability that will certainly effect the development of energy storage technology.

Energy Storage Costs

The final variable associated with energy storage is costs. Although energy storage is expensive, costs have come down in recent years. The reasons for the costs reductions include the benefits of economies of scale, design advances, and streamlined processes. The cost of lithium-ion batteries, for example, have come down because of the demand for batteries in electric cars. As production increases, so too does the efficiency of lithium-ion batteries. To support the development of energy storage technologies, the government can change the market rules that govern energy storage. For example, after the CEC identified streamlining interconnection processes as a goal to increase storage development, CAISO and the CPUC took a number of administrative steps to make that happen. Lastly, the government can influence costs by directly funding projects. Since 2010, more than 30 energy storage projects received financing from the

CEC. Regardless of the reason for changing costs, the important point is to recognize that costs are variable and affected by market activities and government intervention.

Introduction of Storage Alternatives

In this section, I introduce and briefly describe the energy storage technologies analyzed in this thesis. First, it is important to cover some limitations to provide greater context.

The first limitation is this thesis will focus on what the industry calls "bulk storage," or utility-scale storage. Although the state invests heavily in consumer-side storage technology, trying to accommodate current trends and data on consumer-side storage would be too exhaustive for the purpose of this study. It is fair to say, however, that consumer-side storage is almost exclusively limited to battery storage in the home.

Another limitation is the exclusion of some storage technologies. Based on the variables described above, some technologies are not suitable for inclusion. Rather, I will analyze the storage technologies that currently make up the majority of utility-scale storage in California; however, I do include one relatively nascent technology for broader analysis.

The energy storage technologies introduced here can be broken down into three technology classes, which are mechanical, chemical, and electrochemical.

Mechanical: Pumped hydroelectric storage (pumped hydro)

Since its deployment, in the 1890's, pumped hydro has been and "is the dominant utility-scale electricity storage technology in California and worldwide" (CEC, 2018, pg. 5). Pumped hydro facilities consists of an upper elevation reservoir and lower elevation water reservoir, connected by a penstock (tunnel), and infrastructure for energy generation. The technology works by pumping water from the lower reservoir to the upper reservoir, when energy costs are low, and then releasing water from the upper reservoir when the grid needs energy. Because hydro pump facilities can turn on and generate energy within minutes, pumped hydro can provide energy for long durations of time and help fill the ramp identified in the duck curve. In 2017, “more than 4,500 MW of pumped hydro energy storage systems were operational in California” (CEC, 2018, pg. 5). Pumped hydro facilities can be open loop are closed loop (see Figure 6). As note earlier, under AB 2514 and subsequent legislative action, hydro facilities that generate more than 30 MW of energy qualify as carbon-free, but not renewable.

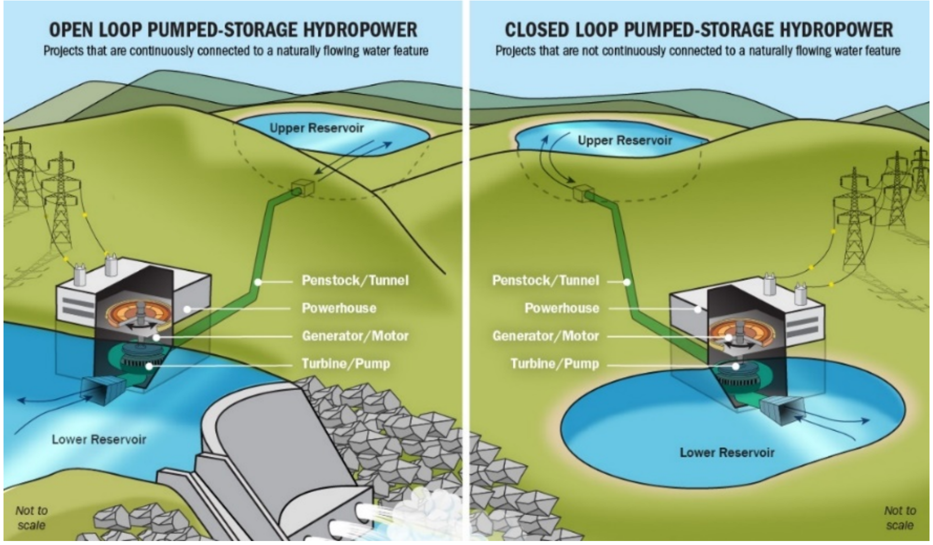


Figure 6. Pumped hydro facilities. From U.S. Department of Energy

Chemical: Hydrogen

Production of hydrogen energy is a newer technology that, while not in widespread use, is gaining recognition. Hydrogen can be produce from natural gas, water, or wind, but water is the most abundant source. Through a process known as electrolysis, water passes through an electrolyzer, splitting its molecular makeup (H_2O) into hydrogen and oxygen (see Figure 7). The oxygen releases into the atmosphere and the hydrogen is then stored on a fuel cell, combusted for energy, or stored and transported for use beyond its generation point. Generating hydrogen through this process emits zero greenhouse gases, and qualifies as 100 percent renewable. Current California policy in regards to hydrogen energy is geared toward use in zero-emission vehicles, but opportunities for utility-scale storage are present.

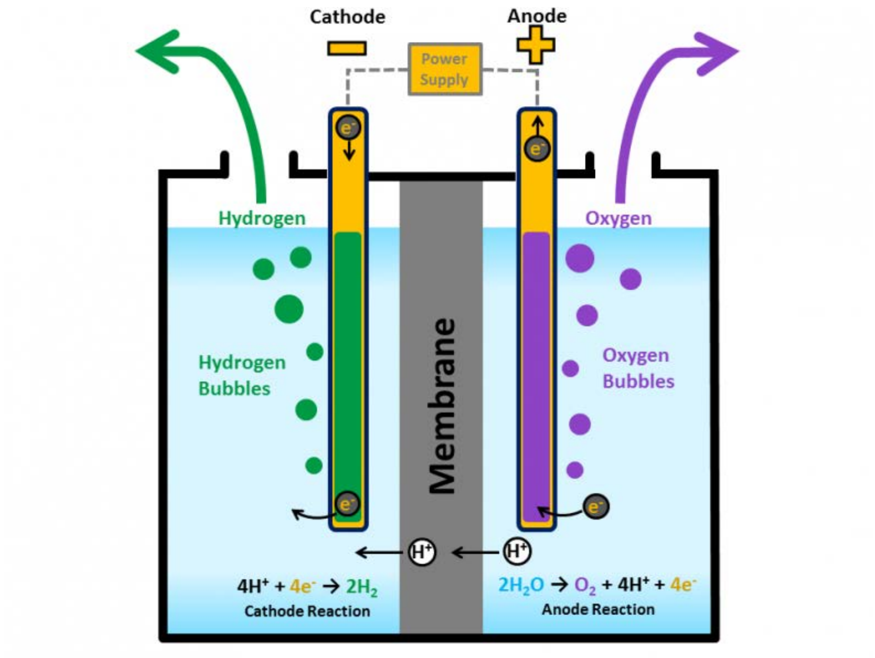


Figure 7. Electrolysis. From U.S. Department of Energy

Electrochemical: Batteries

Battery-types range from lead acid batteries to other chemical batteries, yet lithium-ion batteries will be the focus of this analysis. Because of their widespread use in consumer electronics, lithium-ion batteries have grown in popularity in recent years. In California, they provide the added benefit of easily storing solar energy. Batteries work by creating an electric current when the positive and negative charges in the battery interact. With lithium-ion batteries, the process used to discharge energy can be reversed to generate energy. Like hydrogen, batteries serve a dual purposed of utility-scale storage and emerging transportation technology like electric cars. Because of their relative maturity and large energy density, batteries are the preferred energy storage technology of the State of California. The CEC reports that in June of 2017, “stationary battery energy storage systems totaled 177 MW” (CEC, 2018, pg. 8).

