Adapting Energy Storage Technology for Renewable Energy Generation in California

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ABSTRACT

Greater renewable energy production is becoming critical as fossil fuels are depleted globally and the consequences of climate change intensify. However, resource intermittency largely inhibits the incorporation of renewable energy sources like solar and wind to a small fraction of the energy portfolio. Therefore, electrical energy storage (EES) technology must be incorporated on a greater scale in contemporary energy grid systems to remedy this discrepancy, and to ease transition to more sustainable, diverse energy sources. To identify what type of energy policy would be most effective for incentivizing greater EES integration in California, I examined three energy policy mechanisms: California's energy storage mandate (2011), Germany's feed-in tariff (2001), and Denmark's direct technological subsidy (2004). I assessed to what extent each policy would be effective and feasible for implementation in California by collecting renewable energy production and electrical energy storage installation data for each study site before and after policy adoption. The energy storage mandate resulted in the highest number of EES units installed and renewable energy generated over time, followed by the feed-in tariff and direct technological subsidy, respectively. Each policy's effectiveness was then contextualized based on the preceding policies and path dependent conditions that allowed for its implementation, in order to evaluate how feasibly it could be adopted in California. By evaluating the effectiveness and feasibility of each of these policy mechanisms in incentivizing EES integration, results of this study can inform policymakers in California and elsewhere on how to better incorporate renewable energy into their grid systems.

KEYWORDS

energy storage mandate, feed-in tariff, direct technological subsidy, renewable energy generation, electrical energy storage, comparative policy analysis

INTRODUCTION

Although the renewable energy industry has experienced considerable growth within the past decade, nonrenewable fossil fuel energies still dominate the U.S. electrical production market due to their superior energy content, reliability, and availability (Demirbas 2009). But as fossil fuels are depleted globally, transitioning to renewable energy resources is becoming critical to protect domestic energy security, reduce carbon emissions, and mitigate climate change (Demirbas 2009). Despite recent technological advances in renewable energy, wind and solar renewable energy sources still only represent a small fraction of the total U.S. electrical energy production (Taylor 2008). Physical constraints related to intermittency and transmission have prevented renewable energy from occupying a larger role within the U.S. electrical production system (Evans et al. 2012). However, the integration of innovative electrical energy storage (EES) can largely reduce the scope of these physical constraints and help remedy the current renewable energy deficiency in forthcoming decades (Hall and Bain 2008).

The chief benefit of greater EES implementation is that it will allow the renewable energy supply to better meet contemporary energy demand needs (Landry and Gagnon 2015). Because the electrical distribution system is setup in real-time to balance energy supply and demand, electrical energy originating from renewable sources must be consumed immediately, or a large percentage of it is lost (Walawalkar et al. 2007, Chen et al. 2009). This on-demand model places tremendous pressure on the renewable electrical energy supply and makes it a less desirable option to other, more steady energy sources like fossil fuels (Kousksou et al. 2014). But, EES bridges this barrier by providing a physical mechanism through which renewable energy can be stored and utilized (Beaudin et al. 2014). EES has the capacity to solve a variety of physical inefficiency issues that hamper the renewable electrical system, while simultaneously providing other benefits. For instance, EES has already been used to reduce electrical transmission losses, store surplus electrical energy, and alleviate grid congestion during peak consumption hours (Kaldellis et al. 2009, Hoicka and Rowlands 2011). In addition, EES also has positive economic benefits including the creation of new energy storage markets and consumer and producer utility cost savings (Walawalkar et al. 2007). More specifically, with the recent fluctuation of natural gas prices and a larger demand for energy during peak hours, arbitrage energy storage markets have formed which store and utilize renewables' low-cost off-peak energy for resale during peak hours (Denholm et al. 2010). Although EES boasts these diverse applications, it has not yet been installed on a large scale due mainly to its high capital costs and immature technology (Chen et al. 2009). Therefore, an exploration of energy policy recommendations that incentivize the implementation of EES is needed to help inform policymakers and other decision makers as they address the energy sourcing issues. In performing such an investigation, my analysis will thereby encourage renewable energy production to assume a larger role within the domestic energy system via EES.

Given the scale and complexity of the entire U.S. energy system, I have elected to examine renewable energy policy at the state level. More specifically, I have selected California as my study site because of its rich environmental history and culture. I also find California to be an apt choice given its past environmental leadership in influencing other states and ultimately the U.S. to adopt higher environmental standards – a process which has since become known as the "California effect" (Fredriksson and Millimet 2002). To inform the best EES incentivizing policy for California, I will use Germany and Denmark as comparison study sites. I selected each of these study sites because they feature a comparable geography, political climate, and environmentally-minded culture to California, and they have notably employed at least one of the three renewable energy policy mechanisms I have chosen to investigate to varying degrees of success (Klaassen et al. 2005, Lehr et al. 2008, Brick and Thernstrom 2016).

