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Development and Deployment of an Integrated Microgrid Incorporating Solar PV, Battery Energy Storage and EV Charging

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Abstract—High penetration of intermittent renewable energy creates challenges to system integration. Large solar production during the day shifts peak grid demand to evening hours. These along with random nature of EV charging require distribution scale testbed for thorough analysis. In this paper a larger testbed system that is developed and deployed at the University of California, Riverside (UCR) is described. The technical challenges to implement this testbed and make it operational are discussed. A multiobjective problem is formulated and strategies based on that are developed for the implementation of three microgrids. Operational results and environmental benefits are presented including a zero net energy building (ZNE), battery energy storage, peak shaving to help the local utility on their historic highest demand day**.**

Keywords—Sustainable integrated grid, EV charging, battery energy storage, zero net energy building, renewable energy optimization.

I. INTRODUCTION

For a sustainable future renewable forms of energy are the only viable energy resources. Fossil fuel has been predominant for many years as a source of energy, but it's future use is declining due to adverse impact on environment. Many advanced economies are moving away from conventional energy resources and utilizing more and more sustainable green energy. Policy makers have been making strict rules against Carbon di oxide and other greenhouse gases produced by fossil fuel generated electricity. Renewable energy such as solar and wind energy have become economically and technically viable alternatives.

Renewable energy integration to the grid has always been a challenge from the very beginning due to it's intermittency and cost. The deployment of existing, industrially proven technologies at an unprecedented scale and pace, from now to 2050 as many experts suggest to reverse the impacts on the environment, is a daunting task. Optimal storage and load management strategies offer most opportunities for this massive scale renewable energy integration.

California is the predecessor in increasing the percentage of renewable electricity all over the state. California has been promoting renewable energy adoption as a solution of environmental issues for a long time. In 2002 they set a goal of 20% retail sales of renewable electricity by 2017.The state accelerated the goal a year later and set it 20% by 2010. The most recent clean energy goal set in 2018 is 60% renewable by 2030 and 100% renewable energy by 2045 [1]. This commitment will make California the biggest economy of the world with 100% of renewable energy. University of California with 10 campuses has set its goal even higher at 100% clean energy by 2025. UC will no longer use fossil fuel for water heating by June 2019 for any new or renovated building [2].

Solar production is abundant during daytime, thereby reducing the net load which peaks traditionally in the hot summer afternoons due to air conditioning load. But solar production becomes lower towards the evening while offices, businesses, industries and homes are continuing electricity use. This causes rapid increases in the net load demand creating daily peak in the evening as shown in orange in figure 1 for CAISO on July 24, 2018 [3]. Solar and wind production for that day is shown in grey and the total load is shown in blue. The net load curve in figure 1 resembles the shape of a duck and is commonly referred to as "Duck Curve".

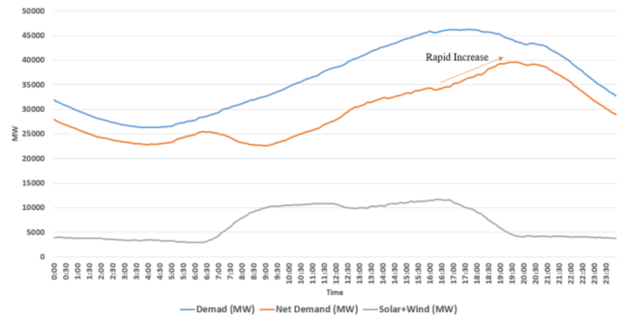

Fig. 1. Duck Curve of California CAISO on July 24, 2018

Many megawatts are needed to be added into the power grid within a couple of hours at a rapid ramping rate. This ramping issue is one of the biggest challenges faced in a grid with high solar penetration. As a result, electric grid operators are progressively increasing cost of electricity and shifting demand charges for the peak period from summer afternoon to evening. The rapid increase in production needed to compensate the lack of solar production requires large number of traditional generators to continuously maintain capacity margins. This spinning reserves or gas fired peaker generators are needed to ramp up quickly. As these generators are needed to run only for a few hours a day, they are economically inefficient.