Mechanical: Compressed Air Energy Storage (CAES)

Compressed-air energy storage, commonly referred to as CAES, is a storage technology that uses low-cost, off-peak electricity to compress air in a storage system. The storage system can be underground or aboveground. Underground storage include porous rock formations, salt caverns, or depilated gas or oilfields; aboveground systems include vessels and pipelines. The CAES process produces energy by withdrawing air from the storage system, heating it by natural gas, and moving the hot air through turbines that power an electric generator. Transmission lines then transfer energy from the generator to the grid. In California, there are currently no CAES systems in operation. In fact, there is only one CAES system located in the United States, in McIntosh, Alabama.

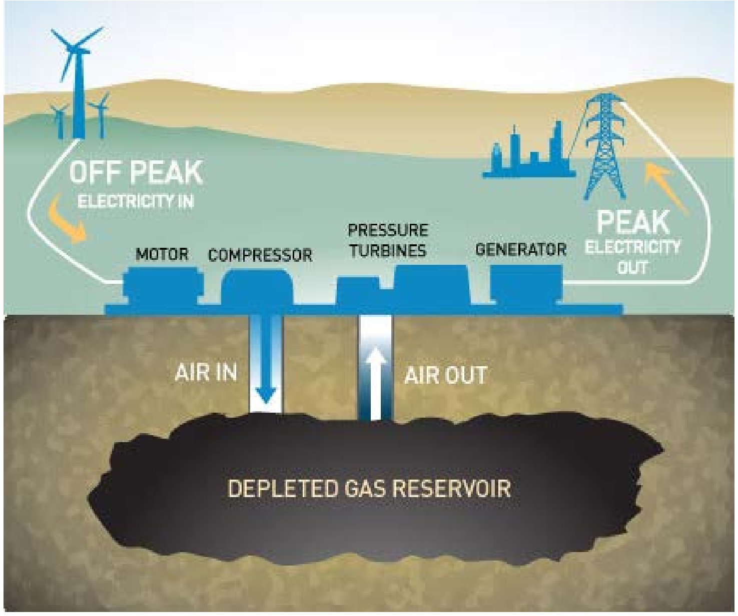


Figure 8.Compressed Air Energy Storage. Adopted from Pacific Gas & Electric

Summary

This chapter identified and discussed some of the alternatives available to address California’s energy storage needs. Part of the discussion focused on the duck curve as a major reason for the need, and how past policy decisions have contributed to the duck curve. As recognition of state’s energy problem has grown in recent years, the government has played an integral role in supporting energy storage. However, decisions regarding which storage technologies are most appropriate to pursue, whether by private entities or government, are not made in a vacuum. The variables that affect those decisions comprised the second part of the chapter. The variable are technology maturity, regulatory and legislative policy, and costs of energy storage. The chapter conclude with a brief discussion of storage technologies that will serve as alternatives for the CAM analysis conducted in Chapter 5. The storage alternatives are pumped-hydro, hydrogen storage, batteries, and CAES.

Chapter 4: Criteria

In Chapter 3, I introduced a number of energy storage alternatives available to California to address its duck curve. The alternatives are pumped-hydro, hydrogen, batteries, and CAES. Determining which alternative is best suited to meet California's growing reliance on intermittent energy sources, and the challenges those sources present for grid stability, requires a rigorous and structured process.

There are many tools available to conduct robust and thorough policy analysis. One common method, identified by Bardach (2000) and Munger (2001), is assessing the benefits and disadvantages of policy alternatives against a battery of selected criteria. As Wassmer (2002) points out, "These criteria serve as measurement tools that can collectively account for the issues and considerations anticipated that would affect the feasibility of a policy's implementation and the achievement of its intended outcomes" (p 41). Because the criteria will be integral to making a policy recommendation, this chapter begins with a discussion explaining how I selected the criteria.

In the second part of this chapter, I identify the criteria used for my analysis of energy storage technologies. I accompany each criterion with a brief description and rationale for inclusion. A final, yet important, aspect of the criteria selection is assigning a weight to each criterion. The weight conveys the value of each criterion within the set, and is crucial to the process of analysis. In theory, every criterion could be weighted equally, but, in practice, it is likely some criteria will carry more importance than others will. Chapter 4 concludes with an introduction to the methodology that I use to conduct the analysis in Chapter 5.

Criteria Selection

Determining the appropriate criteria requires three considerations. The first consideration is the desired outcome of the issue. As I described earlier, the desired outcome of deploying energy storage technologies is to stabilize California’s energy grid without sacrificing the investments made in renewable energy sources. Encompassed in that objective is a desire to expand the use of renewables to a point at which California has a carbon-free energy supply in the next 25 years. To achieve these two seemingly competing outcomes without major disruptions to energy producers and consumers, energy markets and grid operators, and other stakeholders seems unrealistic. Such a perfect outcome, in which the economic conditions of all parties are better off, or at least the same, following the implementation of a policy is known as “Pareto efficient.” However, because the policy alternatives under consideration will include tradeoffs, Pareto efficiency is not attainable.

This leads to the second consideration: should the criteria used should be practical or evaluative? Not only is it good analytical practice to use both, but because some will benefit, while others will not from the chosen policy alternative, it is important that the criteria be robust. Practical criteria, as its name may suggest, are about feasibility. Questions to consider are whether there are political, legal, or administrative barriers to a certain policy. Evaluative criteria addresses the issue of efficacy, but can include normative measures, like equity. In sum, evaluative criteria focuses on policy outcomes, while practical criteria focuses policy implementation.

The third and final consideration of criteria selection is prior research. In the case of energy storage technology, the range of criteria can vary. Ibrahim, Ilinca, & Perron (2007), for example, identify 16 different criteria in their research on energy storage systems. On the other end of the spectrum, Palizban and Kauhaniemi (2016) use only six criteria. The total number of criteria chosen largely depends on the purpose of storing energy. Because the purpose of this thesis is to investigate storage technologies for grid reliability, my criteria must be those most appropriate for large-scale energy storage.

Accounting for the three considerations listed above, I identified six criteria for my analysis inclusive of evaluative and practical criterion. The criteria are as follows:

Cost

Political Feasibility

Environmental Impact

Response Time

Discharge Time

Storage Capacity

In the next section, I define each criterion and provide the rationale for inclusion.

Criteria Definitions

Cost

A common economic refrain is, "There is no such thing a as a free lunch." This is certainly true of energy storage development and deployment, so it is logical and fitting that cost be considered in my analysis. It may also be recalled from earlier chapters that energy storage is very expensive, therefore it cannot be overlooked as a significant factor. If energy storage devices were cheap and plentiful, there would be no need for this thesis.

Government subsidies also effect energy storage costs. Since it would be impossible to account for all available subsidies for every type of technology in this thesis, I decided to address the subsidy issue in my weighting of cost, discussed later.

The issue then turns to how to define cost. There are a number of ways to go about this, and the literature is helpful in this regard. Ibrahim, et al. (2007) define cost with the following equation: $\mathrm{C}=C_1W_{\mathrm{ut}}+C_2P_{\mathrm{d}}$. In laymen's terms, cost is equal to the (dollars per kilowatt hour times the amount of energy released) plus the (dollars per kilowatts times the nominal discharge power). Gustavsson (*n.d.*) uses a friendlier two-metric system of power costs and energy costs.

Power costs are defined as dollars per kilowatt ($/kW), while energy costs are defined as dollar per kilowatt hour ($/KWh).

Another standard for cost, commonly used in the industry, is levelized cost. Levlized cost represents the net present value of the unit-cost of electricity over the generating asset's lifetime. Levlized cost is often used as proxy for the minimum price a generating asset must receive to break even over its lifetime. I use the levelized cost of storage for my cost criterion.

Political Feasibility

A practical criterion included in this analysis is political feasibility. Although California's current political landscape is favorable of more energy storage, it does not mean policymakers support an "all of the above" approach. Pressure from interest groups and other political forces could influence legislation affecting energy storage systems. Policymakers could also have personal preferences on what clean energy sources are acceptable. In sum, political acceptably could influence energy storage development in a number of ways, from mandates, to funding, to outright prohibition of certain storage systems.

In order to remove as much subjectivity as possible, and determine which energy storage alternatives receive the highest or lowest rating, I rely on legislative bill history and/or recent rulings by regulatory bodies. I assign storage alternatives with the most political support with the most positive assessment.

