A Better Way: A Proposal for a Fully-Renewable Utility in the San Diego Area

Saud Almuqaytif, Lucille Banta, Simon Julien, Darin Meeker, and Megan Rose

***Abstract*—With the near- and long-term realities of climate change looming, it is the responsibility of leaders in the utility sector to fully embrace renewable energy. Thanks to economic and technical improvements over the past decades, it is now possible to have a 100% renewable energy grid. California, and San Diego in particular, has always been a leader in renewable energy implementation, with some of the highest penetration rates in the country. In this spirit, the SSDL&M utility is proud to present our bold vision for a reliable, economic, 100% renewable energy grid that will serve a portion of San Diego County's customers and signal to the world what is possible. Our grid design - to be implemented in 2022 - features a completely renewable generation mix of solar, wind, and landfill gas, plus various storage technologies, and utilizes advanced controls to provide fast frequency and voltage support, inertial support, and flexibility under various environmental and load scenarios.**

***Index Terms*—San Diego, renewable energy, energy leadership, grid of the future.**

I. Introduction

As climate change accelerates and fossil fuel reserves dwindle, there is an urgent need to shift energy generation to renewable sources. Many states and utilities in the United States have set climate goals to have most or all of their electric mix generated from renewable energy within the next few decades. For example, one of the most aggressive renewable energy targets has been set by the state of California, which has legislation in place requiring that the state meet 100% of its electric load with net zero carbon emissions by 2045 [25]. However, there is no set road map for what this new status quo will look like. The existing American electric grid was built off of the assumption that the majority of electrical generation will be performed by generators powered by fossil fuels, as it has been in past decades. Although legislation has begun to assert the need to move away from this model, utilities have been slow to make the large changes that will be necessary to overhaul their generation model, and so far no US utility has come anywhere near a fully renewable generation mix.

In the spirit of establishing a viable road map to the future, the following report presents our proposed pathway for moving to a fully renewable grid. We assume that our utility is a virtual power provider that utilizes existing distribution infrastructure, along with geographically-diverse generation and storage assets, to fulfill about 7% of San Diego County's energy needs and meet our aggressive goal to meet 100% of our generation needs from renewable sources by 2022. We hope that by showing how such a target can be met practically and economically, even on such a short timescale, we will demonstrate that this change is possible and establish a successful model that other utilities can follow.

II. Load

When designing a utility-scale grid system, electrical load (i.e. demand) is a critical factor - including the maximum and minimum values, time-dependent patterns, and the types of loads on the grid. The maximum and minimum values of total customer demand determine the capacity of generation required, while the range and ramping rate of the load will determine the amount of storage or other dispatchable power required. Especially when designing a fully renewable grid, how the time-dependency of the load lines up with variable generation is a key consideration that will also determine how much storage is required. Different types of loads connected to the grid will vary in their impedances - both capacitance and inductance - and in the inertia they supply, which will in turn impact the power factor and the amount of inertia required from generation, respectively.

A seen in Table I, our customer base in the San Diego area has, annually, a peak demand of 106.1 MW, a minimum load of 28.7 MW, a range of 77.4 MW, and an average load of 46.5 MW. In our seasonal analysis, summer is defined as April to September and winter as October to March. The seasonal load characteristics differ, with a much lower winter peak of 68.1 MW and a narrower range of 38.6, though the minimum and average are similar from summer to winter. Thus most of the load variability in occurs in summer months. The load exhibits periods of dramatic ramping at a handful of times throughout the year. Most notably, on September 16, the load went from a low of 39.0 MW at 2:43 a.m. to 93.8 MW at 3:43 p.m., totalling a swing of 54.8 MW in a single day. Also happening that day in 2012, was the a particularly exciting Rockies vs. Padres game, played at Petco Park in downtown San Diego. The annual energy required by the customer load is another important figure, at 407,562 MWh per year for our customers. The energy generation will need to exceed this amount since our grid will include storage and some curtailment as well.

III. Generation

The proposed renewable grid is comprised of a variety of generation assets, including utility-scale wind, utility-scale solar PV, residential and commercial rooftop solar PV, landfill gas, and a variety of storage assets that will be described in a subsequent section. Unlike a conventional, fossil-fueled grid, a fully renewable grid requires an understanding of the resources that are locally available. San Diego features a great deal of

Load (MW)	Overall	Winter	Summer
Max	106.1	68.1	106.1
Min	28.7	29.6	28.7
Range	77.4	38.6	77.4
Average	46.5	43.0	47.7

TABLE I: Load maximum, minimum, range, and average by season, showing the wider variability in summer.

Generation Plant	Location	System Size (MW)	Annual Energy (MWh)	% of Energy Generation
Solar Plant 1	Calexico	60	129,474	26.2%
Distributed Solar	Various	16	34,526	7.0%
Wind Plant 1	Live Oak	20	39,948	8.2%
Wind Plant 2	Thing Valley	10	13,466	2.7%
Wind Plant 3	Clover Flat	10	9,702	2.0%
Wind Plant 4	Santa Ysabel	10	6,397	1.3%
Wind Plant 5	Julian	10	18,000	3.7%
Landfill Plant 1	Otay Landfill	13.8	112,920	22.9%
Landfill Plant 2	Miramar Landfill	15.8	128,481	26.0%
TOTAL		**165.6**	**492,913**	**100.0%**

TABLE II: A breakdown of generation asset type, location, size, and energy contribution as a percentage of total energy generation.

solar insolation, having 5.7 peak sun-hours per day for fixed tilt systems and 7.2 peak sun-hours per day for single-axis tracking systems [21], which is partly why the City of San Diego has the second highest rates of rooftop solar per capita of any US city [6] at 295 W per capita.