To identify the best suite of policy recommendations for EES integration within California, I assumed that renewable energy production and EES integration share a positive relationship given that greater renewable energy generation implicitly requires a proportional number of EES units to be efficient (Makarov et al. 2008). My analysis involved collecting renewable electrical energy production and EES installation data preceding and following the implementation of a given policy mechanism within my comparison study sites. I then compared and evaluated both datasets before and after policy adoption to see if and to what extent there existed an association among each energy policy mechanism, EES installation, and renewable energy production. In order to validate my findings, I then explored relevant policies and scholarly literature to determine if the policy was truly effective where it was implemented and to what extent it could be feasibly reproduced in California. My findings ultimately encourage the greater integration of EES in California, and were used to formulate recommendations for a suite of renewable energy policy mechanisms that might be implemented in California, which drew from insights derived from my comparison study sites.

California study site

As a national and international leader in environmental policy, California has set the precedent for renewable energy generation and energy storage integration in recent years. In 2002, the State passed Senate Bill 1078, a Renewables Portfolio Standard (RPS) which after being updated in 2011 now requires electric service providers to increase energy production from renewable energy resources to 33% of the total production in California by 2020 (CA Senate 2002). Following the adoption of the RPS, California also more recently implemented Assembly Bill 2514, which mandates 1,325 MW of energy storage by 2020 into the electrical grid (California ISO 2014). Both bills represent an ongoing commitment to renewable energy production, energy storage integration, and grid efficiency. However, while both policies lay the foundation for EES and renewable energy integration, they fail to provide concrete incentives, subsidies, and other means to help reach these new standards, which has caused electrical utilities producers to bear the high economic costs attached to EES installation and maintenance (Kousksou et al. 2014). Consequently, California's existing policy must be modified to better incentivize EES and account for these shortcomings.

Comparison study site policy mechanisms

To inform the best policy recommendations for California, I will examine the renewable energy incentivizing schemes employed by Germany and Denmark. Both of these governments have successfully employed a renewable energy policy mechanism: Germany the feed-in tariff and Denmark the direct technological subsidy. Germany has experienced widespread renewable energy growth through the feed-in tariff, which requires transmission and utility companies pay renewable energy producers premiums[1] (Butler and Neuhoff 2008). Similarly, direct technological subsidies have proven successful in Denmark, where both the wind and solar energy markets have grown as more cost-effective technologies have been discovered and implemented (Klaassen et al. 2005). Examinations of each of these policies will help contextualize California's current policy

[1] Under a feed-in tariff, renewable energy producers sell their electricity to the grid at a guaranteed higher price, which incentivizes renewable energy generation and keeps it competitive with fossil fuel energy generation.

situation and provide insight for developing a suite of policy recommendations to incentivize and facilitate greater EES integration and renewable energy generation in California.

METHODS

Data collection

To quantify differences in policy effectiveness between California's energy storage mandate (2011), Germany's feed-in tariff (2001), and Denmark's technological subsidy (2004), I used various public energy databases to collate the amount of renewable energy produced, electrical energy storage (EES) units installed, and EES projects initiated for each case before and after implementation of the given policy (Table 1). Annual renewable energy production data for each study site was readily available from these databases, but for the number of EES projects initiated and units installed, I had to conduct additional calculations. For my study, I defined EES in kWh, which I calculated by multiplying rated power, or the maximum power input (kW), and charge duration (hours). I then summed the total number of EES units installed within a given study site per year. Similarly, I counted all the initiated EES projects for each study site from the U.S. Department of Energy (DOE) Global Energy Storage Database and separated them by year. I only considered EES projects that were initiated, active, or proposed for my analysis and excluded projects that were inactive or decommissioned.

Table 1. Summary of energy policy datasets used in the study. Data was downloaded from the listed databases in January 2017.

Energy Policy	Site	Datasets
Energy Storage Mandate	California	U.S. Energy Information Administration (EIA) http://bit.ly/2p3RPZ2 U.S. DOE Global Energy Storage Database http://bit.ly/2p45O0K
Feed-In Tariff	Germany	International Energy Agency (IEA) http://bit.ly/2qznRMn U.S. DOE Global Energy Storage Database http://bit.ly/2pNwcLK

Technological Subsidy	Denmark	International Energy Agency (IEA) http://bit.ly/2pHeqJD U.S. DOE Global Energy Storage Database http://bit.ly/2pHeIjw

Data analysis

I used R statistical software to execute a t-test between renewable energy generation and EES installation (R Development Team 2017). My null hypotheses for the test was that policy's influence on EES installation would have no effect on renewable energy generation. Then, I ranked each policy based on the amount of renewable energy produced, EES units installed, and EES projects initiated since the policy's initial implementation. I considered the policy that produced the greatest increase in each of these three categories as the most effective.

