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THE ROLE OF ENERGY STORAGE AT GRID RELIABILITY AND SYSTEM RECONFIGURATION: A SYSTEMIC APPROACH

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ABSTRACT

The energy transition urgency is fostering energy storage's role as the key peace towards a clean energy future. However, the role of this technology on future electricity grid is still under analysis. We consider energy storage as a niche technology in transition to the regime. Therefore, public policies and directed investments are the key drivers to the technology diffusion. California (CA) and South Australia (SA) cases were assessed, and both provided a view on the increasing relevance of energy storage on decarbonization goals and reliability of a renewable grid. The quantitative analysis made by a Bayesian dynamic linear model showed that, despite CA's null impacts, each GWh added in SA's energy storage provided about a 1.2 and 1-point reduction of the (natural) logarithm of SAIDI and SAIFI in 2020, respectively. Furthermore, with announced battery storage projects data, we estimated the effect of the increase of capacity on SA reliability indexes. Our results showed that, if 2020 announced capacity was already operational, a 70% reduction on both frequency and duration of interruptions could be obtained.

INTRODUCTION

Energy storage systems (ESS) are technologies able to capture energy produced at one time in one form for use at a later time in another form (Kalair et al., 2021). Despite being recognized for decades, the ESS role in the electricity supply chain is being changed as energy transition evolves. Shaped by the need to reduce greenhouse gas emissions, this transformation is associated with increasing levels of innovation to foster the diffusion of renewable energy sources (RES). However, the large-scale integration of RES has led to growing concerns about key performance indicators to power system operation, such as reliability. In this context, ESS emerge as innovations with potential applications in relevant sectoral challenges (Kalair et al., 2021).

The services provided by ESS can contribute to decarbonization by expanding the efficiency of system, integrating variable RES, encouraging decentralized energy production, expanding energy access, and improving grid flexibility, reliability, and resilience (GAEDE; ROWLANDS, 2018). Thus, ESSs are one of the solutions for stabilizing electricity supply to avoid less efficient production and higher prices during peak periods (ZAKERI; SYRI, 2015). This paper addresses the gap around the role of this technology in the transition to the future electricity sector. With an emphasis on the sector's resilience and the ongoing energy transformation, the paper analyzes to what extent energy storage is a key element for the reliability of the power sector, promoting both the acceleration of decarbonization and the security of supply. Our central hypothesis is that storage is already presenting significative impacts on distribution grid reliability, with a trend of increasing relevance in the long term. Two secondary hypotheses underlie the qualitative analysis of this paper: storage has developed as a solution to emerging challenges in the context of the energy transition, in a niche to regime transition; and public policies and the alignment of public and private agents are relevant to the acceleration of the diffusion of this technology. We conducted a multiple case study, drawing on the experiences of the states of California (CA, USA) and South Australia (SA, Australia). The study is divided into two stages: the first, qualitative, aims to analyze the evolution of public policies around ESS. In this first step, we highlight the relevance of ESS on decarbonization policies. Next, a quantitative analysis of the evolution of System Average Interruption Duration Index (SAIDI) and the System Average Interruption Frequency Index (SAIFI), the main indices for measuring system reliability, is undertaken.

LITERATURE REVIEW

Electricity sector's recent innovation analysis from a systemic perspective starts from the so-called transitions studies. The multilevel perspective, as a framework for analyzing socio-technical transitions, establishes an interrelationship between radical innovations, through the concept of niches as the locus of innovation; dynamic stability, in which regimes represents the institutional structuring of the system; and the influence of the landscape, which is associated with long-term change (GEELS, 2002). As they diffuse, niche innovations can compete with the existing regime, when they aim to overcome it; or relate to it, if they are adopted as a complement to improve the regime's performance or solve problems. From the interaction between agents and coevolution of elements at diverse levels, transitions result in five potential paths. In each of those, there is a specific way about how innovations diffuse and what their roles on the regime are. Despite being a recognized niche technology, the transition from ESS to the regime remains uncertain. We analyze that ESS diffusion towards the socio-technical regime assumes a reconfiguration trajectory in the long run. In this path, symbiotic innovations are initially adopted into the regime as solutions to local problems. As they integrate into the system, they result in additional adjustments to the basic regime architecture. In order to analyze the ongoing innovation paths related to ESS, we analyze CA and SA's public policies on energy transition and the integration of ESS at the electricity sector.