The wind resource, while less optimal closer to San Diego, is quite abundant in the surrounding mountains with a maximum of about 20-25 m/s in the locations chosen for our wind projects. In the interest of providing baseload power, we decided to utilize two of the several landfills in the San Diego area to generate methane and run gas turbines, a method of power generation that is already employed for a total of 34 MW of existing landfill gas power systems [4]. Finally, pumped hydro will be used as an emergency power backup and to top off any storage assets that are running low due to the unavailability of other generation. We chose not to rely heavily on pumped hydro for generation due to the very low rate of rainfall in the area at about 10 inches per year [2]. Generation assets sizes and their percentage contribution to annual energy production can be seen in Table II.

A. Variable Generation

The 60 MW of utility-scale solar is the largest singular component of the generation mix, by plant capacity, and provides about 130,000 MWh of energy to the grid annually. The system is located in Calexico, CA very close to the Mount Signal Solar Project, an 800 MW-peak solar PV plant with single-axis tracking. The proposed system is a 60-MW DC fixed-mount, south-facing PV plant with silicon-based, high-efficiency panels and state-of-the-art grid-forming inverters. This new plant will feature a control system that intelligently and automatically stores excess energy in a co-located, DC-coupled battery energy storage system (BESS). The power generated will be sent along the same transmission wires used by the Mount Signal plant, eliminating the need to build additional transmission lines. The system produces about 26% of annual energy generation.

As mentioned previously, there is a great deal of existing rooftop solar in the San Diego area due to high solar resources, as well as incentives from the local utility. These existing rooftop systems are estimated to total about 28 MW since our utility's load is estimated to be about 7% of that of SDG&E, and SDG&E's territory has about 400 MW of rooftop solar [12]. Our renewable grid will add 16 MW of additional rooftop solar over the next two years on about 5,000 homes and businesses. These systems will be utility-owned and paid for by the customer via power-purchase agreement, and the utility will be capable of of curtailing and islanding these systems as needed in accordance with IEEE 1547-2018 [14]. Rooftop solar accounts for 7% of annual energy production on this grid.

The wind energy system is broken into five plants, each ranging from 10 MW to 20 MW and totalling 60 MW in capacity altogether. The reason these plants are spread out in different locations is to smooth out the wind energy variability on the system by harnessing different wind patterns from each of the five locations. The plants and their sizes are detailed in Table II, along with the annual energy production from the plants. Wind energy accounts for about 17.8% of the total annual energy generation on the grid. The plants themselves are composed of a total of 24 2.5-MW wind turbines, each with 100-meter hub heights. These wind energy systems also have co-located storage systems to decrease the severity of ramping from each plant. The plants will take up a total of about 3,600 acres of land [8]. The 20 MW site, located at Live Oak, is co-located with battery storage and can be curtailed to provide steady, baseload power at about 10 MW.

B. Non-Variable Baseload

All generation assets previously mentioned are variable and non-dispatchable, unless storage is included. With a minimum annual load of 28.7 MW, at least this much demand is almost guaranteed at all times so it makes sense to have a baseload generation plant serving this load. For this reason, our system has 29.6 MW of landfill gas (LFG) plants. Two major landfills are used for this purpose, with one located to the south of the city in Otay of 13.8 MW and one located in the north at Miramar of 15.8 MW. See Table II for the sizes and locations.

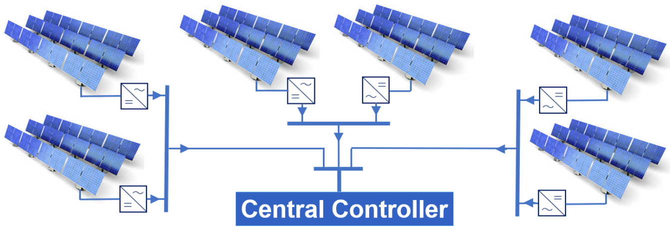


Fig. 1: Conceptual rendering of a hierarchical control structure. This visualization shows how a utility may control multiple PV plants, but in application this concept can be extended many more levels of control to operate our independent power system.

The LFG plants make up 49% of annual energy generation for our utility.

In addition to replacing non-renewable resources, landfill gas plants reduce the emission of methane and $CO2$, and help to improve air quality. LFG is a natural byproduct of the decomposition of organic material and is comprised of about half methane and half carbon dioxide. LFG collection typically begins after a portion of the landfill is closed to additional waste placement, but can also occur in areas of active filling [20]. When the landfill is still active, supply of methane and $CO2$ gas varies over time, since the amount of waste varies and may be undergoing several phases of decomposition at once, so the power output of the plant also varies somewhat throughout the year, ramping down to sometimes as low as 85 percent of the plant's capacity, but generally LFG serves as a steady baseload. Each project is a combined-cycle application that uses one or more gas engines, combined with a steam turbine that uses the gas engine's exhaust to create additional electricity.