Environmental Impact

Environmental impact may be one of the harder criterion to measure; however, it is crucial. In Chapter 2, I reported that the public and current political regime strongly support investments in renewable energy in order to combat climate change. I also noted that current policies coming from regulatory agencies will increase our reliance on renewable energy. Therefore, it is reasonable to assert that development of energy storage technologies should follow suit. In the very least, storage technologies should not hinder or turn back advancements towards a cleaner environment.

Despite discussions about environmental impacts throughout the literature (Ibrahim, et al. (2007), and Daim, Li, Kim, and Simms (2012)), there is no settled scientific measurement for environmental impacts. Raza, Janajreh, and Ghenai (2014) provide the most comprehensive analysis looking at the environmental impact over the lifetime of different energy storage systems. In their analysis, a “lifetime” includes the production, operation, and disposal of different technologies.

I will follow a similar formula in developing my own measurement, while adding two other metrics. The first metric is cycle life, which is the number of charge-discharge cycles before the storage system becomes inoperable; cycle life is also identified as one of the most important energy storage factors for gird operators (see Chapter 3). Because a scientific measurement can be applied to a storage technology’s cycle life, and, in theory, a longer cycle life is more beneficial to the environment than a shorter one that needs continual replacement, it is appropriate apply a higher score to a technology with a longer cycle life.

The second metric I include in my environmental impact criterion is land requirements, or siting. Storage technologies that require less land will score higher than those that require more land. By combining land requirements and cycle life, I can provide a quantitative measure to this relatively qualitative criterion.

Response Time

Another metric important to large-scale energy operations such as CAISO is the response time of energy storage technologies. Simply stated, response time is the time it takes for the storage system to reach peak energy production. According to protocol developed by the U.S Department of Energy, an energy storage system must be within plus or minus two percent of its rate power (max power output) to qualify as official response time. As noted in Chapter 3, response times can range from seconds to hours.

Discharge Time

Similar to response time, discharge time is critical to the efficacy of large-scale energy storage systems. Discharge time is the duration for which a storage system can maintain its energy output. Discharge time is normally measured in megawatts per hour (Mhr), and can last anywhere from seconds to hours. In cases where only the megawatt generation is provided, a simple calculation of the megawatts expended multiplied against the hours discharged (or fraction thereof) will provide a Mhr for that system.

Storage Capacity

The last criterion I use my analysis is storage capacity. The choice of storage capacity is justified due to its relation to depth of discharge. As discussed in Chapter 3, the depth of discharge is storage characteristic important for large-scale storage. However, depth of discharge is the ratio of stored energy used in relation to the storage capacity. Since there is no way to measure the ratio in a theoretical exercise, there is no way to measure depth of discharge or use as a criterion. However, the storage capacity can be measured, in most cases. In effect, I use storage capacity as a proxy for depth of discharge. Storage capacity is measured in megawatts.

A Word on Efficiency and Equity

Academic consensus holds that efficiency and equity are normally the most important criterion in policy analysis (Wassmer, 2002). While both are not explicitly part my analysis, both are covered. In describing my criterion above, I noted the most important aspects of large-scale energy storage are cycle life, response time, discharge time, and depth of discharge. By including all four components, or elements thereof (e.g. storage capacity), I incorporate efficiency as part of my criterion.

Admittedly, equity is harder consideration for which to account. Since any policy decision made in favor of one energy storage technology over another will likely create “winners” and “losers,” I rely on cost efficiency and political feasibility to account for equity. With regard to cost, finding the most cost-efficient alternative is one way to protect taxpayers and consumers from frivolous government-backed ventures, which is certainly an issue of equity. With political feasibility, there is the following argument: nothing can be politically feasible without some form of effective advocacy. Because each alternative in my analysis has advocates, with the ability to lobby legislators and regulators, there is the semblance of fairness. Although it is true that some advocacy may be more effective than other’s advocacy, there is, at least, an opportunity to influence the decision-making progress. To try to account for this same level of equity in this analysis would be difficult.

Weighting of Criteria

With the criteria identified and defined, the next step is to apply weights to each criteria. Wassmer (2002) notes that “Any science behind establishing weights for these criterions in a policy evaluation is not well established and generates controversy” (p 44); nonetheless, it is a crucial part of the process. Otherwise, it would have to be assumed that each criterion carried equal weight, which is not reasonable as described earlier. Due to the subjective nature of assigning weights to each criterion, this section concludes with a discussion about the rationale for the weights I assign.

While there a number of different ways I can go about assigning weights, for simplicity’s sake, I apply a decimal value for each one of my criterion. The sum of all the decimals will be equal to one. Another way to consider this formula is to assume all the weights are percentages, which would equal 100 if added together. The relative weighting applied to each criterion are in Table 1.

Table 1

Relative Weights for Each Criterion Used in Analysis

Criterion	**Weight**
Cost	0.10
Political Feasibility	0.10
Environmental Impact	0.30
Response Time	0.20
Discharge Time	0.20
Storage Capacity	0.10
Total	1.00

Cost

I assigned the criterion of cost a relative weighting of .10, or 10 percent if the weights represented a percentage in my analysis. The reason for my weighting is three-fold. First, defining cost is not an exact science. Although I use the unsubsidized levelized cost of storage as my cost factor, there are a number of ways one could determine cost. In their analysis of lead acid batteries, lithium polymer batteries, and fuel cells, for example, Raza, et al. (2014) determine costs using geographical statistical data in addition to battery, fuel cell, and photovoltaic cells cost. The second reason is the issue of subsidies. As covered in previous chapters, the California Legislature and regulatory bodies have been more than willing to subsidize not only the production of renewable energy, but systems to store excess energy. By creating a distortion in price signals, however, subsidies can hide the true cost of energy storage systems. On the flip side, subsidies can also help lower the cost of emerging technologies as more participants enter the marketplace to take advantage of lower costs. This is certainly true in relation to renewable energy, as prices of solar energy and batteries, for example, have fallen in concert with maturing technology. I suspect that as government or private industry devotes more money to energy storage, prices will fall, reducing the importance of cost in the long run. While cost cannot be overlooked, consideration of all the variables requires restraint in the influence provided this criterion.

Political Feasibility

Similar to cost, I assigned political feasibility a relative weighting of .10. This weighting is not to diminish the importance of the political process in developing and deploying more energy storage systems in the state, but California is on a collision with reality. In earlier chapters, I discussed how California policymakers are looking at multiple ways, including energy storage, to address the duck curve. Politically feasible or not, storage systems that may not be politically favored are probably going to have to be part of the solution, especially if the state wants to become 100 percent reliant on carbon-free, renewable energy. Additionally, recently legislated energy storage mandates show that the legislature recognizes the need for more storage. With all of that said, politics will play a role in the future growth of energy storage. California regulatory agencies will still regulate, and politicians will still want to have a say in how California meets its SB 100 goals. For these reasons, political feasibility is included as a criterion, albeit a less influential one.

Environmental Impact

I assigned criterion environmental impacts, a relative weighting of .30, which is the highest of all my criteria. The reason for weighting it the highest originates from the fact that California’s move toward more renewable energy is largely based on the argument that “green energy” benefits the environment. If true, then it is incumbent that we should not store clean energy with systems that harm the environment. Because we can assume there are less negative externalities associated with renewable energy production, distribution, and storage than fossil fuels, considering the environmental externalities of one storage system against another is paramount.

Another reason I have weighted environmental impact so high is my definition includes a measure of efficiency in cycle life. By itself, cycle like would assume the same or close to equal weight of other efficiency measures. Because I include other elements in addition to life cycle (land requirements and disposal), environmental impacts represent more than efficiency standards alone.

Lastly, within the literature, inclusion of environmental impacts appears to be the exception rather than the norm. By providing a relative high importance in this analysis, I provide another way to consider this important criterion.

Response Time

The fourth criterion, response time, is another measure of efficiency. I apply a relative weighing of .20 for response time, meaning I believe to be more important the cost and political feasibility and less important than environmental impacts. Because there are four factors important to a large-scale, energy storage system an equal weight could be applied to all four. This is represented in the .20 weight applied to response time (taking into consideration cost and political feasibility). Response time is important because a fast response time provides the grid with energy on a moment’s notice. In order to minimize generation fluctuations caused by intermittent energy sources in early evening ramps (the duck’s neck) CAISO needs a rapid response time from energy storage systems. Considering this reality and the four measures identified as constituting efficiency, .20 if the proper weight for response time. In my analysis, the quicker the response time the higher the numeric rating.