RESULTS

California's energy storage mandate (2011)

After collating the renewable energy production and energy storage installation data for the California energy storage mandate (2011), I found a significant increase in renewable energy generation before and after the policy was adopted, from 715,209 Btu (2010) to 766,125 Btu (2014) (Figure 1). Likewise, there was a distinct increase in the number of electrical energy storage (EES) unit installations initiated and planned, from 148,413 Mwh (2011) to 158,714 Mwh (2020) (Figure 2). The number of EES projects also markedly increased from 13 preceding 2011 to 240 ongoing and scheduled through 2020 (Table 2).

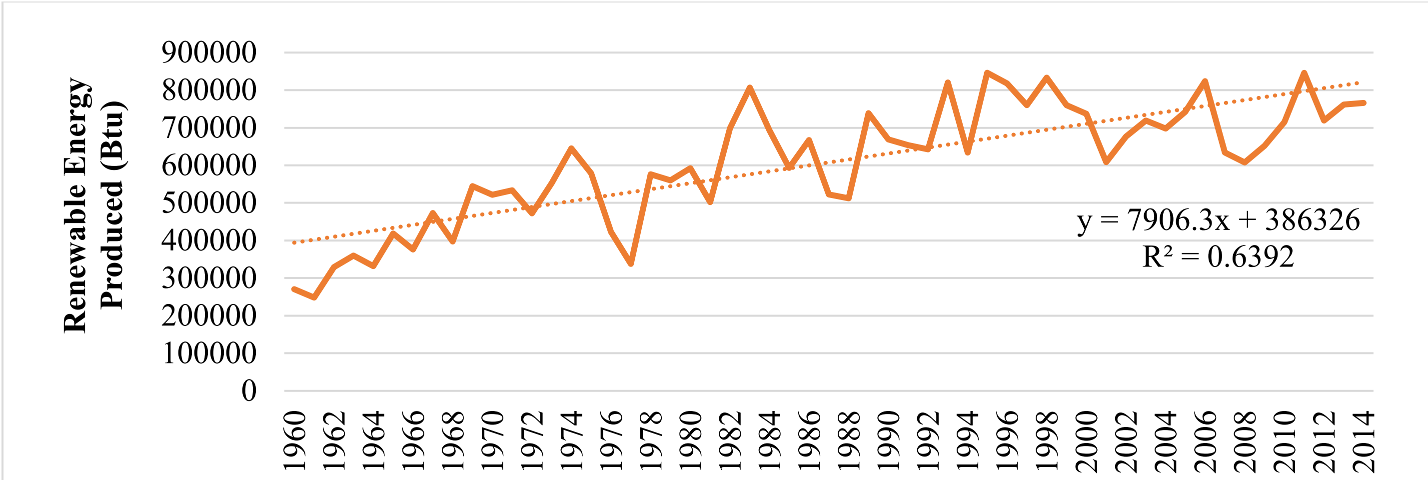

Figure 1. Annual California renewable energy production (1960-2014). Data as reported by the U.S. Energy Information Administration (EIA). The California energy storage mandate was instituted in 2011. The linear trendline reflects a steady increase in renewable energy production dating back to 1960.