IV. Ancillary Services

Planning and installing enough generation capacity to meet San Diego's electricity demand is indeed a fundamental component to our 100% renewable power system design, but ancillary service grid support will be equally essential for providing real-time stability correction throughout the network. Traditionally, ancillary service operations provide frequency response (including frequency control, load stability, and operational reserves), voltage control, and emergency start-up generation almost exclusively with fossil-fueled technology called operational ramping reserves. Thermal reserve generation is designed to precisely and reliably ramp its generation to fill any minor or major gaps in the balance between load and demand.

In order for renewable energy systems to wholly replace traditional reserves, we will need effective smart control systems integrated into a large majority of our wind, solar, and storage expansions. In our proposed design, we have taken a hierarchical control approach that branches from the most central bus in the transmission network, down to the level of a neighborhood substation. Figure 1 shows a basic representation of how a hierarchical controller is structured.

The original design of our control approach stems from research [10][18] involving curtailment control for generational headroom management. Simply put, curtailment control reduces the intermittency of solar and wind generation output by sometimes operating the plants below 100% inverter efficiency. This leaves enough *headroom* for the power plants to instantly scale up or down their production to meet the demand for ancillary services.

Curtailment of power electronic-interfaced renewable generation would positively support the stability of our grid, but may result in a lack of generation capacity overall. This is why the final control approach we have implemented into our simulation of controlled variable generation does not practice efficiency "shedding" for curtailment. Rather, it operates with output power "splitting" where headroom margins are sent to short-term battery storage. This control method allows us to retain power capacity as well as become even less dependent on decent weather conditions or time of day. The battery systems will also have the capability, when needed, to inject extra power onto the grid and participate in ancillary services.

With smart centralized control and forecasting (described more in depth in section VI) various storage technologies provide two-dimensional stability support through demand response and generation reserve. For specific application to our proposed power system, the centralized controller uses battery storage for ancillary support at the minute or hourly resolution. With reasonable forecasting abilities and the hierarchical computational control, these batteries act as the lowest hierarchical tier of control to smooth the intermittency of wind and solar generation. On more central nodes, gravitational vaults and pumped hydro are used for long-term (seasonal) storage and are signalled for dispatch to replenish depleted batteries, or charge/discharge in extreme cases of load demand.

A. Demand Response Programs

In addition to smart controls and well-designed generation and storage, it is important to take advantage of load management tactics, such as demand response (DR), which can play an important role in reducing the peak load. Well-implemented DR programs can help to decrease stress on the power system, improve economics by demanding less power from expensive peaker plants, and also accommodate shifts in supply due to variable generation from sources such as solar and wind. A demand response program typically incentives customers to implement direct or indirect load control measures by cycling loads such as storage, water heaters, or air conditioners during peak periods [23].

According to the load data, peak load occurs in summer (June, July and August) during the afternoon hours. Historically, the highest temperature tends to range between 72 °F to 77 °F and the lowest from 62 °F to 67 °F, and it is safe to assume that much of this peak load is due to customers turning on their air conditioners. To diminish these large peaks in demand, it is necessary to manage the load by providing incentive plans that encourage consumers to reduce their consumption at such critical times.

To take a closer look, we examined three days in June, July, and August where the demand was particularly high. On June 26, the load increases dramatically from 46.94 MW (above the average of the total load which is 46.5 MW) at 6:00 AM to 94.87 MW at 16:00 PM, and then goes down gradually to be close to the average load. One July 13, the load ramps sharply from 77.05 MW at 9:30 AM to 106.10 MW at 13:10 PM which is the maximum load. On August 13, a similar scenario occurs where load goes up from 76.99 MW at 10:44 AM to 103.05 MW at 15:44 PM, and then goes down gradually to reach the average load. A similar pattern can be observed during most of the summer days. Therefore, a component of our demand response program encourages consumers to reduce their consumption during summer afternoons.

There are many successful demand response programs in widespread use, including the AC Saver and Capacity Bidding Programs, which SSDL&M will adopt to manage our load during the peak periods.

1) AC Saver (Summer Saver) Program: The AC saver program run by the San Diego Gas and Electric (SDG&E) utility for both residential and business consumers offers an annual credit to customer bills when they participate in this incentive program. Such a program can help to manage air conditioning load during the summer season (April through October). Once the consumer signs up for the program, a third-party company will install the AC saver device at no cost. It is a small wireless device that installs near the central A/C to cycle the cooling function on and off for a periods of 1 to 4 hours. The customer can earn different amounts of credits on their annual bills based on the enrollment options, which are 50% to 100% cycling for residential, and 30% to 50% cycling for business. Therefore, for the convenience of consumers, pre-cooling is a good choice to make sure the desired temperature is reached before peak load occurs. Thus air conditioning load is shifted to an earlier time, mitigating stress on the power system [1].

2) Capacity Bidding Program (CBP): Many utilities in the U.S. and abroad have demonstrated the success of a Capacity Building Program (CBP), which also helps to manage load at peak periods. When the load is at peak, the utility will ask the consumer to reduce their consumption for 2-4 hours that day. The customer can participate under a day-ahead option, where the consumer gets notice the day prior to the event, or a day-of option, which would be 2-3 hours prior to the event. Any consumer who participates in this program will receive a credit or payment. Utilities such as SDG&E have successfully used CBP to lower peak demand [5].