Discharge Time

Because discharge time is a component of efficiency, like response time, I assigned the same .20 relative weighting. For large-scale storage, long discharge times are preferable to short discharge times. Considering the amount of photovoltaic energy being put on the grid, the ability to use it over long periods of time could cover major grid disruptions and, potentially, bring down energy prices in the long term as reliability increases and solar power more valuable. The longer the duration available from a storage system, the higher the score under my methodology.

Storage Capacity

In my earlier description of storage capacity, I noted it represented one-half of the fourth efficiency measure: depth of discharge. Because it is only one-half, and storage capacity can cover a range of different sizes, I assigned the relative weight of .10, half of the other efficiency measures. However, the importance of storage capacity cannot be disregarded; that is, storage capacity directly relates to the amount of excess solar generation that can be removed from the grid during times of solar overgeneration.

Methodology

The remainder of Chapter 4 is dedicated to the methodology that I utilize in the next chapter. As I wrote in Chapter 1, I complete my analysis by using a quantitative criterion-alternative matrix (CAM) analysis. The matrix is setup listing the criterion in columns and the alternatives in rows. Within each cell, where the criterion and the alternatives meet, is the weight of each criteria, a rating based on analysis, and “score” (the rating multiplied by the weight). After tabulating all the scores of across the range of criterion, it is given a total score. The total score provides the policy analyst with a quantitative picture of how each alternative performs when compared against chosen criteria; armed with that information the analyst can make a decision on the best policy alternative.

The rating used to determine the alternative’s score is an ordinal scale of one through five (1 – 5). While there is no requirement exactly what the scale must be, the one through five scale provides a broad enough spectrum differentiate between those polices that perform well and those that perform not so well. In this analysis, the following is make five-scale ranking: (1) equals “very weak,” (2) equals “somewhat weak,” (3) equals “fair,” (4) equals “somewhat strong, and (5) equals “ very strong.”. Put simply, the higher the number the better. Table 2, provides an outline of what a rating of five and one mean per the criteria.

Table 2
Criteria Rating Scale

Criteria	**Ratings Interpretation**	
	5 – Very Strong	**1 – Very Weak**
Cost	Cost in dollars is inexpensive with lots of current public investment. Likely effect of economies of scale is significant.	Cost in dollars is prohibitive with little current public investment. Likely effect of economies of scale is negligible.
Political Feasibility	Political bias already exists in favor of alternative. California Legislature enthusiastically endorses its further development.	Political bias already exists against alternative. Very unlikely that California Legislature would endorse further development of resource.
Environmental Impact	Requisite land requirements are negligible. Cycle life is long, and disposal of storage system poses low threat to environment.	Requisite land requirements are significant. Cycle life is short, and disposal of storage system poses elevated threat to environment.
Response Time	Time it takes disperse energy is seconds or less. Flexible enough to adjust to variations in load.	Time it takes to respond is hours. Inflexible and unable to adjust to variations in load.
Discharge Time	Discharge can last for hours, and duration has no effect on power output.	Discharge can last for seconds, and duration can effect power output.
Storage Capacity	Storage capacity is deep and large.	Storage capacity is shallow and small.

Summary

The purpose of Chapter 4 was to provide the criterion that I use to analyze the energy storage technologies identified in Chapter 3. The chapter started with a discussion about important considerations when choosing criteria. This includes a clear understanding of the goal of the policy, the difference between practical and evaluative criteria, and prior research. After providing a detailed description and justification of criteria, I discussed the importance of assigning weights to each, which I then did to my criteria with explanation. Lastly, I provided a brief overview of a quantitative CAM analysis, discussing the ordinal rating scale I will use in Chapter 5 for my analysis.

Chapter 5: Analysis of Energy Storage Alternatives

The objective of Chapter 5 is to determine the best storage alternative to address California’s duck curve and achieve the policy goals set by recent legislation. Based on the criteria identified in the previous chapter, the chosen storage alternative should not only be effective, but feasible.

To set the proper context for my analysis, the first section of this chapter revisits California’s duck curve problem, reviewing the need for energy storage development and government’s responsibility in responding to the challenge. Following this discussion, I describe my energy storage alternatives, detailing their current utilizations, benefits and drawbacks, and specifications in terms of my criteria. This part of the analysis includes the projected outcomes of each alternative in addressing the duck curve. The third and final section of this chapter presents the quantified assessment of each storage alternative using the CAM system introduced in Chapter 4.

Revisiting the Duck Curve

Put succinctly, California’s duck curve represents a system-wide electrical imbalance exhibited by the state’s grid. The primary cause of this imbalance is the aggressive saturation of renewable energy generation, namely solar power, onto the grid. More specifically, California’s grid experiences a large influx of solar power during the day, when demand is low, and a steep drop off in the early evening hours, when demand is high. To accommodate the large influx and drop-off of solar energy, traditional energy sources, primarily gas-fired energy plants, must reduce their load during the day and then ramp up at night. The range and ramp required to accommodate solar energy penetration strains California’s current power infrastructure to the point that the state cannot fully utilize solar energy, increasing overall costs and reducing environmental benefits.

As discussed in Chapter 2, the duck curve represents a distortion in the supply and demand model. What the belly of the duck signifies, economically speaking, is an artificial increase in solar demand resulting in artificial scarcity of natural gas energy. The distortion has not only created grid instability is has also resulted in the highest energy prices in the country. Furthermore, California produces such an abundance of solar energy that, occasionally, the state has to pay other states to take its excess solar energy. When conditions are right, overgeneration of solar power can also force traditional energy prices to turn negative during the day, making generation of traditional energy sources uneconomical despite the need for them.

If the decarburization of Californian's electrical gird was solely the result of market forces, one could chalk it up to an example of "creative destruction" – an economic theory positing that innovation has the tendency to dismantle long-established, traditional practices of economic exchange. However, the move to a less carbon-reliant energy supply, and subsequent challenges, have largely been the result of government intervention. While government intervention can take many forms, in this case of energy policy it has mostly taken the form of subsidies for consumers and producers to generate more renewable energy, and regulation requiring more renewable energy utilization. California's RPS, discussed in Chapter 1, is the most conspicuous example of government intervention in the energy market. Actions by the CPUC and CEC, two state regulatory agencies, also play a role in California energy policy.

As policymakers have become more aware of the duck curve in recent years, there has been an effort to ameliorate its effects; many of these efforts have taken legislative form. AB 813, for example, sought to regionalize California's energy grid with other western states in an effort to dilute excess energy through interstate transfers. AB 813 ultimately failed to receive legislative approval. Other efforts have looked at energy storage as solution. After a number of legislative and regulatory actions over the last decade, California has a mandate to procure and install 1,325 MW of energy storage by 2024.

The promise of energy storage lies in its ability to mitigate the intermittent nature of renewable energy. With solar power, for example, storage systems can absorb excess energy from the grid during the day, store it, and then distribute it after the sun goes down. In other words, storage shifts energy supply to later in the day when demand is high, stabilizing the grid. As referenced in Chapter 1, researchers refer to this change in supply and demand patterns as flattening the duck. Because the duck curve represents a distortion of energy supply and demand, flattening the duck with energy storage is reasonable and appropriate. Moreover, prior government intervention, overlapping layers of bureaucracy, ongoing regulatory mandates, and public interest in electric grid stability justify analysis of storage technologies as a matter of public policy.

Energy Storage Specifics and Projected Outcomes

In this section of the chapter, I provide more detail on the energy storage alternatives identified in Chapter 3. While I analyze each alternative separately, for simplicity, it is important to note that policymakers could choose to utilize a combination of the alternatives or advance them independently. Additionally, while the objective of this chapter is to identify the best energy storage alternative, results of similar analysis could differ. Munger (2001) observes that the weight assigned to each criterion heavily influences the analysis outcome, and that greatest value provided by the CAM approach is organizing a policy decision. Therefore, this analysis does not try to discover one alternative that “solves” California’s duck curve; rather, it attempts to provide enough data for policymakers to use to make informed decisions.