Storing surplus energy during good solar production at daytime and using it in the evening can help to reduce the problems associated with rapid ramping. Large scale battery energy storage are only becoming practical due to recent availability of li-ion batteries. These batteries are also making driving range for electric vehicles longer and more affordable. These cutting edge technologies offer opportunities for complementing each other including incorporating Time of Use (TOU) rates offered by the electric utilities. Distribution scale testbeds need to be implemented to deploy and demonstrate the practicality of this approach. Electric utilities are typically very conservative in nature. They will only adapt new technologies in their complicated grids if it has been successfully demonstrated somewhere before.

This paper describes the testbed and integration of solar, battery, EV and building load that has been implemented at the College of Engineering - Center for Environmental Research and Technology (CE-CERT) in UC Riverside. Prior works typically involve a single technology deployment or smaller scale multi-technology deployment in a laboratory environment. Multiple distribution feeder level microgrids have been implemented at UCR's Sustainable Integrated Grid Initiative (SIGI) Testbed.

II. System Description

CE-CERT at UCR has three microgrids with an aggregated capacity of : 500 kilowatt (kW) solar PV carport system, 2.08 Megawatt-hours (MWh) battery energy storage systems, diesel Trolley Bus conversion to electric drive (500 kWh), and four level 2 charger stations and one Level 3 fast DC electric vehicle (EV) charger [4].

The CE-CERT facility is supplied by two independent feeders and two transformers, with a total metered capacity of 3,400 A at 480 V 3-Ph allowing for managed energy profiles greater than 1.0 MW. The microgrid has spare capacity to integrate up to 750 kW of instantaneous power and several MWh of storage capacity.

This integrated renewable energy system as shown in figure 2, has created a unique fully instrumented utility-connected smart-grid research testbed coupling energy generation, energy storage, and electric transportation.

This testbed has been operational for over three and a half years, and is one of the most versatile of its kind, featuring: 1) easily interchangeable technologies to demonstrate new prototypes; 2) highly re-configurable switching systems to route energy through different buildings (e.g. research laboratories, industrial facilities, and office buildings); and, 3) an open source control platform to optimize operations for different strategies (e.g. minimize electricity costs, demonstrate zero net energy (ZNE) operation with or without exporting any power to the grid).

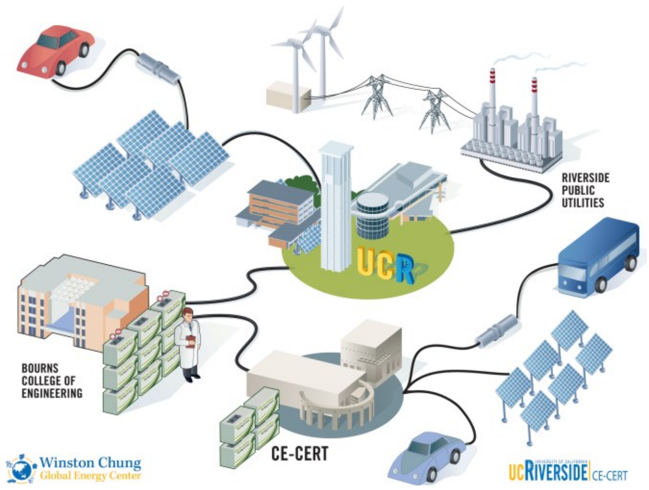

Fig. 2. Sustainable Integrated Grid Initiative (SIGI) Microgrid

TABLE I Characteristics of Three Microgrids

Building	Solar (kW)	Battery	EV
Admin	180	500 kWh (trolley)	Yes
APL	180	No	No
CAEE	100	Trolley + 1 MWh	Yes

The testbed continuously collects a wide array of information on the performance and characteristics of each component to help evaluate the benefits of various strategies under different conditions. Energy use is continuously monitored within the research facilities in conjunction with the distribution feeder and the overall utility grid. Smart grid management decisions are implemented and utilized to maximize grid stability, reliability, and efficiency. Strategies, protocols, and methods have been developed, explored, and documented relative to emissions reductions, cost, and effectiveness while supporting EV charging events.