V. Storage

The inclusion of energy storage technologies in the electric grid allows for increased penetration of wind and solar generation. Consequently, energy storage is especially necessary for a power system to become 100% renewable as the variable generation of wind and solar cannot match the load like thermal plants can. When designing such a system, the amount of storage needed for a system is determined alongside the capacity of variable generation, as both times of excess generation as well as an insufficient (i.e. unmet load) need to be considered. In Figures 2 and 3, the "Net" curve represents these values; it is positive when there is unmet load and negative when there is excess generation. This curve will directly correlate to the storage behavior, as the storage system will charge up when there is excess generation and discharge when there is unmet load. For an ideal system, the area under this net curve (measured in MWh) should be close to zero but trend towards being more negative because a positive overall net load indicates that there is not enough total generation to cover the total load.

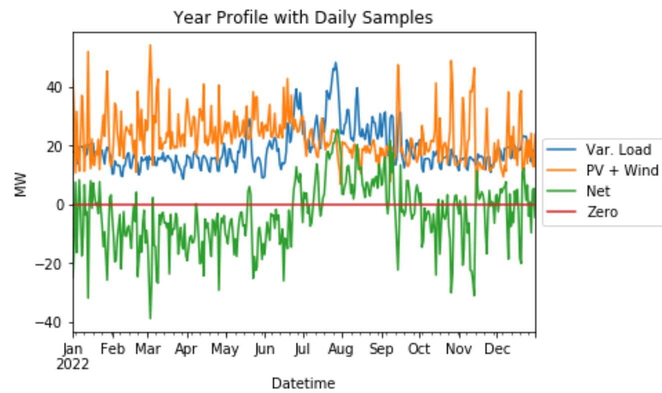


Fig. 2: Graph depicting Variable Load, Net Load, and Renewable Generation over a year, resampled as daily data for clarity. Var. Load represents the load minus the baseload generation (LFG). Net is the Var. Load minus the renewable generation, and it represents the storage behavior

A. Storage by Timescale

As seen in Figure 2, the year can be split up into three sections dictated by the net curve: negative until May, positive between May and October, and then negative after October until December. Visually, it is apparent that there is enough excess generation early in the year that can be stored to cover the peak season. This is mathematically evident by the calculations shown in Table III. These numbers show that our energy storage system must store at least 10,648 MWh during Jan-May in order to reach the demand of the peak season.

Season	Net Storage (MWh)
Jan-May	-35,065
June-Sept (Peak)	10,648
Oct-Dec	-8,839
Total	**-33,256**

TABLE III: Net Possible Storage by Season

Aside from long-term seasonal storage, utilities need to consider how to meet the demands at a weekly, daily, and hourly level. This analysis is shown in Table IV, after finding the most demanding time periods throughout the year that must be accounted for. The table provides the amount of storage we need to have on hand at critical times of operation and will inform the scale and type of storage we need to meet this demand.

B. Storage Technologies Employed

As stated previously, we must have at least 10,648 MWh of seasonal storage in order to meet the peak season's demand.

Timescale	Max Storage Needed (MWh)	Date
Weekly	1,541	7/31-8/6
Daily	616	7/28
Hourly	121	8/13 @ 3pm

TABLE IV: Net Possible Storage by Timescale

This number climbs to about 13,310 MWh after considering the round-trip efficiency of 80% of our seasonal storage technology, pumped hydro [11]. We can easily meet this energy capacity using our acquired Lake Hodges Pumped Storage facility from SDG&E, which features a nominal power capacity of 40 MW and energy capacity of 32,000 MWh [16]. Pumped hydro is an effective technology for long-term storage because other than the evaporation of water and catchment area/equipment maintenance requirements, it does not degrade over time. While this large amount of storage seems sufficient, we would be limited by its 40 MW power capacity as well as having no back up in case a line goes down running from this facility. For this reason, we suggest adding a second transmission line to Lake Hodges for redundancy. Pumped storage also has a response time of about 90 seconds, which is sometimes too long when there is an unexpected spike in the load.

Another long-term storage system we have in conjunction with pumped storage is gravity storage, referring to the technology developed by the company Energy Vault. Their gravity storage technology includes a giant crane that builds up a building of concrete blocks to store potential energy and then lowers the bricks to turn a generator to create electricity. We have employed two 20 MWh and two 35 MWh gravity systems, each with a nominal power capacity of 4 MW [19]. This technology is unique in that it takes up a relatively small amount of space compared to pumped hydro with minimal environmental effects, and it has a much faster response time of about 2.9 seconds. It also does not degrade over time and has a round-trip efficiency of 80-90%. This gravity storage is ideal for contributing to the weekly, daily, and even hourly demand of the load, as we have can have our four units spread out to reduce transmission costs and to increase the redundancy and reliability of our system. The fast response time allows us to use it for short and medium term ancillary services in addition to long-term storage.

Considering both of these technologies, we have a total of 32,110 MWh of energy and 56 MW of power from storage. This gives us plenty of wiggle room in terms of energy, but it leaves us short in power during our peak season. We need to have more power to meet the high demands during the peak season, with the highest net load occurring on August 13th at 3:00pm at 67.96 MW when solar generation drops and the afternoon load is high, shown in Figure 3.