Typically, a CAM analysis also includes an alternative of “no change in policy,” or the status quo. Because no policy for energy storage alternatives currently exists, other than a megawatt mandate, this thesis only analyzes the four technologies previously identified. With that said, Chapter 1 provides a preview of what could happen should California continuing pursing its current path. Without a change in policy, the duck curve could grow to become similar the Nessie curve in Hawaii, with a deeper belly and more acute ramp when demand peaks. More growth in solar energy without the ability to store it would lead more curtailment of solar energy, reducing the environmental benefits. Moving on to the storage technologies under consideration, the analysis starts with the alternative of pumped-hydro storage.

Alternative I: Pumped-Hydro Storage

Pumped-hydro storage (pumped-hydro) was first developed and deployed in the 1890s. Today, it “is the dominant utility-scale electricity storage technology in California and worldwide” (CEC, 2018, pg. 5). Pumped-hydro facilities consists of an upper elevation reservoir and lower elevation water reservoir, connected by a penstock (tunnel), and dams with electricity-generating turbines. At a pumped-hydro facility, reservoir operators pump water from the lower reservoir to the upper reservoir, which holds the water, and then releases it. The released water spins the turbines, generating electricity than can be dispatched to California’s grid. As noted in Chapter 3, pumped-hydro facilities can be open loop or closed loop. As of 2017, there were eight pumped-hydro projects in California accounting for 4,517 nameplate megawatts of energy (CEC, 2018).

Due to the maturity of pumped-hydro energy storage, costs are relatively low. In 2016, the levelized cost for pumped-hydro ranged from $152 – $198 per megawatt hour (Lazard, 2016). While this cost is on the more affordable side of the cost scale, opportunities for declining costs over time are limited. For example, estimates for the years 2016 – 2020 show little decrease in the capital costs of pumped-hydro, which range from roughly $1.5 million to $2.5 million per megawatt (Vaughn & West, 2017).

There are a number of reasons the cost of pumped-hydro energy is unlikely to continue declining. The first reason is the limited number of suitable locations. Not only are the footprints of reservoirs very large, one cannot just place a water reservoir anywhere one desires. In most cases, the dam must span seismically-stable canyons with a river flowing through it. To identify a location where one can situate two water reservoirs is doubly hard. In fact, at the time of this writing, there are only two planned pumped-hydro projects in California's pipeline. Whether those projects will ever be developed remains an open question. One of those projects, the Eagle Mountain Hydroelectric Pumped Storage Project in Riverside County, has been under development for 25 years, yet remains unlicensed.

The second reason why costs for pumped-hydro projects are not likely to decline is that the costs of building in California are exceptionally expensive. California's environmental policies, like the California Environmental Quality Act, add layers of cost and bureaucracy to big infrastructure projects like a dam – or two in the case of pumped-hydro facilities. In 2016, the Sacramento Municipal Utility District shelved its Iowa Hill pumped storage project after cost estimates doubled. Originally price-tagged at $520 million in 2007, costs ballooned to $1.45 billion in less than a decade. While permitting costs and environmental compliance are not the only contributing factors to the increase, they played a large role.

Because pumped-hydro systems require dams, they are politically unpopular in California. Dams, critics argue, alter the natural flow and sediment transport of a river leading to environmental harm, such as declining fish populations and degraded aquatic habit. The reservoirs created by dams also attract recreation, which increases human interaction and, therefore, further environmental harm, the argument goes. Despite wide use in California, there is more talk today about tearing dams down than building them up. When the California Legislature starting setting renewable energy standards back in 2002 and then in 2011, it legislated hydroelectric facilities generating more than 30 megawatts of energy could not count toward the renewable energy standard. The reason for this was two-fold: first, the state would have reached its renewable target upon passage of the legislation (without the exemption), and, two, the state was actively pushing solar as the renewable energy choice de jour.

Despite some of the drawbacks associated with pumped-hydro energy storage, the technology has an astoundingly long cycle life. Most pumped-hydro projects can operate anywhere from 80 to 100 years; however, because tearing down reservoirs is an expensive and highly-technical proposition, the cycle life is theoretically unlimited. Once constructed, retrofitting reservoirs can extend their ability to continue producing and storing energy, or storing water. Pumped-hydro storage systems also have a very quick response. Hydroelectric generators typically can start up instantaneously when the grid needs energy. After starting up, they can run for upwards of ten hours. In terms of storage capacity, pumped-hydro storage leads the pack with an energy range of up to 100 gigawatt hours.

The potential of pumped-hydro energy storage is its ability to instantaneously adjust its energy supply, reduce the gap between peak and off-peak hours, and play a role in stabilizing grid power.

Alternative II: Hydrogen Storage

Although hydrogen energy storage is not in widespread use, it is gaining recognition. Hydrogen energy can be produced from natural gas, wind, or water, which is the most abundant source. Through a process known as electrolysis, water passes through an electrolyzer, splitting its molecular makeup (H_2O) into hydrogen and oxygen. The oxygen releases into the atmosphere, while infrastructure such as steel tanks store the hydrogen to be used on site or transported for use beyond its generation point (e.g. hydrogen filling station). Of all the components necessary for hydrogen storage to be useful, the fuel cell may the most important part. The fuel cell converts stored hydrogen into electricity and transports it to the electrical grid. For this reason, most of the following analysis focuses on fuel cells.

Recent studies looking at the levlized cost of hydrogen storage are scant, but according to Steward, Saur, Penev, and Ramsden (2009) the net present cost ranges from $350,000,000 on the high-end to $175,000,000 on the low end. Compared to lithium-ion batteries, fuel cells for hydrogen storage are twice as much (Raza et al, 2014). Put in simpler terms, it is one of the most expensive storage technologies. Fuel cells account for most of the cost. On the upside, there is reason to believe that with the proper investment, the trend for fuel cells will decrease. For example, since 2006, investment in transportation fuel cells by the United States Department of Energy decreased costs by 60 percent (Department of Energy, 2017).

In terms of political feasibility, hydrogen energy storage rates neutral. Raza et al. (2014) note that risk factors are present with hydrogen storage, due to hydrogen’s high flammability, yet also observe that the probability of a catastrophic explosion is low. Notwithstanding potential risk factors, there has been movement on the development of hydrogen storage. In 2018, Governor Brown signed in to law SB 1369, which lays the groundwork for expanded use of hydrogen energy. More specifically, the law directs the Energy Commission to “review technology incentive, research, development, deployment, and market facilitation programs” (SB 1369) to advance hydrogen energy.

The most laudable attribute of hydrogen storage is its negligible environmental impacts. Although not perfect, due to the risk factor discussed above, the infrastructure needed to store hydrogen produces few negative externalities whether during production, operation, or disposal. Fuel cells, in particular, are recyclable; and, when creating hydrogen from renewable sources like water, there is essentially a benign effect on the environment. The size of fuel cells is scalable to meet the intended use, and the hydrogen can be stored in steel tanks or underground. Currently, the cycle life of a fuel cell is about 20 years.

The response time of a fuel cell is comparable, yet a bit slower, than other storage technologies. Some have the ability to respond in seconds, while others may take a few minutes. Each day, as long as there is hydrogen stored, fuel cells have a discharge time of roughly 10 hours. Because fuel cells are scalable, storage capacity is scalable as well. However, the more storage capacity desired, the larger the fuel cell. There are considerations for the other components of hydrogen storage (e.g. storage tanks, electrolyzer) and site restrictions.

In addition to potentially bolstering energy reliability to California's grid, hydrogen storage has shown other promises as well. Economic analyses have shown hydrogen energy's value in providing ancillary services to the grid (Eichman, et al., 2016), and hydrogen-powered vehicles are gaining a lot of attention as an alternative to the internal combustion engine vehicle.