California

Considered the cradle of great innovations, CA is a state at the forefront in several aspects, including energy. The energy crisis in the early 2000s is a precursor to climate and energy strategies, with energy storage policy embedded in these strategies (OSSENBRINK et al, 2019). In 2020, energy utilities served around 14,8 million customers (EIA, 2021a). In proportional terms, wind and solar energy sources accounted for 3% of the installed capacity of the CA power sector in 2001. By 2020, this share was of 25% (CEC, 2021). Because of its proactive role, the state is also considered a global leader in the development and application of ESS technologies (TELARETTI; DUSONCHET, 2017; KUMAR, SHRIMALI, 2020). In 2014, ESS was consolidated as a strategic priority for achieving energy transition goals, resulting in the publication of a state roadmap (OSSENBRINK, 2019; CAISO; CPUC; CEC, 2014). At the federal level, Federal Energy Regulatory Commission (FERC) has issued several decisions related to ESS. In 2008, Order 719 allowed distributed energy resources (DER) to participate on electricity markets. Similarly, Order 755 and 784 assured ESSs competitive advantages in ancillary services markets, given their rapid response. Finally, Order 841 allowed the participation of ESS in the energy, capacity, and ancillary services markets. At CA state level, Assembly Bill (AB) 2514 established an ESS mandate at each investor-owned utility (IOU) in 2010, totaling 1,325 MW to be completed by 2020 and implemented by 2024. AB 2514 also encouraged utilities to consider the value of ESSs in different services provided to the grid, the so-called "value stacking" (MULHAUSER, 2020). Additionally, distributed generation (DG) funding programs promoted by the California Public Utilities Commission (CPUC), such as the Self Generation Incentive Program (SGIP), encouraged consumer adoption of the technology (CAISO; CPUC; ENERGY COMISSION, 2014). Although not initially aimed at developing ESS, SGIP is considered the first state program to promote incentives for behind-the-meter ESS adoption (MCNAMARA, 2020). In 2018, SB 700 extended the incentive program to 2024. Moreover, in 2014 CPUC established that ESS associated with net metering eligible systems were exempt from interconnection charges, distribution improvement costs, and stand-by tariffs. The adoption of this regulation ensured that ESSs eligible for exemptions were only those associated with RES installations (TELARETTI; DUSONCHET, 2017). In 2016, AB 2868 established the need for utilities to develop programs and direct investments to accelerate the development of distributed ESSs. However, the Energy Storage Grand Challenge (ESGC) program, launched by DOE in December 2020, highlights that despite the investment directed to storage (over $1.6 billion, 2017-2020), the goals and objectives around the technology have been developed individually by DOE technology offices, revealing the absence of a targeted strategy (DOE, 2020). Therefore, ESGC inaugurated DOE's adoption of a systemic approach towards ESS. The DOE analysis points out to an integrated and interrelated process between user-centered case studies and the strategic goal of ESGC of developing a portfolio of ESS technologies, catalyzing a domestic ESS supply chain, and developing US market abroad.

South Australia

Australia is a federation consisting of six self-governing states and two territories. Despite its favorable condition for the diffusion of RES, one of the main challenges for this country is the integration of the growing wind power generation to the grid, mainly in the state of SA (MOORE; SHABANI, 2016). The state has a population of approximately 1.8 million, making it the second smallest state by population in the country (MCGREEVY et al, 2021; ABS, 2021). The energy transition verified in SA stands out due to the rapid diffusion of RES (MCGREEVY et al, 2021). In less than 15 years, the state, which in 2006 generated all its electricity from fossil fuels, had 60% of its demand met by intermittent renewable generation sources by 2020. Thus, SA was considered an example of the electricity grid of the future, dominated by RES, and supported by ESS (BOWYER; KUIPER, 2021). However, Australia has faced difficulties in coordinating policies to encourage the diffusion of DER and RES. A Renewable Energy Target (RETs) was established in 2001, with the initial goal of achieving 2% of renewable electricity generation. In 2015, the Renewable Energy Amendment Bill reduced the Large-Scale RET target for 2020 from 41 TWh to 33 TWh, with targets for subsequent years also adjusted (LI et al., 2020). However, SA has consistently extended its target, with a current goal of 100% share of renewable generation in the electricity sector by 2030. On October 11, 2020, solar generation in SA was sufficient to meet 100% of the state's electricity demand for one hour, between 12:30 and 13:30. Nevertheless, consumers in the SA have been investing in