Our final storage technology includes ten Tesla Megapacks with 2.514 MWh of energy capacity and 1.257 MW of AC power each [24]. Tesla Megapacks are slightly cheaper than gravity storage, have a faster response time of less than 1s, have a round trip system efficiency of 87%, and are smaller-scale. This allows us to strategically place them around the grid for reliability and ancillary services. Although they do

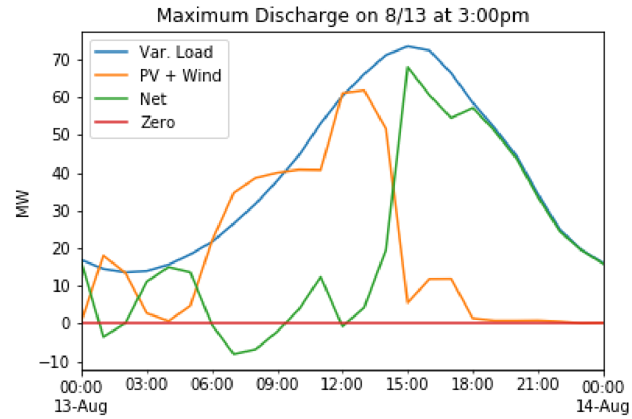


Fig. 3: Graph depicting the maximum demand that our storage must meet when renewable and baseload generation aren't sufficient. Storage must discharge a maximum of 67.96 MW

degrade over time, these lithium-ion batteries are necessary for us to reach the peak net load of 68 MW in the summer. The addition of these batteries brings the total energy and power capacities to the values shown in Table V.

Storage Technology	Quantity	Energy (MWh)	Power (MW)
Lake Hodges Pumped Storage	1	32,000	40
Energy Vault Gravity Storage	4	110	16
Tesla Megapack	10	25	13
Total	**15**	**32,135**	**69**

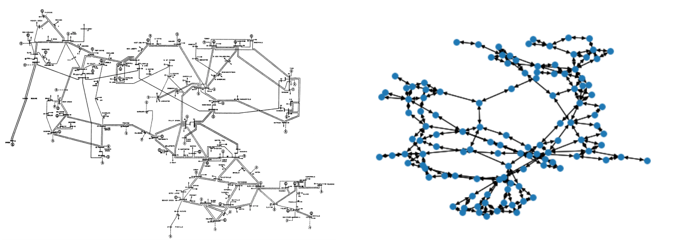
TABLE V: Total Storage System Values

VI. Computational Dynamics & Simulation

Re-configuring San Diego's existing transmission and distribution systems is certainly not within our budget and likely could not be accomplished by 2022. Therefore, as we replace large amounts of generation capacity in the area, we must ensure that it remains compatible with the transmission backbone of the grid. The following analysis in this section assesses the effectiveness and stability of our power system model by fitting San Diego's instantaneous load, solar irradiance, wind availability, and general load profile onto the accredited IEEE 118 bus, DC-optimized power flow, test power system. Each bus in the test power system admittance matrix has been assigned topological and geographical correlation to the data from real locations in San Diego as suggested in Figure 4.

The hierarchical control method mentioned earlier and illustrated in Figure 1 has been applied throughout this power system. The topological layout of the controls was established through network centrality metrics (summing across the transmission connections in the admittance matrix) to establish a ranking of the most central and least central busses. The framework applied to this branching structure of control has to numerically find equilibrium in real-time before continuing to the next time increment.

The operational logic of this "smart system" progresses as follows for each time interval. Initially, the centralized control sends out generation request signals down the hierarchical tree based on the predicted load demand (forecasting was



(a) IEEE 118 Test Power System **(b)** Computational Mesh Interpretation assuming lossless lines

Fig. 4: IEEE 118 bus, DC-optimized power flow, test power system. Geographical parameters and characteristics for San Diego have been encoded into the behaviors of each node

simulated by reading ahead in the data and adding noise to impersonate reasonable forecasting abilities). Every node that does not have enough resource availability (solar irradiance, wind speed, etc.) to meet its requested generation level then asks its "parent bus" for generational support. The parent node either taps into any assigned battery storage assigned to the bus, finds an alternative "child" generator that has the ability to overcompensate for the lacking generator, or again asks a more central parent node for help. These decisions are recursively called upwards until load demand is satisfied or the executive chain hits the central controller (which has no parent).

Operating the storage of the power system as ancillary support is the more computationally expensive task in the simulation due to charging rates and implementing effective storage for longer-term dynamics. Battery charging and discharging decisions are initially queued ahead of time from the load forecast, and adjusted to the small amount of forecasting error closer to real-time. Seasonal storage is used to "reset" the system from the hours of 2am to 5am. The reset is able to meet the small load demand while equilibrating all battery storage stations back to 50% capacity. This method makes the system very flexible for unexpected load peaks and substitutes well for the general lack of solar irradiance in the winter.