Alternative III: Batteries

When people refer to "energy storage," it usually conjures up an image of batteries. In many ways, the two have become synonymous. There are a number of different battery types; however, because of its relative popularity, the lithium-ion battery is the focus of this analysis. Similar to hydrogen, lithium-ion batteries serve a number of different purposes beyond utility-scale storage. Uses include transportation technology like electric cars, and other consumer electronics like cellular phones. In terms of energy storage, lithium-ion batteries easily store solar energy. A lithium-ion is comprised of an anode, cathode, separator, electrolyte, and a negative and positive collector. When discharging energy, lithium-ions flow from the anode to the cathode, creating free electrons in the anode resulting in a charge at the positive collector. When the lithium-ion battery charges, the opposite process occurs. The CEC reports that in June of 2017, "stationary battery energy storage systems totaled 177 MW" (CEC, 2018, pg. 8).

Despite wide-use in consumer goods, lithium-ion batteries are expensive. The costs, however, vary depending on the use. If designed to replace gas-turbine peaker plants, essentially covering the late-hour ramp of the duck curve, the levelized cost ranges from $204 to $298 per megawatt hour (Lazard, 2016). If grid considerations are a secondary concern, and you pair the battery with a solar photovoltaic facility, the levelized cost drops to a range of $108 to $140 per megawatt hour (Lazard, 2016). In terms of cost trends, lithium-ion batteries show promise. In 2014, lithium-ion installation cost totaled around $6,200 per kilowatt; today, the cost is roughly $1,500 per kilowatt. Because lithium-ion batteries power much of California's electric car market, and electronic goods demanded by the public, the cost of batteries should continue to decline as related markets expand.

The dominance of lithium-ion batteries in consumer goods makes it a "low-hanging fruit," and a favorite among politicians and regulators. In a number of instances, in the last five years, the CPUC has scuttled plans to utilize existing gas-fired plants, to address grid deficiencies and ensure reliability, in favor of batteries. In 2018, Pacific Gas & Electric secured one of the state's largest procurements of battery energy storage at its Moss Landing facility, after the CPUC rejected payments to three gas-fired plants PG&E planned to use. The commission's decision sparked outrage among the CPUC's own Office of Ratepayer Advocate, which claimed the decision was a bad use of ratepayer funds. On a similar note, when Southern Edison California procured large battery energy storage to cover peak electrical demands following the well failure at its Aliso Canyon Natural Gas Storage Facility, the CPUC voted to grant full cost recovery for the project.

One of the drawbacks associated with lithium-ion batteries is the relatively short cycle life. According to a study conducted by the National Renewable Energy Laboratory, a grid-connected, lithium-ion battery storage system has a life cycle of seven to ten years (Smith, Saxson, Keyser, & Lundstrom, 2017). Although lithium-ion batteries currently used in electric vehicles can be recycled for a "second-life," there are serious concerns as to its negative environmental externalities. The CEC notes "hazard concerns related to battery disposal" (CEC, 2018, p. 8), and Raza, e. al. (2014) claims the production of lithium-ion batteries incur large environmental costs. In terms of land requirements, lithium-ion batteries are scalable with larger energy needs requiring more real estate.

As for some of the efficacy measures, lithium-ion batteries have a very fast response time. Most batteries respond within seconds. In terms of discharge time, however, batteries can only discharge for about four hours at a time. Like fuel cells above, storage capacity depends upon the amount of batteries utilized and is scalable upon site specifics.

A recent working paper from the Massachusetts Institute of Technology reports that lithium-ion batteries account for a least 90 percent of the global energy storage market (Hart, Bonvillian, & Austin, 2018). The trend for California is heading in a similar direction. The widespread use of lithium-on batteries in consumer goods makes it an inescapable player in the energy storage debate, with opportunity for declining costs.

Alternative IV: Compressed-Air Energy Storage

Compressed-air energy storage, commonly referred to as CAES, is a storage technology that uses low-cost, off-peak electricity to compress air in a storage system. The storage system can be underground or aboveground. Underground storage includes porous rock formations, salt caverns, or depilated gas or oilfields; aboveground systems include vessels and pipelines. The CAES process produces energy by withdrawing air from the storage system, heating it by natural gas, and moving the hot air through turbines that power an electric generator. Transmission lines then transfer energy from the generator to the grid. In California, there are currently no CAES systems in operation. In fact, there is only one CAES system located in the United States, in McIntosh, Alabama.

Although not a popular form of energy storage, CAES is relatively cheap with a levelized cost of $116 - $140 per megawatt hour (Lazard, 2016). When air is stored aboveground, however, the cost can raise by almost 50 percent (Zakeri & Syri, 2015). Similar to pumped-hydro storage, the costs for CAES become problematic when siting increases transmission costs. As with damming two water reservoirs within a canyon, finding salt caverns near an energy distribution center is not an easy task. This is not to say opportunities for CAES do not exist. PG&E, for example, is currently working on the initial phases of its San Joaquin County CAES project, which PG&E hopes to have online by the mid-2020s.

Financing for the San Joaquin County CAES project came from three funding sources in addition to PG&E. The United States Department of Energy and the CPUC both awarded grants worth $25 million apiece, while the CEC chipped in with a $1 million of its own. While there has been no legislative action in regards to CAES, the financial backing shows political support from California regulators, albeit on a testing/feasibility basis. The outcome of the San Joaquin County CAES project could turn political favorability more towards CAES, or away from it.

The cycle life of a CAES is comparable to that of a pumped-hydro system. Aside from retrofitting infrastructure such as generators and turbines, once a cavern can serve as a storage reservoir, it can always serve as a storage reservoir. The two CAES projects currently in operation have been in operation for over 50 years, combined. In terms of land requirements, the storage available comes from existing holes in the ground. With the San Joaquin County CAES project, for example, the CEC’s final technical feasibility report concluded, “the project could be permitted with minimal impacts” on the environment (Medeiros et al., 2018, p. 2-12).

On efficacy measures, the biggest benefit of CAES is discharge time; the average discharge time is about ten hours. The response time of CAES usually takes minutes, making in the slowest of the alternatives analyzed in this report. The depth of the reservoir determines storage capacity for CAES; however, depleted gas reservoirs, for example, normally range from half a mile to one mile in depth. In other words, the storage capacity for CAES can be significant, but variable.

The rare utilization of CAES leaves room for growth of this energy storage alternative. The relative low cost for underground storage processes shows potential, but its location limitations temper full-scale deployment. Nonetheless, its minimal environmental impacts and large discharge time could pair well with the needs of the grid, and goals of California energy policy.

With the specifics and projected outcomes of each storage alternative complete, the next section provides a quantitative assessment based on the CAM matrix discussed earlier.

Quantitative Assessment of Energy Storage Alternatives

This final section of Chapter 5 evaluates the four energy storage alternatives in terms of the criteria detailed in Chapter 4. The six criteria are cost, political feasibility, environmental impacts, response time, discharge time, and storage capacity. I assigned each criterion a weight to signify the importance of the criterion in terms of my analysis, and I assigned each storage alternative a score based on a five-point scale of “very strong” (5) to “very weak” (1). It is important to recall that the weights and scores assigned are not scientific, but rather based on my interpretation of the existing literature and the goals of California energy policy. A different interpretation could lead to different results. What follows is a brief narrative of the scores assigned to each energy storage alternative as illustrated in Table 3.

Of the four energy storage alternatives considered, compressed air energy storage, CAES (Alternative IV), ranked the highest with a score of 4.00 on a total scale of 5.00. The ratings for CAES stayed constant across the range of criterion and did not experience some of the wild rating swings experienced by some of the other alternatives. It also shared the highest rating on environmental impact, with hydrogen, which was the heaviest-weighted criterion. The scarcity of CAES storage systems in California may have actually helped on the criterion of political feasibility. Considering a neutral rating equal to 3, I bumped CAES up to 4 due to the fact that state regulators invested $26 million dollars into a feasibility study on the San Joaquin County CAES project. Additionally, CAES is the lowest cost of the four alternatives but tied for the highest score in discharge time.

Hydrogen and pumped-hydro storage came in behind CAES by a respectable 0.20 and 0.30 points, respectively. Although hydrogen was the most expensive of the storage alternatives, it benefited from its high rating for environmental impact and discharge time. Similar to CAES, the ratings for hydrogen remained relatively stable with its highest ratings assigned to the highest weighted criterion. Pumped-hydro was hurt by the low rating of 1 given on political feasibly, which was the lowest score of any alternative across any criterion. Additionally, although pumped-hydro is less costly than batteries, both received the same score of 3 in the cost criterion since the cost trend for batteries is down, while the cost trend for pumped-hydro is up or stagnant.