DERs (mainly DG), with solar panel installation reaching 33% of consumer units (AEMO, 2021). Complementing this process, the diffusion of innovative technologies, resulting in non-traditional energy products and services, has led to increasing discussion about the modernization of the Australian electricity sector (MCGREEVY et al, 2021). Thus, in the Australian Energy Market Commission (AEMC) view, technologies such ESS and DERs were not initially envisaged in the National Energy Customer Framework (NECF), and are testing its limits (AEMC, 2020).

Although not restricted and focused on ESSs, Australia has a set of government policies and incentives associated with the achievement of its decarbonization goals, such as national and state RETs, feed-in tariffs, research, and development programs for emerging technologies (LI et al, 2020). In 2015, the low-carbon investment strategy launched by the SA government also allowed for increased uptake of ESSs, used especially to prevent the system from reliability problems and outages due to intermittent renewable generation. The strategy aims to achieve $10 billion of investment in low-carbon power generation by 2025, in addition to obtaining 50% of its output from RES by the same year. This strategy already pointed to ESS as an important solution to meet the challenges associated with the increasing level of diffusion of RES in the state of SA. In 2017, the SA government released an energy security plan (Our Energy Plan), which outlines the foundation for transformation toward a sustainable energy system. To this end, the Growth and Low Carbon (GLC) division of the SA government's department of energy and mining identifies that the challenges of energy transition, added to regional characteristics, will be overcome, among other measures, by the diffusion of batteries and ESS in general. On October 2018, SA government launched the Home Battery Scheme, with the goal of reaching a target of 40,000 battery systems installed in residential consumer units. In addition to the $100 million budget in grants from the SA government, the program relied on $100 million in funding from the Clean Energy Finance Corporation (CEFC) for loans at attractive rates for DG and ESS. Besides these targets, the program aimed to reduce demand on the grid at peak periods and, as a result, reduce electricity prices for all consumers. Also in 2018, the SA government announced the Grid Scale Storage Fund as one of the core elements of state energy policy, aiming to accelerate the diffusion of new large-scale storage facilities that can solve the challenge of intermittency in SA's electricity sector. In recent years, the expansion of power supply interruptions, climatic events, and limitations of renewable energy generation sources have incited the discussion about the use of ESSs in the country (MARTIN; RICE, 2021). In this regard, the authors highlight the storm faced by the state of SA in September 2016, which led to multiple outages in transmission networks and, consequently, the cutting of supply across the state. The restoration of supply, which initially took three days, was even more critical in light of reduced wind generation conditions and overloading on the interstate connection. In February 2017, a new blackout hit about 90,000 SA households as a result of a combination of the heat wave, causing an increase in demand for electricity, and the markets' difficulty in promoting the balancing of energy supply and demand. This context inserted the state of SA and its sustainable transition into national and international discussion (MCGREEVY et al, 2021).

METHODS

To estimate the time evolution of effects that information about energy demand and storage can have on the reliability indexes of the distributions systems, we propose a Bayesian dynamic linear model (DLM, West and Harrison, 1997). This general class arise via state-space formulation of standard time series models (i.e., Box-Jenkins models, Box et al., 2015) and as natural structures for modeling time series with non-stationary components and external variables. For further details, see Prado and West (2010). In the context of reliability analysis and forecasting, other statistical approaches are also suitable, such as neural networks and ARIMA models. For example, see Xie et al. (2016) and Li et al. (2011). However, these techniques have limitations regarding the practical interpretation (Krishnan, 2020), temporal flexibility of the model parameters, and poor fitting in short time series (Watson and Nicholls, 1992). In contrast, the proposed approach has attractive features such as naturally considering the uncertainty about parameter estimation via a fully Bayesian inference, prior (expert) information, and interpretable time-varying parametric components.