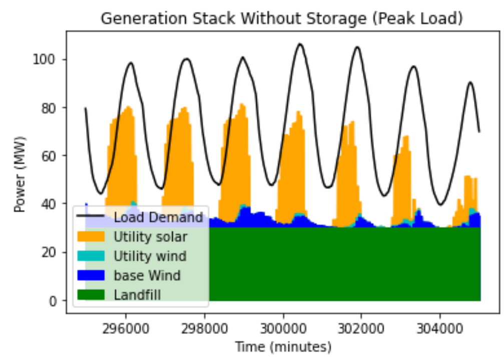
The DC-optimized power flow is a common approximation done in power systems research and industry analysis, however we need to double check that our system harmonics will not blow up. To measure this in our simulation, we added an additional "infeasible solution" infinite capacity storage source. With this we would have seen any instances in our generation dispatch results if our system was unable to satisfy load demand.

Additionally, we have had some previous experience in network dynamics and modelling the Kuramoto model, so we have included a brief extension to this project that would investigate the frequency stability of the oscillating system. The Kuramoto model is a second order power solution for dynamical networks that keeps track of the phase variations across generators in the transmission system. [9] goes further in depth into the derivation of the model, but frequency oscillations follow the second-order relationship:

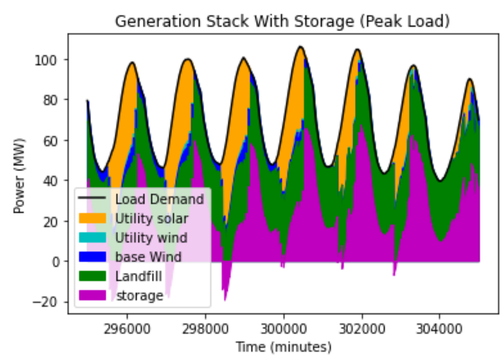
$$\frac{d\omega_n}{dt} = P_n - \alpha_n \omega_n + \sum_{m=1}^{N} K_{nm} sin(\theta_m - \theta_n) \qquad (1)$$

where P_n is the power output value associated with node n, α_n is a damping constant, and the term $\sum_{m=1}^{N} K_{nm} sin(\theta_m - \theta_n)$ is the "coupling factor" of the influence from other transmission connections of n. Control boundaries around 59.4 Hz could be set to request the system maintains frequency around 60 Hz, and contingency responses of the system could also be achieved through frequency harmonics.

The final results of the dynamic simulation of our 100% power grid have suggested very promising results. The hierarchical control strategy with which our smart power system will operate has managed to meet load with zero infeasibilities during the DC optimized power flow approximation. Figure 5 shows the generation stack results of our model during the last week of July.



(a) Standard generation stack without storage

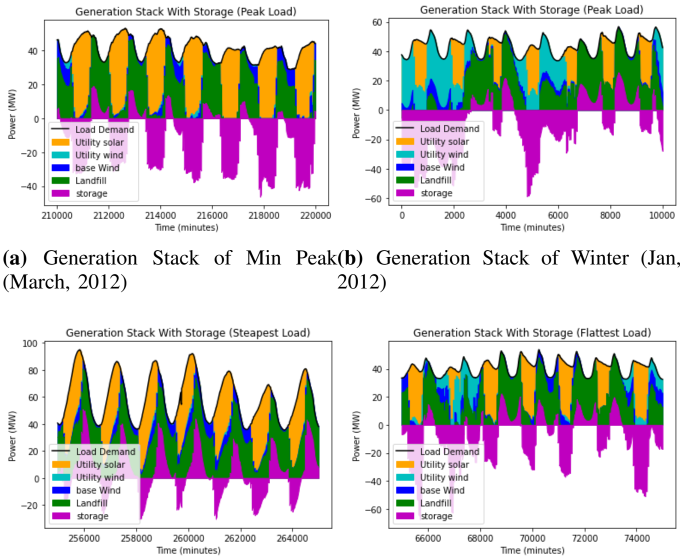


(b) Generation stack with storage

Fig. 5: Generation stack of power system satisfying peak load demand at the end of July.

Subfigure 5(a) shows our generation stack in the familiar fashion that does not consider storage support, and subfigure 5(b) visualizes how demand response and computationally-timed discharging of storage fits our generation inconsistencies to even the most extreme load demand curves with precision. Figure 6 illustrates how the charging to discharging ratio is heavily dependent on the profile of resource availability during different seasons.

At first glance it is clear that in a large majority of non-extreme, peaking load demand, summer months cause seasonal storage to net charge, which is unlike what is seen in Figure 5(b). In all cases, it is clear that the technology of our system is now successfully satisfying the load of our small San Diego grid.



(a) Generation Stack of Min Peak (March, 2012)

(b) Generation Stack of Winter (Jan, 2012)

(c) Generation Stack of Extreme Ramping Load (April, 2012)

(d) Generation stack of Min Ramping Load (September, 2012)

Fig. 6: Additional generation stacks of power system comparing low peaks and the spectrum of ramping load.