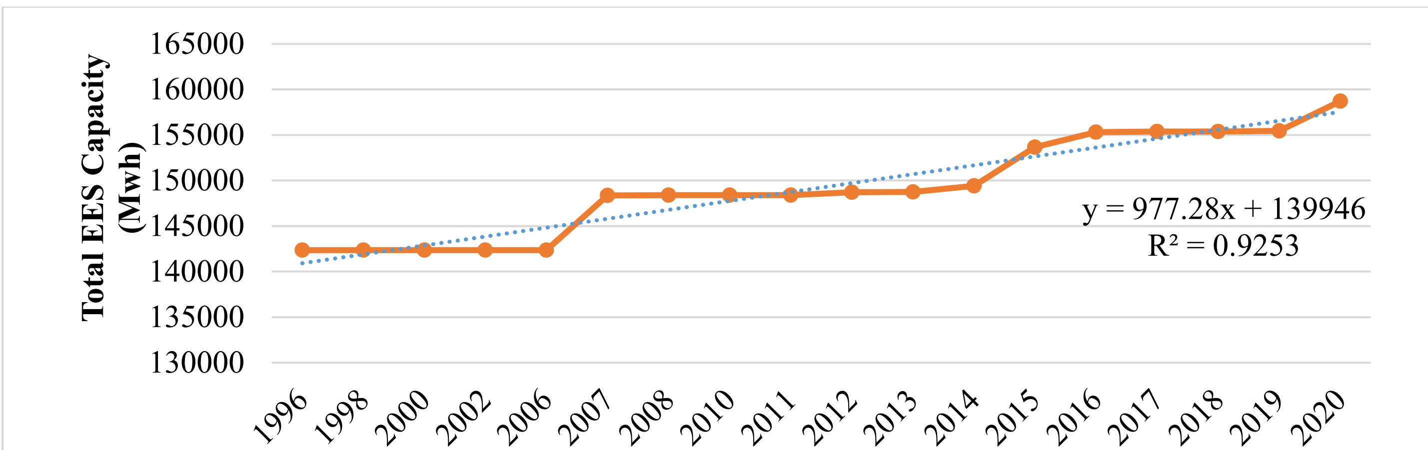

Figure 2. Annual California electrical energy storage (EES) installation (1996-2020). Data as reported by U.S. DOE Global Energy Storage Database. The California energy storage mandate was instituted in 2011. The linear trendline reflects a consistent increase in EES integration dating back to 1996.

Table 2. California electrical energy storage (EES) projects (1968-2020). Data as reported by U.S. DOE Global Energy Storage Database. The California energy storage was adopted in 2011, resulting in an immediate, distinct increase in EES projects beginning in 2012.

Years	Number of Energy Storage Projects
1968 – 2010	13
2011	5
2012	16
2013	51
2014	46
2015	95
2016	21
2017 – 2020	11

My t-test suggested there exists a statistically significant relationship between renewable energy production and EES installation resulting from the energy storage mandate (2011), with a p-value of .042 (Figures 1 and 2).

Germany's feed-in tariff (2001)

The effect of Germany's feed-in tariff (2001) resulted in an EES project increase from 19 between 1951 and 1989 to 61 between 2004 and 2017 (Table 3). The tariff also increased renewable energy production, from 50,266 GWh (2001) to 136,014 GWh (2011) (Figure 3). And, it also resulted in a distinct increase in the number of electrical energy storage (EES) unit installations initiated and planned, from 24,698 Mwh (1989) to 41,518 Mwh (2017) (Figure 4).

Table 3. Germany's electrical energy storage (EES) projects (1951-2017). Data as reported by U.S. DOE Global Energy Storage Database. The German feed-in tariff was adopted in 2001, resulting in a delayed increase in EES projects beginning in 2004.

Years	Number of Energy Storage Projects
1951 – 1989	19
2004 – 2012	8
2013	11
2014 – 2017	40

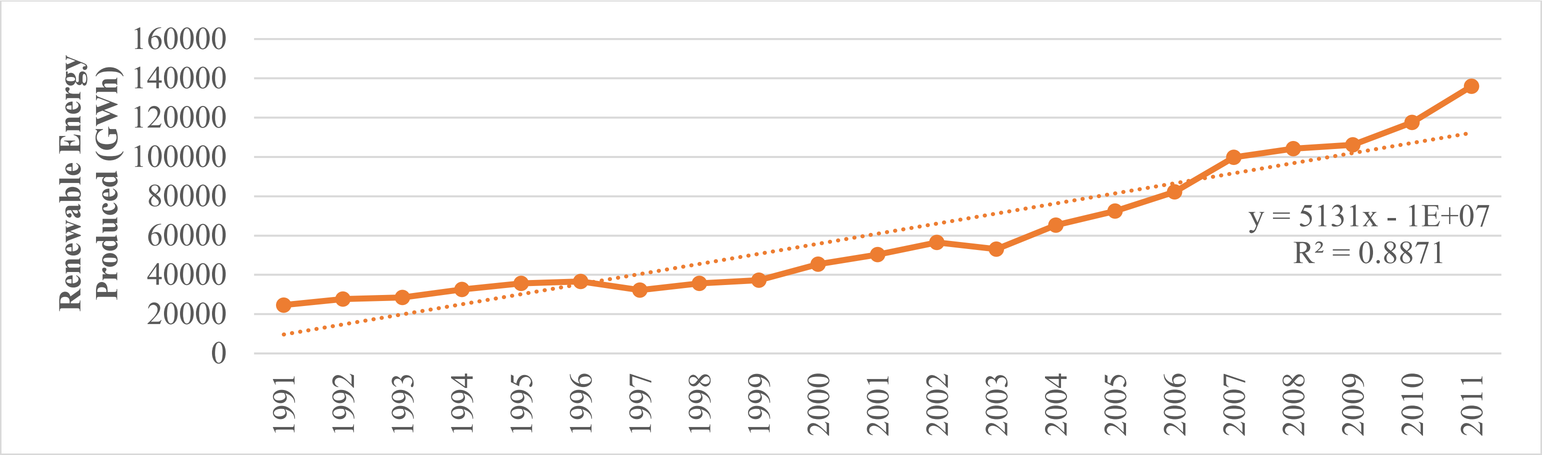

Figure 3. Annual Germany renewable energy production (1991-2011). Data as reported by the U.S. Energy Information Administration (EIA). The feed-in tariff was instituted in Germany in 2001. The linear trendline reflects a steady increase in renewable energy production dating back to 1991.