For each reliability index, the proposed model was defined as follows:

$$\begin{aligned} y_t &= X_t\beta_t + \varepsilon_t, \qquad (1)\\ \beta_t &= Z_t\beta_{t-1} + \omega_t, \end{aligned}$$

where, at time t, y_t represents the (natural) logarithm of reliability index, β_t represents the linear parameters of the demand and storage variables allocated into a design matrix X_t. The time evolution of parameter is led through the evolution matrix Z_t. The error $\varepsilon_t \sim N(0, \sigma_t^2)$ and evolution terms $\omega_t \sim N(0, \psi_t^2)$ are internally and mutually independents. The univariate DLM presented in (1) was implemented in the R programming language, version 4.1.2 (R Core Team 2022).

Dataset

To analyze our variables of interest, namely SAIDI and SAIFI, we collected official data of CA and SA. Our explanatory variables are the number of customers (million), peak demand in summer and winter (GW) and utilities' energy storage capacity (GW). CA data was retrieved from U. S. Energy Information Administration forms EIA-860 (EIA, 2021b) and EIA-861 (EIA, 2021a). Our dataset comprehends the four main electric utilities of the state (all with more than a million customers: Pacific Gas & Electric, Southern Edison, Los Angeles Department of Water & Power and San Diego Gas &

Electric), which represents 94% of electricity customers of CA. SA data was retrieved from Australian Energy Regulator's Electricity Network Performance Report 2021, which provides information on electricity distribution network operational performance from 2006 to 2020 (AER, 2021). The time span on CA analysis was determined by energy storage and reliability data availability. Since 2013, generation data on EIA's Form-860 includes energy storage technologies. From 2016 until now, energy storage is analyzed on a proper form, with detailed information of the services provided from each technology to the grid. Nonetheless, reliability data is only available from 2013 from now.

RESULTS

From a socio-technical perspective, both CA and SA showed an evolution from isolated initiatives seen at the beginning of the decade to ESS integration and innovative activities of incumbent agents. An example is the USA's ESGC, which presents the integration between industry, market, technology, and institutions to ESSs integration to the grid. At the state level, the main drivers of technology diffusion are incentive programs at the consumer level, characterized as niche creation policies, or utility-level technology substitution, which can be considered the first steps towards a destabilization of the regime (KIVIMAA; KERN, 2016). On the other hand, SA presented an accelerated development of energy matrix and integration of new technologies in the recent period. With the emergence of technical and operational challenges associated with the rapid integration of RES into the local grid, ESS was considered the solution for an efficient and secure energy transition. Thus, recent policies and initiatives around ESSs in SA exhibit a trend towards a reconfiguration trajectory. The perspectives of modernization of the regulatory framework aiming at the integration of the ESSs, and the diffusion of new projects, associated with the mobilization of public and private agents, substantiate the perspective of evolution within this trajectory. The analysis of the CA and SA cases highlights that the states have extensive history and experience in policies to encourage the niche of energy storage. Since ESSs are related to DERs and RES, the policies surrounding these technologies also provided incentives for the diffusion of storage, as predicted by Geels and Schot (2007) about sequential - or cascading - innovations.

Despite their similarities, our quantitative analysis showed that SA and CA's ESS diffusion is impacting reliability indexes in different manners. SAIDI and SAIFI analysis (Figure 1) showed that CA kept its reliability steady between 2013 and 2020. As previously stated, this could be related to its proactive role towards energy efficiency and integration of innovative technologies to improve system functioning. SA, however, presents an expressive declining of both frequency and duration of interruptions. In 2017-2018 and 2018-2019 summers, the state faced reliability risk projections by AEMO, related to major coal and gas plant closures. However, over the past 4 summers (up to and including 2020-2021) AEMO intervened and activated the Reliability and Emergency Reserve Trader (RERT), which allows to procure additional supply or demand management at times of system stress (AER, 2021).