VII. Results & Economics

As with any utility upgrade, cost is a major concern of transitioning to a fully renewable system. Since we are assuming that we already have a distribution network in place, the main cost will be associated with deploying assets - both generation and storage, plus some smaller costs for transmission from far-flung solar and wind resources to the city center. The cost of deploying generation assets is highly variable, and the costs of solar and storage are both dropping rapidly, so it is difficult to pin down an exact price for asset deployment in our system. However, we can make the following estimates:

Solar: The average price of utility-scale solar sized in the 50-100 MW-AC range installed in the United States in 2019 was $1.4/W [26]. Our 50MW-AC/60MW-DC solar installation is on the the small side of this range, however, solar prices are dropping rapidly so it seems reasonable to assume the project can be installed for this price. This results in a $70 million installation. Additionally, projects installed in 2019 saw an average operations and maintenance (O&M) cost of $17/kW-DC/y and an expected lifetime of 32.4 years. This totals out to a cost of $103.05 million over the life of the project, or $3.18 million per year and a levelized cost of energy (LCOE) of $24.565/MWh. Rooftop solar is more variable in cost, but can generally be deployed for around $3/W [7]. Therefore the additional 16 MW that will be added will cost$48 million. O&M is even more difficult since most pricing information available is for individual systems, while the large utility-owned portfolio will likely benefit from an economy of scale. Therefore, we assume that the O&M cost will be double what it is for utility scale systems just like the install cost, resulting in an annual cost of $32/kW/y for a LCOE of $107.51/MWh

Wind: The wind system being deployed consists of a single 20 MW project plus 4 additional 10 MW projects scattered around the hills to the East of San Diego. The average installed cost of wind in 2018 was $1470/kW [27]. While these numbers appear the be dropping slightly, the above listed sizes are on the small side for wind farms, so it is likely the cost of deployment will stay close to this number, resulting in a capital cost of $88.2 million. Average O&M costs for wind have remained steady at $29/kW/year for the past two decades. There is less data on other annual costs such as personnel and land lease costs, but EDPR estimates these two line items to average $24/kW/year for their US portfolio. Therefore the estimated price will come out to about $53/kW/year. With the average wind turbine lasting 20 years with proper O&M[13], the expected cost would be $151.8 million over the life of the projects, or $7.59 million per year. This results in an LCOE of $86.73/MWh.

Landfill Gas: Larger generators, such as those used in our projects, typically cost about $1,700/kW, with annual operation and maintenance costs of $180/kW. The average landfill can produce enough methane to power a landfill gas plant for 20 years, making the LCOE $32.49/MWh [17].

Battery and Gravity Storage: Deployment of Tesla Megapacks costs $300/kWh including 15 years of O&M, so the 10 packs will cost $7.5 million resulting in a LCOE of $1158.3/MWh. Energy vault gravity storage is too new to get accurate installed cost numbers, however, the company asserts that their gravity storage has an LCOE of $0.05/kWh [3], so that number will be used for LCOE calculations.

Pumped Hydropower Storage: The pumped hydro used in our simulations is based on the existing system at installed at Lake Hodges. As such, realistically the capital cost associated with procurement would likely be structured as a PPA or some sort of long-term lease agreement. That said, in order to compare the cost of pumped hydro deployment to the cost of the other resources in play it's best to represent the cost of pumped hydro as if it is being purchased outright. The Lake Hodges pumped hydro project cost was $196 million [16] as of its completion in 2011, or $226.89 million in 2020 dollars. This is a somewhat steep price compared to the other assets listed, but pumped hydro has a much longer lifetime than the other technologies, meaning that it can be expected to perform for 50-150 years with little to no degradation in performance [15] resulting in a $2.27 million annual cost assuming that the installation lasts another 100 years. This brings the LCOE to $85.27/MWh.

Market Structure: Energy market structure is an important topic to consider when determining a utility's expected profits. The conventional market structure in the United States is, much like the grid, built on the assumption that all resources bidding in to the market are dispatchable. Therefore, a generation system that is mostly based around variable generation will need to be structured differently. Our proposed model is that all generation will be deployed on a PPA basis, with ancillary services such as storage and the additional ramping capacity of the baseload plants bidding in as they are able to provide services, and getting paid to be on standby where applicable.

The resulting LCOE of all the above sources of energy and storage is $61.81/MWh or 6.2 cents/kWh. This would be equivalent to the base PPA rate. For the ancillary service market, SDG&E currently charges 28 cents/kWh to its lowest tier of energy users [22], so with these energy costs it is very reasonable to continue charging this rate and setting aside 21.8 cents/kWh - totalling in a $88.9 million in 2022 - for paying for ancillary services, operations and transmission costs.

VIII. Future Improvements

As the demand grows in the SSDL&M service territory, future improvements and expansions will need to be made to the generation and storage assets powering the grid. One such proposed improvement is a new wave power plant to be located outside San Diego bay. An environmental impact statement is already under-way for the 3-MW pilot plant, which is expected to be completed in five years. Subsequent phases of the wave power project will expand the project in future years. We also plan to acquire and retrofit another potential pumped hydropower site for future additional seasonal storage and power backup. Additionally, as battery and fuel cell storage becomes cheaper, more storage capacity will be added to the existing storage plants to offer more energy storage, fast frequency response, synthetic inertia, and other grid services. Additional storage will also mean less reliance on LFG as a baseload technology.

Finally, our utility plans to continue to be at the cutting edge of smart grid technology, starting with our curtailment and control of renewable generation. As our utility embraces more advanced controls in the future, more benefits will emerge, such as being able to control the charging and discharging of electric vehicles. We will continue to research and adopt technologies that support a more reliable, renewable grid into the future.