III. Technical Challenges for Adoption

Several technical challenges were faced while the microgrid integration was being done. One of the technical limitations was the size of the inverter. Though the solar production from the strings of panels totals to a value of 500 kW, the three inverters produce a total output solar power of 460kW. Due to the limitation of the inverter size, the output solar production of CAEE building is curtailed and a sizable amount of solar generation is unusable due to this limitation. Another technical challenge is the faulty batteries in the battery energy storage systems. It is difficult to find batteries with similar state of health. When connecting them together in series, similarity in state of health is crucial. Only one faulty battery in the connection can damage the entire system. To prevent this type of event, each battery was charged and discharged individually and their voltage and current measurements were taken at every 3 minute interval. Then by analyzing their charge/discharge profile the faulty batteries were detected and discarded. Another concerning issue was the control of charging/discharging of the trailer battery. In order to do charging/discharging in an intelligent manner, a PID algorithm was written for this purpose. The code written for this algorithm contained several bugs. Before applying the code on the controller, simulations were done to see how the code performs. The bugs were removed one by one based on analyzing the results from the simulation.

Integration of a microgrid is not an easy task and can pose numerous technical challenges. As we can see from the experience of integrating the SIGI microgrid, some challenges are due to the limitation of available resources and cannot be solved unless the required procurement or system upgradation is done. Other ones can be solved with following some steps like testing, analyzing and taking proper measures to address these challenges.

IV. Problem Formulation

The three microgrids have been used for different purposes. Admin building has been used for regular office work whereas the APL and CAEE mainly provide the research facilities for CE-CERT researchers and students. Hence, the main purpose for three microgrids varies, so the zero net energy goal has been only implemented in admin building. A multiobjective problem has been formulated for admin building whereas a single objective problem has been considered for the other two microgrids. The objectives and constraints for the three microgrids are given as follows.

Objective 1:

$$\text{minimize} \sum_{i=1}^{n} E_{net,i}$$

Objective 2:

$$\text{minimize } [(\sum_{i=1}^{n} CE_i \times E_{net,i}) + (CD_i \times \max(P_{net,i}))]$$

Constraints:

1. $P_{net} = P_{G2B} + P_{G2V} + P_{BC} - P_{BDC} - P_S$
2. $E_{net} = P_{net} \times \Delta t$
3. $(\sum_{i=1}^{n} E_{net}) \leq 0$

where,
i= index of a time slot
n= total time slots
Δt = Time interval
P_{net} = Net Power
P_{G2B} = Power delivered from grid to building
P_{G2V} = Power delivered from grid to vehicle
P_{BC} = Charging Power for Battery
P_{BDC} = Power discharged from Battery
P_S = Power generated due to solar
E_{net} = Net energy
CE_i = Energy cost at ith instant
CD_i = Demand cost at ith instant

The goal of the first objective is the reduction of net energy over a time period for the first microgrid. The second objective includes the minimization of electricity cost for a fixed billing cycle. While the first objective is dedicated to admin microgrid, the second objective is common for all three microgrids.The first constraint calculates the net power for any microgrid. The exported power includes the battery discharging power and solar production during any given time slot. The imported power equals to the power required for the building load, battery charging and EV charging. The second constraint denotes the net energy calculated for any individual microgrid. The third constraint is required for the first objective to ensure the zero net energy.

V. Proposed Strategy

Two scenarios have been considered to develop the strategy for the microgrids. For the admin microgrid, the two scenarios are 1) while the remote storage (trolley) is not available and 2) while the trolley is available.

1) While the remote storage (trolley) is not available

With a view to reducing both energy and electricity bill, the proposed strategy for admin microgrid is shown in figure 3. At first, the net power is calculated. If it ensures that it is lesser or equal to zero, then the time of day is being checked. If the time period is on-peak, then HVAC and building load control is turned on. On the other hand, Plugged-in electric vehicles are being charged during off-peak hours. If the net power is greater than zero, then EV charging is halted and plug-in loads are being controlled.