Speaking of batteries, that storage alternative came in last place. It is possible that the current dominance of batteries in the energy storage market exposed some of the technology’s drawbacks in this analysis. While batteries received a couple ratings of 5, it was the only technology, other than hydrogen, to receive a rating of 2 and it was in both environmental impacts and discharge time, which were the heaviest weighted criteria. Table 3, at the end of this chapter, provides a complete breakdown of my quantitative analysis.

Summary

Chapter 5 focused on a CAM analysis of energy storage alternatives to address California’s duck curve. In order to provide context for the analysis, the chapter started by revisiting California’s duck curve problem, reviewing the need for energy storage development and the government’s responsibility in responding to the challenge. A detailed discussion of each energy storage alternative along with projected outcomes followed. Chapter 5 concluded with the results of my quantitative CAM analysis, including a brief narrative and a table. The CAM analysis ranked the energy storage alternatives on scale of 1 to 5, with 1 being “very weak” and 5 being “very strong.” Based on the CAM the rankings were as follows (from strongest to weakest): CAES, hydrogen storage, pumped-hydro storage, and batteries. The next and final chapter of this thesis uses the results from the CAM analysis to make a number of recommendations to address California’s duck curve.

Table 3

Quantitative Alternative-Criterion Matrix for Energy Storage in California

	Criterion 1: Cost	**Criterion 2: Political Feasibility**	**Criterion 3: Environmental Impact**	**Criterion 4: Response Time**	**Criterion 5: Discharge Time**	**Criterion 6: Storage Capacity**	**Total Score**
Alternative I: Pumped-hydro	Rating: 3 Weight: 0.10 **Total: 0.30**	Rating: 1 Weight: 0.10 **Total: 0.10**	Rating: 3 Weight: 0.30 **Total: 0.90**	Rating: 5 Weight: 0.20 **Total: 1.00**	Rating: 5 Weight: 0.20 **Total: 1.00**	Rating: 4 Weight: 0.10 **Total: 0.40**	3.7
Alternative II: Hydrogen	Rating: 2 Weight: 0.10 **Total: 0.20**	Rating: 3 Weight: 0.10 **Total: 0.30**	Rating: 4 Weight: 0.30 **Total: 1.20**	Rating: 4 Weight: 0.20 **Total: 0.80**	Rating: 5 Weight: 0.20 **Total: 1.00**	Rating: 3 Weight: 0.10 **Total: 0.30**	3.8
Alternative III: Batteries	Rating: 3 Weight: 0.10 **Total: 0.30**	Rating: 5 Weight: 0.10 **Total: 0.50**	Rating: 2 Weight: 0.30 **Total: 0.60**	Rating: 5 Weight: 0.20 **Total: 1.00**	Rating: 2 Weight: 0.20 **Total: 0.40**	Rating: 3 Weight: 0.10 **Total: 0.30**	3.1
Alternative IV: CAES	Rating: 4 Weight: 0.10 **Total: 0.40**	Rating: 4 Weight: 0.10 **Total: 0.40**	Rating: 4 Weight: 0.30 **Total: 1.20**	Rating: 3 Weight: 0.20 **Total: 0.60**	Rating: 5 Weight: 0.20 **Total: 1.00**	Rating: 4 Weight: 0.10 **Total: 0.40**	4.0

Chapter 6: Conclusion and Recommendations

Since California began decarbonizing its energy supply nearly 20 years ago, the state has become a leader in the clean energy revolution. Through a combination of economic incentives, legislative actions, and regulatory mandates, California leads the nation in renewable energy generation. In 2018, California staked its claim as the frontrunner of the clean energy movement when it enacted SB 100, which puts California on a path to a carbon-free energy supply by 2045. Although California's growth in renewable energy, particularly solar energy, and its ambitious energy goals are impressive, they do not come without challenges.

This thesis highlighted a few of the challenges, such as the highest retail energy rates in the nation, but the thrust of the thesis is the inability of California's grid to accommodate the large influx of solar power. California's duck curve, a phenomenon in which California's energy grid experiences a large drop of traditional energy during the day, followed by a large ramp up in the evening, poses a risk to California's energy reliability and has the potential to devalue the large public investment in solar energy over the last two decades.

In Chapter 1, I posed the following questions: first, what alternatives are available for policymakers to invest in to address the duck curve? Second, which alternative best balances grid load while fulfilling California's energy goals? Through an examination of the literature; an assessment of California's social, political, and economic environments regarding renewable energy; and a review of legislative and regulatory actions, one alternative became the clear favorite: energy storage. With energy storage, however, there are a number of options. Accordingly, this thesis compared different storage technologies using a criteria-alternative matrix analysis, also known as CAM analysis. My four storage alternatives consisted of pumped-hydro, hydrogen fuel cells, lithium-ion batteries, and compressed air energy storage. My six criteria, selected because of their importance in both the literature and in practice, were cost, political feasibility, environmental impact, response time, discharge time, and storage capacity; the literature identified the last three criteria as the most important criteria to large grid operators like the CAISO. Chapter 5 contains the results of the CAM analysis.

In this final chapter, I summarize the findings of the previous chapters and provide recommendations for addressing California's duck curve and achieving the state's policy goals via energy storage. I begin with a discussion on the current state of California's energy paradigm, with a focus on how much energy storage California actually needs. Based on that discussion, the second section identifies a set of policy recommendations. I conclude this chapter with a brief discussion on implementing the recommendations.

California's Energy Paradigm

In order to properly assess and make recommendations for the role of energy storage in addressing California's duck curve and meeting the policy goals of SB 100, it is helpful to start with a current accounting of the state's energy paradigm. This means examining California's energy demands, current supply portfolio, and needs for the future.

In 2017, California's electric system generation totaled 292,031 gigawatt hours. California generated roughly 70 percent of the total in state, with the other 30 percent imported from neighboring states. Natural gas made up the bulk of energy generation at 31 percent. Utility-scale hydropower out produced solar generation 15 percent to 8 percent; however, when factoring in distributed solar (rooftop solar), solar generation more than doubles to 19 percent.

Grid capacity netted 76,414 megawatts in 2017, with demand peaking on September 1 at 50,116 megawatts. Just as a theoretical supply and demand model aims for equilibrium, excess supply of energy causes market distortions. Too much capacity raises costs with little effect on reliability and, as seen with the duck curve, causes gird instability.

As California's grid continues to transform from a centralized system to a decentralized system, as discussed in Chapter 2, and the state retires gas-fired and nuclear power plants in favor of solar and other renewable power, the need for energy storage is evident. In a 2016 study, the National Renewable Energy Laboratory (NREL) conducted an analysis to determine the amount of storage necessary if solar photovoltaic energy supplied up to 50 percent of California's electrical demand. Because SB 100 prescribes that 60 percent of California's energy supply be renewable by 2030 (and carbon free by 2045), the 50 percent solar penetration level provides a sound basis for this thesis.

The NREL report authors, Denholm and Margolis (2016), deliver two key findings. First, a key factor affecting storage needs is the cost of solar energy. In order to be economically feasible, the net-levelized cost of solar energy (net-LCOE) must remain below the costs of gas cycle generators in California, about 7 cents per kilowatt-hour. Second, achieving 50 percent solar penetration is not economically feasible without substantial changes to grid flexibility. Considering these factors and assuming four flexibility options, the authors establish three scenarios for 50 percent solar penetration with low flexibility, mid flexibility, and high flexibility. The lower the cost and higher the flexibility, the less storage required; higher cost and lower flexibility requires more storage. The authors believe that solar costs will reach the magic net-LCOE of 7 cents per kilowatt-hour number by 2030; therefore, grid flexibility becomes the real driver.

Denholm and Margolis add two other factors into their study: the megawatts of pumped-hydro storage currently in use, and the 1,325 megawatts of storage mandated by 2024 under SB

2514. Current and anticipated storage capabilities are important to keep in mind. Under a high-flexibility scenario, the additional storage needed is about 19 gigawatts, or 19,000 megawatts; that is 15,000 megawatts more than what is currently available and anticipated under the state mandate. Under a low-flexibility scenario, the additional storage needed 32 gigawatts, or 32,000 megawatts; that is 28,000 megawatts more than what is currently available and anticipated under the state mandate.