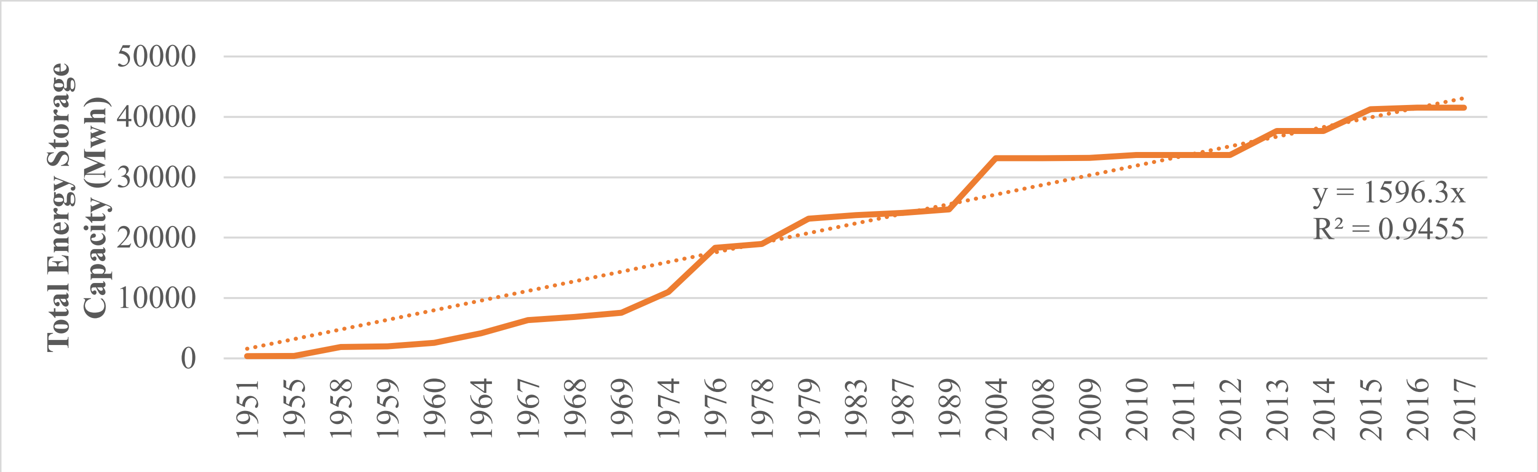

Figure 4. Annual Germany electrical energy storage (EES) installation (1951-2017). Data as reported by U.S. DOE Global Energy Storage Database. The feed-in tariff was adopted in Germany in 2001. The linear trendline reflects a distinct increase in EES installation since 1951.

For the feed-in tariff, my t-test also suggested there exists a statistically significant relationship between renewable energy production and EES installation with a p-value of .033 (Figures 3 and 4).

Denmark's direct technological subsidy (2004)

Denmark's direct technological subsidy (2004) resulted in only a subtle increase in EES projects between 2007 and 2017 (Table 4). The direct technological subsidy also increased renewable energy production, from 6,583 GWh (2004) to 11,123 GWh (2013) (Figure 5). Additionally, it resulted in a distinct increase in the number of electrical energy storage (EES) unit installations initiated and planned, from 120 kWh (2007) to 869 kWh (2017) (Figure 6).

Table 4. Denmark's electrical energy storage (EES) projects (2007-2017). Data as reported by U.S. DOE Global Energy Storage Database. Denmark's direct technological subsidy was adopted in 2004, resulting in a marginal increase in EES projects, starting in 2007.

Years	**Number of Energy Storage Projects**
Pre – 2007	Unreported; only small scale operations
2007 – 2017	5