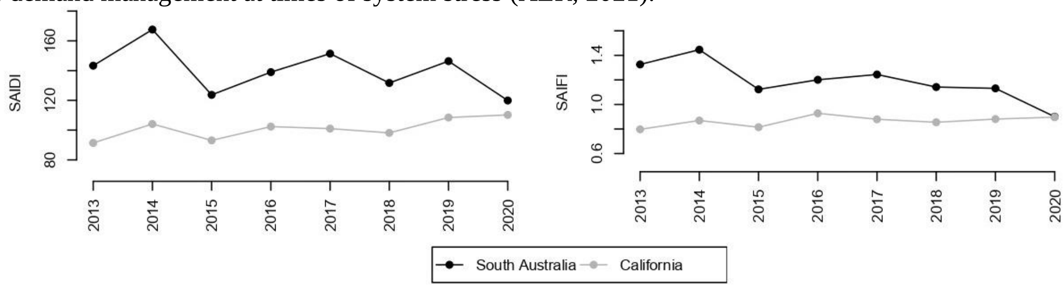

Figure 1: Time evolution of SAIDI and SAIFI - 2013-2020

In the context of renewable sources integration, CA has a goal of creating a robust smart grid that can respond to the increasing diffusion of intermittent power generation sources. To this end, the state uses an integrated approach towards the technologies and the agents inserted in the transition process, analyzing the importance of energy efficiency and demand participation, as well as energy storage, integrated into the grid from generation to the end consumer (AECOM, 2015). The analysis of ESGC related to U.S. DOE's lack of integration at ESS objectives and programs could be related to an absence of impacts of ESS on reliability indexes in the short term, with a 95% credible interval (Figure 2).

On the other hand, SA presents an expressive estimated effect of energy storage on both SAIDI and SAIFI. Despite of the efficiency of the investments and strategies deployed at SA, these results could also be related to energy storage capacity compared to the peak demand. Our analysis showed that, while in SA the share of energy storage corresponds to 6,4 and 8,2% of summer and winter peak demand at 2020 (about 3 GW of peak), respectively, in CA these numbers are under 0,5% (considering a 17 GW peak).

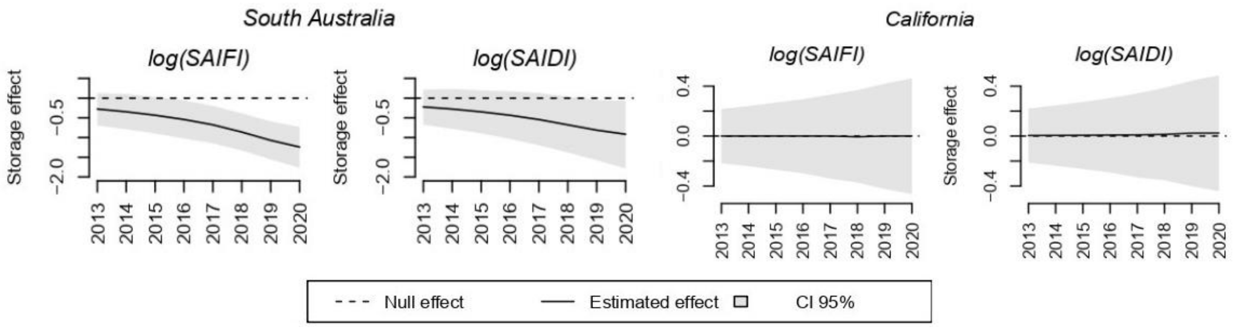

Figure 2: Estimated trajectory of the available storage amount effect on the (natural) logarithm of reliability indexes

Therefore, Figure 2 shows that, at current levels of diffusion, each GW of ESS added to SA leads to a 1,2 reduction at log (SAIFI), in 2020. Similarly, besides this reduction on interruptions frequency, their duration (SAIDI) is also significatively reduced (around 1-point reduction at SAIDI logarithm for each GW of ESS). It should also be noted that ESS data on CA and SA is provided by utilities. Therefore, other data sources, including distributed energy storage, could be further analyzed to provide a better view of ESS diffusion in the state. Furthermore, SA data shows a significant amount of proposed (i.e., publicly announced) ESS capacity being developed. By 2021, the state had about 2.8 GW in announced ESS projects (Table 1).