To get a better grasp on just how much storage 19,000 to 28,000 megawatts is, consider the storage capacity of some the largest storage systems worldwide. The largest pumped-hydro project in the world is the Bath County Pumped Storage Station in Virginia; the system has a maximum generating capacity of 3,003 megawatts. The largest hydrogen fuel cell system in the world is located in South Korea, with a capacity of 59 megawatts. Also located in South Korea is the world's largest lithium-ion battery, with a capacity of 150 megawatts. The largest CAES storage system in the world, located in Germany, has a capacity of up to 290 megawatts. What the numbers show is that to reach just the high-flexibility scenario, California will need to build hundreds of energy storage systems in the coming decades, depending on the type of storage. Having examined California's current energy paradigm, the next section offers policy recommendations.

Recommendations

The following recommendations serve as the findings of this thesis. Based on the results from the CAM analysis performed in the last chapter and a fuller understanding of California's energy needs, the recommendations provide one approach to mitigate negative effects of the duck curve and achieve California's policy goals. With that said, I base these findings on the current information available and further research will be necessary as time and technologies advance. I also do not claim the recommendations posited here act as a panacea for California’s many energy challenges.

Recommendation #1: Adopt an “all of the above” strategy in terms of storage technologies.

As mentioned in Chapter 5, lithium-ion batteries currently control more than 90 percent of the emerging grid-scale storage market worldwide (Hart et al., 2018). In California, a similar trend is emerging. Although pumped-hydro storage leads the pack statewide, lithium-ion batteries are the second most used storage system and a favorite of policymakers and regulators. Furthermore, because it is unlikely California will build more pumped-hydro anytime soon, batteries could soon dominate California’s storage supply. An overreliance on batteries, however, risk the possibility of what industry leaders call “lock-in” – a form of path dependence in which excessive market concentration creates barriers of entry for other technologies that could be more beneficial to the desired outcome.

In order to diminish the risk of battery lock-in, my first recommendation is to adopt an “all of the above” strategy in storage technologies. As the literature and this analysis show, each available storage technology has its own benefits and drawbacks. In fact, the benefits and drawbacks discussed in this analysis form the basis of subsequent recommendations. However, it is also true that policy or, in this case, technology dominance is a political process, which can inhibit innovation. Adopting an “all of the above” strategy should mitigate some political bias, and defend against technology lock-in. (One clarifying point: the “all of the above” approach means all technologies, not just those covered in this analysis.)

Recommendation #2: Pursue underground CAES as a priority for utility-scale energy storage.

In accordance with the findings of the CAM analysis, the second recommendation is for policymakers and energy regulators pursue underground compressed air energy storage (CAES) as a priority for utility-scale storage. The long cycle life, extensive discharge time, and massive storage capacity of CAES makes it an optimal candidate for utility-scale energy storage. Despite its highly limited use, CAES is the cheapest of the technologies in terms of unsubsidized levelized cost. Furthermore, CAES does not face the political and logistical headwinds of pumped-hydro, its mechanical storage counterpart.

Perhaps most important, the potential applications of CAES technology are in-line with California grid needs. CAES can address demand-side management by storing energy during non-peak hours, and offsetting power generation shortfalls when demand peaks. Other applications include seamless integration of renewable power generation and back-up power. CAES systems have also demonstrated the potential to provide capacity for black start – the process of restoring power to an electric grid or power station, in the event of a partial or complete shutdown of the electricity transmission system.

In order to increase in the installation and use of CAES, California’s regulatory agencies, the CPUC and CEC, should fund feasibility studies with the state’s major investor-owned utilities, similar to what they did with PG&E at the San Joaquin County CAES project.

Recommendation #3: Expand the use hydrogen fuel cells for increased grid flexibility.

My third recommendation relates to the second highest ranked storage technology in the CAM analysis, hydrogen fuel cells. Although hydrogen fuel cells embody characteristics favorable to utility-scale storage, such as discharge time, one study shows that hydrogen storage is most economical serving ancillary purposes and participating in capacity markets (Eicahman, et al., 2016). Put another way, the economic value for hydrogen is not in producing and storing energy for later energy production. Economics and efficacy, however, are two different matters and the literature shows that hydrogen fuel cell technology is capable of meeting grid needs; and, as batteries and other renewable technologies demonstrate, public investment in emerging technologies spurs growth of the that technology and reducing costs. As hydrogen fuel cells become more economical, California could benefit from the technology's low environmental impacts, especially if strategically placed near hydroelectric facilities where there is a ready source of water (to split) and transmission lines to load electricity onto.

Until such a time that it is economical for hydrogen energy storage can provide utility-scale storage needs, some of the ancillary services hydrogen can provide include heating fuel, industrial process, and transportation. Using stored hydrogen energy for these purposes has the potential create greater grid flexibility, which Denholm and Margolis identify as essential to allowing more solar penetration. In fact, in the high-flexibility scenario presented by the authors, electric vehicles play a pivotal role in increasing flexibility. The same is true for hydrogen-powered vehicles.

California took a positive step forward for stored hydrogen energy with the enactment of SB 1369 discussed in Chapter 5. Carrying out that law and identifying other opportunities to expand the use of hydrogen will benefit grid flexibility.

Recommendation #4: Reduce solar reliance by classifying large hydro as "renewable" energy.

In order for California to meet energy goals set out in preceding decades, the state has gone "full bore" toward solar energy. With the passage of SB 100, the solar temptation has only intensified. The 2018 CEC decision to require all new houses, of less than three stories, built in California include solar panels in their construction, is just one example. This year, in the legislative halls of Sacramento, there is talk of a new solar "bill of rights."

The impulsivity to support solar at any cost has resulted in the duck curve, which forms the basis of this thesis, and now leaves California's grid in a precarious situation. All the while, California's most utilized renewable energy receives tacit acknowledgement. Whether limiting the renewability of hydroelectric power, to those facilities with a capacity 30 megawatts or less, was right at the time legislated, it is high time to revisit that restriction.

California's 269 hydroelectric facilities have a nameplate capacity of 14,000 megawatts. However, of the 14,000 megawatts available, only 1,746 megawatts count as renewable. Based on a 50,000-megawatt demand, identified as peak demand in the preceding section, only 3 percent of hydroelectric power is renewable. Including large hydro would increase the renewable contribution to 28 percent, based on the 50,000-megawatt scenario. Large hydro, those facilities with capacity over 30 megawatts, should be counted as renewable.

Over the last few legislative sessions, lawmakers have introduced bills to include all hydropower production as renewable. However, none of the bills moved past the first committee. In the current legislative session (2019-2020), AB 915 redefines hydroelectric plants of any capacity as renewable, and eligible to count toward California's renewable energy portfolio standard.

Implementation

The recommendations suggested above are wide-ranging and, in some instances, ambitious. Lighter lifts, like recommendation #4, could become reality if policymakers passed legislation already in print. Heavier lifts, like pursuing more CAES storage (recommendation #2), would not only require action by a decision-making body, but also funding. Short of a direct appropriation from the legislature, funding sources could include California’s cap-and-trade system, which investment in programs to reduce greenhouse gas emissions in the state. In addition, state regulatory agencies such as the CEC and CPUC have grant and loan programs available to energy producers. The shift away from battery storage as the end-all, be-all would require a shift in strategy by the state. Nonetheless, it seems like batteries will continue to play an important role in California’s electric car market and household storage systems. Over the long run, regulatory officials and policymakers will need to remain flexible to technological advances of energy storage systems and other changes in the energy landscape.

Summary and Conclusion

This concluding chapter of the thesis presented my findings as four recommendations. I based the recommendations not only on the results from the CAM analysis conducted in Chapter 5, but also on California’s current energy paradigm, which made up the second part of this chapter. The last section of Chapter 6 presented a brief discussion on implementing the recommendations.

While this thesis is but one report on the growing literature about California’s duck curve, it is original in terms of methodology and specificity of addressing California’s energy challenges with energy storage. As energy storage technologies and the duck curve change over time, the information contained within can be a reference for study.

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