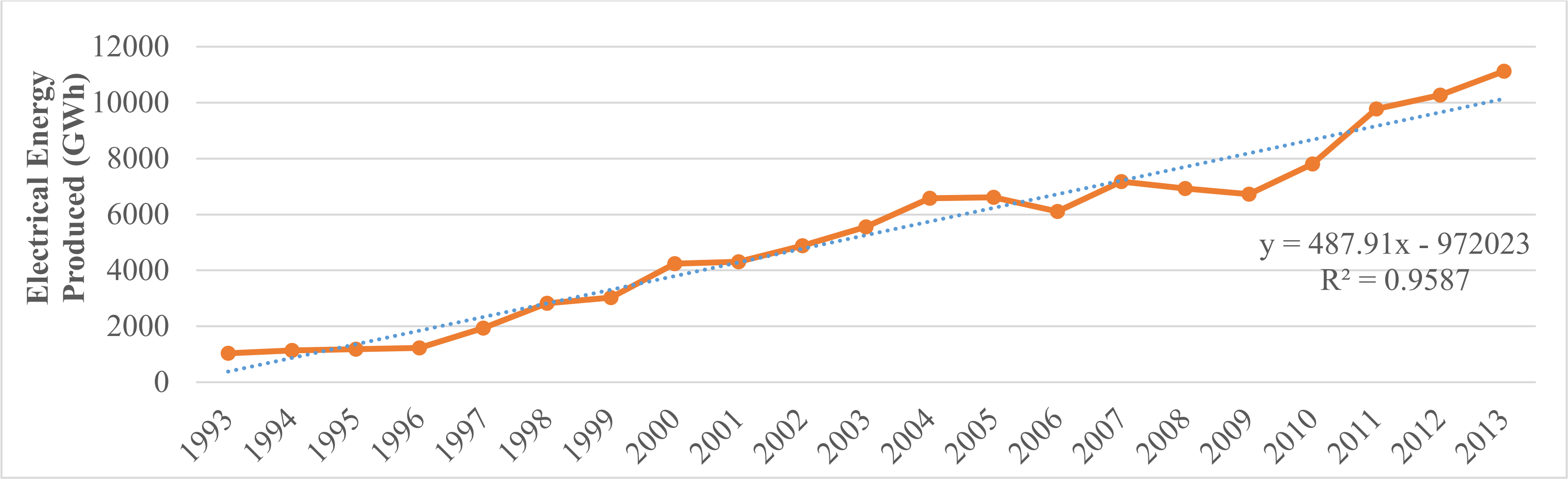

Figure 5. Annual Denmark electrical energy storage (EES) installation (1993-2013). Data as reported by U.S. DOE Global Energy Storage Database. Denmark's direct technological subsidy was adopted in 2004. The linear trendline reflects a steady increase in renewable energy generation since 1993.

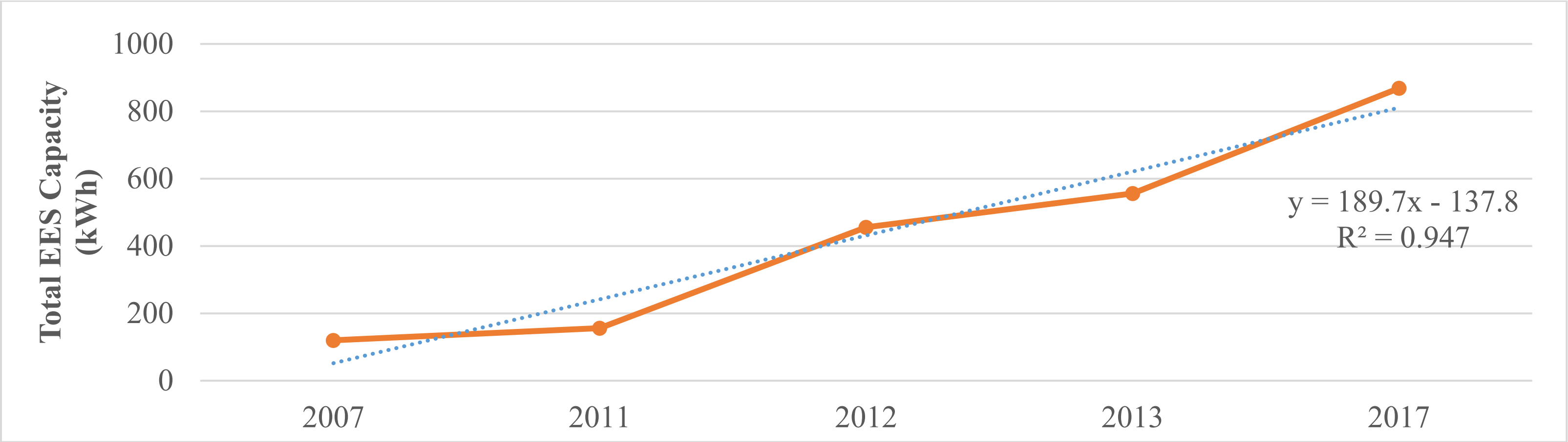

Figure 6. Annual Denmark electrical energy storage (EES) installation (2007-2017). Data as reported by U.S. DOE Global Energy Storage Database. Denmark's direct technological subsidy was adopted in 2004. The linear trendline reflects a distinct increase in EES installation since 2007.

My t-test for Denmark's direct technological subsidy suggested there exists a statistically significant relationship between renewable energy production and EES installation, with a p-value of .047 (Figures 5 and 6).