IX. Conclusion

There are many challenges to designing a fully renewable grid when the current system is based on dispatchable generation with spinning inertia. That said, our ability to meet a significantly sized load for an entire year at a reasonable cost shows that it is possible for utilities to make the change, and the rapidly changing climate shows that they must.

References

[1] *AC saver (Summer Saver)*. 2020. URL: https://www.sdge.com/residential/savings-center/rebates/your-heating-cooling-systems/summer-saver-program.

[2] *Annual Rainfall - Lindbergh Field*. 2020. URL: https://www.sdcwa.org/annual-rainfall-lindbergh-field.

[3] Rina Diane Caballar. *Beyond batteries: How new technologies are fueling energy storage*. 2020. URL: https://www.hpe.com/us/en/insights/articles/new-technologies-fueling-energy-storage-2009.html.

[4] *California Biomass and Waste-To-Energy Statistics and Data*. 2019. URL: https://ww2.energy.ca.gov/almanac/renewables_data/biomass/index_cms.php.

[5] *Capacity Bidding Program*. 2020. URL: https://www.sdge.com/businesses/savings-center/energy-management-programs/demand-response/capacity-bidding-program.

[6] *Cities 'could generate hundreds of times more solar power than they do today'*. 2020. URL: https://pv-magazine-usa.com/2020/06/01/cities-could-generate-hundreds-of-times-more-solar-power-than-they-do-today/.

[7] *Cost of Solar*. 2020. URL: https://www.sunrun.com/solar-lease/cost-of-solar.

[8] Paul Denholm et al. *Land-Use Requirements of Modern Wind Power Plants in the United States (NREL/TP-6A2-45834)*. Tech. rep. National Renewable Energy Laboratory, Aug. 2009.

[9] Florian Dörfler and Francesco Bullo. "Synchronization and Transient Stability in Power Networks and Nonuniform Kuramoto Oscillators". In: *SIAM Journal on Control and Optimization* 50 (2012), pp. 1616–1642.

[10] Vahan Gevorgian. "Highly Accurate Method for Real-Time Active Power Reserve Estimation for Utility-Scale Photovoltaic Power Plants". In: (2019).

[11] Omar J. Guerra et al. "The value of seasonal energy storage technologies for the integration of wind and solar power". In: *Energy Environ. Sci.* 13 (7 2020), pp. 1909–1922. DOI: 10.1039/D0EE00771D. URL: http://dx.doi.org/10.1039/D0EE00771D.

[12] Lisa Halverstadt. *Rooftop Solar Doesn't Help SDG&E with Clean Goals*. 2015. URL: https://www.voiceofsandiego.org/topics/science-environment/rooftop-solar-doesnt-help-sdge-with-clean-goals/.

[13] *How long does a wind turbine last?* 2020. URL: https://www.renewablesfirst.co.uk/windpower/windpower-learning-centre/how-long-do-wind-turbines-installations-last/.

[14] *IEEE 1547-2018 - IEEE Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*. 2018. URL: https://standards.ieee.org/standard/1547-2018.html.

[15] Tietze A Immendoerfer et al. "Life-cycle impacts of pumped hydropower storage and battery storage". In: *International Journal of Energy and Environmental Engineering* 8 (Sept. 2017), pp. 231–245.

[16] *Lake Hodges Project Begins Pumped Storage and Power Generation Operations*. 2011. URL: https://www.sdcwa.org/node/2691.

[17] *Landfill Gas Energy Basics*. 2020. URL: https://www.epa.gov/sites/production/files/2016-07/documents/pdh_chapter1.pdf.

[18] M. El Mokadem et al. "Experimental study of variable speed wind generator contribution to primary frequency control". In: *Renewable Energy* 34 (2009), pp. 833–844.

[19] *Operating Parameters*. 2020. URL: https://energyvault.com/.

[20] Landfill Methane Outreach Program. *LFG Energy Project Development Handbook*. Tech. rep. US Environmental Protection Agency, Mar. 2020.

[21] *San Diego Solar Power Information and Peak Sun Hours*. 2020. URL: https://www.turbinegenerator.org/solar/california/san-diego/.

[22] *Standard Plan*. 2020. URL: https://www.sdge.com/residential/pricing-plans/about-our-pricing-plans/standard-rate-plan.

[23] Joel N. Swisher. "The Role of Demand-Side Resources in Integration of Renewable Power". In: *ACEEE Summer Study on Energy Efficiency in Buildings* (2012), pp. 300–413. URL: https://www.aceee.org/files/proceedings/2012/data/papers/0193-000178.pdf..

[24] Tesla. *Megapack*. Tesla Megapack datasheet. 2020. URL: https://www.intermepro.com/wp-content/uploads/2020/07/Datasheet_Megapack.pdf.

[25] *U.S. State Greenhouse Gas Emissions Targets*. 2020. URL: https://www.c2es.org/document/greenhouse-gas-emissions-targets/.

[26] *Utility-Scale Solar Data Update: 2020 Edition*. 2020. URL: https://emp.lbl.gov/sites/default/files/2020_utility-scale_solar_data_update.pdf.

[27] Ryan H. Wiser and Mark Bolinger. "2018 Wind Technologies Market Report". In: (2019). URL: https://escholarship.org/uc/item/2tc1819q.