Table 1: Battery Storage capacity in South Australia (MW) – 2017-2021

Status	**2017**	**2018**	**2019**	**2020**	**2021**
Existing	100	130	130	206	206
Committed	-	-	25	11	17
Anticipated	-	-	-	-	268
Proposed	30	488	488	1.568	2.793

Based on this capacity, we can simulate scenarios in which we evaluate the impact of the proposed storage on reliability indices. Our results (Figure 3) show that if the proposed capacity had already been put into operation, both indices could be reduced by about 70% in 2020.

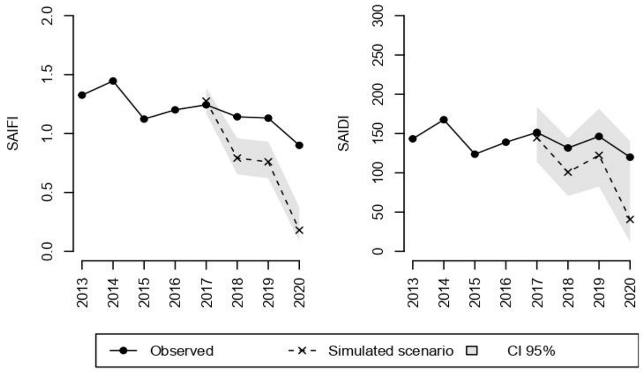

Figure 3: Simulated scenario, SA

CONCLUSIONS AND FURTHER RESEARCH

Our qualitative results showed that public policies were the main drivers of ESS diffusion. The analysis shows that CA's pioneering spirit and SA's proactivity in defining ambitious goals in the climate-energy nexus, often against the national level, were decisive in achieving more significant levels of ESS diffusion. Also, these states are characterized by incentive policies aimed at residential consumers. These programs were the central element of analysis in the literature about the diffusion of ESSs, with emphasis on batteries. On the other hand, CA and South Australia differ in their approach to large-scale ESS diffusion. While in CA, regulation was the major driver of development, through development targets for utilities, in South Australia, the indication of storage needs by state government, including the provision of an energy security plan, was the driver for the diffusion of projects by utilities and companies in general. Nonetheless, that the private sector's interest in building large-scale storage plants in Australia was due both to the opportunity for financing and low-interest loans, promoted by the SA government, and to the vision of rapid recovery of the investment through revenues from the provision of services to the system. In any case, public policy incentives, regulatory adjustments (in CA), and state strategies, including financing (in SA) were the drivers of ESS diffusion in the cases analyzed. As states saw increasing participation of ESSs, as well as their potential for providing ancillary services and enhancing security and reliability of supply, these policies unfolded into broader reforms in electricity markets. Thus, as conventional plants were decommissioned, the contribution of ESS as a source of flexibility and a solution to variations in supply and demand became more evident. This result is consistent with the hypothesis that ESS diffusion has taken the path of reconfiguration in both CA and South Australia. Nonetheless, the impact of ESS on reliability indexes showed that SA grid is already benefiting from the governmental uptake on policies and investments.

Further developments could be achieved with a review on CA and SA's energy storage data. Since the information was retrieved from EIA's form and AEMO data, distributed batteries are not under discussion. As market barriers to these technologies are under revision, their role on grid reliability could be relevant in the medium-term. In CA, since ESGC program was developed in 2020, this integrated approach towards ESS could spur a relevant uptake on ESS diffusion and availability to grid reinforcement. By contrast, SA results showed that ESS diffusion is already fostering a significative reduction on reliability indexes. Further analysis of the dynamic model proposed could estimate the economic viability of ESS according to the cost of reliability to the electricity grid and utilities.

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