DISCUSSION

My findings indicate that of the compared policy strategies an energy storage mandate yielded the largest increase in electrical energy storage (EES) installation and renewable energy generation based on the predicted values derived from each study site for California, followed by feed-in tariffs and technological subsidies respectively. However, contextualizing these results in California's geography and sociopolitical climate suggests that each policy has relevant characteristics that could make them viable options for implementation, depending on the conditions framing policy adoption. While my findings from the comparison study sites, Germany and Denmark, cannot be applied perfectly to California, they can still be reasonably adapted and contextualized to inform Californian energy policy since each site features similarly strong environmentally conscious political support and extensive existing energy infrastructure systems. Some of the imperfections attached to my comparison include differences in political systems, physical geography, data availability, and size. For the purposes of my study, the effectiveness of each policy was interpreted directly from my quantitative metrics, where higher EES implementation and renewable energy generation values over time were associated with effective policy. The feasibility of each policy for implementation in California was assessed based on path dependency, where the underlying political processes and parameters surrounding each policy were examined to evaluate to what extent its success was reproducible or a result of special circumstances. Under these contexts, my comparative policy analysis related the effectiveness and feasibility of each policy mechanism and helped determine the strengths and weaknesses attached to each policy.

California's energy storage mandate

The energy storage mandate's steep, positive slope for EES integration, 977, and renewable energy generation 7906 over time indicate that it was and continues to be the most effective policy mechanism for California out of the tested three (Figures 1 and 2). Its dramatic effect on the number of EES projects initiated in California since policy adoption is also significantly greater than the other two policies (Table 2). But, a few contextual factors weaken the integrity of these slope values and findings. For instance, because the policy was recently adopted in 2011, much of the data is based on projections and proposals, suggesting that future ongoing assessments are needed to fully confirm the effect that the policy has on EES integration and renewable energy generation. In addition, California's Renewable Portfolio Standard (RPS) (2002) preceded the adoption of the mandate and functioned as a critical foundational piece of legislation for the development of renewable energy infrastructure and policy in California (Golden 2003). Moreover, though California's RPS was enacted in 2002, it has been actively updated both in 2006 and more recently in 2011. California's RPS thereby established a precedent framework for renewable energy policies that continues to be maintained and refreshed, which directly facilitated the adoption of policy like the energy storage mandate in order to help meet its standards (Wiser et al. 2007). In addition, the feasibility, success, and influence of the energy storage mandate is tied to California's preexisting environmental culture and leadership, which helped expedite the adoption and development of renewable energy policies given that legislators already had widespread public and political support (Carlson 2013). Lastly, the introduction of approximately 100MW of EES units to remedy the Aliso Canyon gas leak (2015) also undermines my results since it occurred independently from the mandate (Cardwell 2017). Thus, the success of California's energy storage mandate so far is attributed not only to the strict standards set by the policy itself, but also the favorable conditions in which it was adopted and maintained.

Germany's renewable energy feed-in tariff

The feed-in tariff's steep, positive slopes for renewable energy generation, 5131, and EES installation, 1596, indicate that it is an effective policy for consideration in California. Although the feed-in tariff's slope for renewable energy generation and number of EES projects initiated are less than the energy storage mandate, the policy resulted in a higher EES integration slope value. However, the tariff's higher EES integration slope value is likely a result of Germany beginning with significantly less EES infrastructure than California, which allowed them to install EES more rapidly. Yet, despite its comparatively lower values to the energy storage mandate, the tariff may be more effective and feasible for California than the metrics suggest. For instance, while Germany and California do not share the same political system or history, they do share a common environmentally conscious culture that makes feed-in tariff implementation politically feasible and more likely to be utilized by residents and industries at a high rate (Lehr et al. 2008). Nevertheless, the unique path dependent policy history of Germany's feed-in tariff could make its application in California more difficult than expected since different political parties, policy decisions, and legislative histories were involved (Laird and Stefes 2009). Still historically, both the United States and Germany, have responded similarly to pivotal global energy events, namely the 1973 oil embargo crisis, where they both created new governmental energy institutions and departments, and dramatically increased funding in these sectors (Laird and Stefes 2009). Therefore, these social and historical similarities make the feed-in tariff a viable option for EES integration and renewable energy generation in California.

But for the feed-in tariff to be feasible in California, it would need to be adjusted to account for the preexisting conditions set by the renewable portfolio standard (RPS), while guaranteeing reliable revenue streams for investors (Cory et al. 2009). Although California did establish a moderately effective statewide feed-in tariff as early as 2008, its premium pricing was funded only off of diverted costs and, unlike Germany, does not include additional government subsidies. In contrast, Germany's feed-in tariff was originally a much more generous government subsidy for energy suppliers and residence, which was scaled back over time as renewable investment increased dramatically (Butler and Neuhoff 2008). This feed-in tariff subsidy thereby provided an even greater incentive for renewable energy generation and EES integration in Germany, which make it a more effective strategy than the existing policy in California (Cory et al. 2009). Therefore, Germany's specific feed-in tariff is a powerful policy incentive mechanism that has great potential to increase EES integration, but at the same time it is situated in a more complex history than what my data analysis indicates.

Denmark's direct renewable energy technological subsidy

Denmark's direct technological subsidy produced a comparatively low renewable generation slope of 488 and EES integration slope of 189. These weak, positive policy slopes are complemented by the limited number of EES projects initiated since the policy was adopted.

Nonetheless, these results do not capture some of the policy's underlying beneficial effects. One of the major positive benefits exclusive to the technological subsidy policy mechanism is referred to as "technological learning," which is defined as the process in which the cost of a given technology decreases as its cumulative installation increases (Klaassen et al. 2005). Technological learning is closely associated with the traditional economic learning curve concept, where the introduction of a subsidy allows for greater distribution, innovation, and reduced costs for a given investment (Klaassen et al. 2005). More specifically, some of the underlying economic forces that drive the technological subsidy's benefits include the creation of new technological niche markets and the potential discovery of new inventions or innovative techniques (Buen 2006).

However, despite these more broad positive implications, the technological subsidy also risks concentrating new technology in a select few industries, and limiting technological diffusion if the policy is not written carefully enough (Ibenholt 2002). Additionally, the technological subsidy comes at a large monetary expense to the government and does not necessarily guarantee technological advancement within a certain timeframe, which makes it a less desirable option than the other policy mechanisms in my analysis. But, likewise, if the selected EES technology is still immature and has great capacity to grow, the direct technological subsidy would prove to be an extremely effective catalyst for greater EES integration and renewable energy production (Ibenholt 2002). As a result, the technological subsidy would be a feasible option for EES integration in California given its array of long-term technological and economic benefits, though it requires substantial government funding and does not guarantee the same concrete results that mandates or feed-in tariffs do.

Policy comparison

My findings largely confirm that feed-in tariffs and energy storage mandates are likely the best policy mechanisms for encouraging greater integration of EES in California for renewable energy generation. As described previously, both feed-in tariffs and energy storage mandates have already been employed in California with varying degrees of success. However, by using Germany as a model, California's feed-in tariff could be better adapted to subsidize and greater incentivize EES and renewable energy integration. Similarly, direct technological subsidies like those employed in Denmark, remain feasible and effective policy options in California, but the magnitude of funding must be adjusted to the State's budget and to the maturity of the specific EES technology selected. As a result, to best incentivize EES and renewable energy generation in California, policy that establishes higher energy storage mandate standards must be implemented in conjunction with equally high feed-in tariff and technological subsidy incentives.

Limitations

Despite the measures taken to compare the three policy mechanisms, my analysis cannot fully account for differences in each study site, namely with respect to time, path dependency, and geography. Because each policy was adopted at a different time and over different time periods, comparing each policy and adjusting for the sociopolitical, economic, and technological development is difficult. Denmark's direct technological subsidy specifically had limited datasets compared to the other policies, which make the trends that I calculated less reliable. Furthermore, while each study site does share a similarly environmental conscious history and social awareness, this common relationship is obscured by path dependent processes for each site: situational political discourse and negotiations likely shaped policy in unique and to an extent irreproducible ways (Peters et al. 2005). Geographically, each features a unique physical landscape, resource availability, existing infrastructure, and population size relative to one other, which again prevents my results from being fully comparable. Therefore, these inconsistencies must be considered when contextualizing my results and used to inform future EES policy analyses by exploring the policy history and background of each study site in closer detail.

Future directions

Moving forward, studies that examine EES policy over longer periods and that review the renewable industry within California are needed to validate my findings. Because my study only analyzed certain policies over specific time periods, the scope of my findings is limited and future studies will need to evaluate additional policies while following up on those analyzed in my study (Gaul and Carley 2012). The status of the renewable energy industry in California itself must also be more closely researched to contextualize its capacity for growth and identify the economic conditions which may hinder or facilitate greater EES integration (Landry and Gagnon 2015).

Other factors like electrical grid infrastructure development and climate change mitigation pressures must be accounted for, as well. And identifying what specific types of energy storage options are best for capturing California's renewable energy assets would also potentially strengthen and weaken future policy choices (Landry and Gagnon 2015). By addressing the development of EES technology and infrastructure in the context of a growing renewable energy sector over a longer period, the precise effects of each mechanism and how they compare with each other can more effectively inform EES policy.

Broader implications

My study provides a framework for further exploration of EES technology and policy, particularly as the renewable energy industry continues to grow with the advent of climate change mitigation, sustainability issues, a growing global population, and a need for energy efficient infrastructure. Despite the fact that renewable energy only represents a small fraction of total electrical energy production in most areas, these sources are becoming more relevant as energy security becomes a priority for countries of all backgrounds and the effects of climate change continue (Demirbas 2009). As a result, EES physically acts as an instrumental piece in remedying the global discrepancy in renewable energy generation. But for EES to be adopted under current conditions, effective and well-informed energy policy must be enacted to facilitate this process. Thus, EES integration allows for more efficient and extensive energy infrastructure systems and greater renewable energy production, but it requires the support of region-specific renewable energy policy mechanisms to be successful.

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