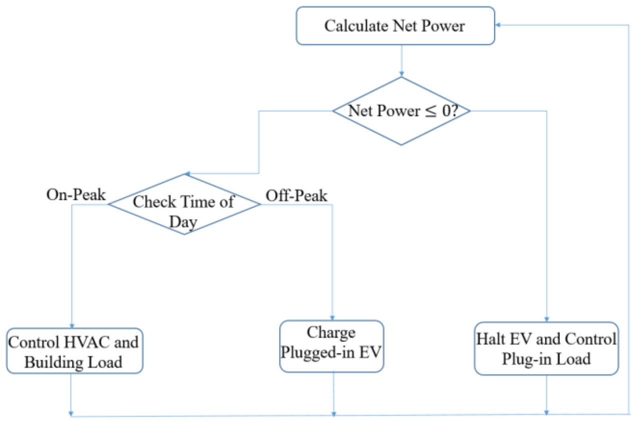

Fig. 3. Admin Microgrid Proposed Strategy: While Trolley is unavailable

2) While the remote storage (trolley) is available

The proposed strategy for admin microgrid with the consideration of availability of trolley is shown in figure 4. At first, the net power is calculated as before. If it ensures that it is lesser or equal to zero, then depending on time schedule, batteries are being charged and discharged along with HVAC and EV charging control strategy. If the net power is greater than zero, batteries discharge power to make the net power below zero.

The other two microgrids follow the same strategy without the net zero energy constraint. As battery and EV are not available in APL, it mostly optimizes it's net uses depending on solar only whereas the CAEE follows the second strategy without the net zero energy limitation.

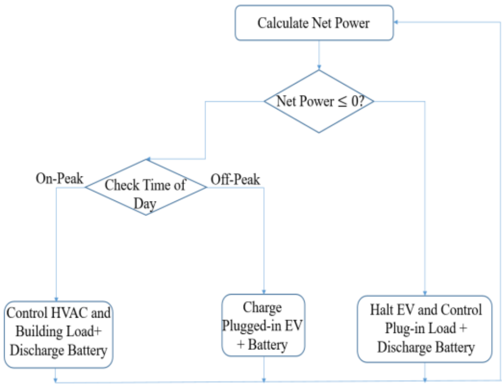

Fig. 4. Admin Microgrid Proposed Strategy: While Trolley is available

VI. Results

The microgrid system of CAEE Building has been a success on saving energy and cutting the cost of the electricity bill. After the implementation of the system in November 2013, it helped to reduce the on peak demand and saved a significant amount of money in in the subsequent months. Table I shows the comparison of the bills of December 2012, 2013 and 2014 respectively. We can see that there is an 88.7% reduction in on peak demand and on peak demand charge in the year 2014 compared to previous year.

TABLE II Comparison of On Peak Demand and Charges from Utility Bills

Billing Month	**On Peak Demand (kW)**	**On Peak Demand Charge ($)**
December 2012	102.0	701.76
December 2013	106.8	734.78
December 2014	12.0	82.56

Figure 5 shows the results of the Administration Building's new configuration with additional PV production, shown in green with 100 kW inverter limiting solar production during mid-day hours. The figure shows actual data for May 3rd and May 4th 2016. The net electricity usage of the building, as seen by the power company meter, is shown in blue. The blue values above horizontal zero axis are energy being imported from the grid at night while, the blue values under zero axis are energy being exported to the grid during the day due to surplus solar production. This building is net zero because the exported energy is equal to or larger than the imported energy usage averaged over a year.

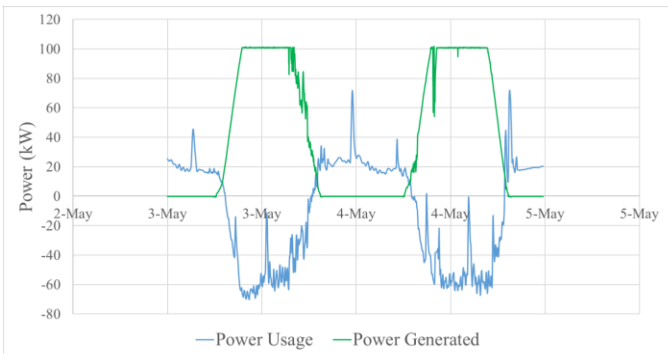

Fig. 5. The net zero administration building: PV generation and usage

Also shown in figure 5 are spikes caused by EV chargers. EV charging impacts negatively depending on it's charging characteristics and real time building load [5-6]. The smaller spikes of between 3 to 6 kW are due to level II chargers or rooftop packaged air conditioning units. The larger 50 kW jumps in power use are due to level III chargers which also causes a high peak demand at night, while the daytime peak is compensated by surplus solar production.

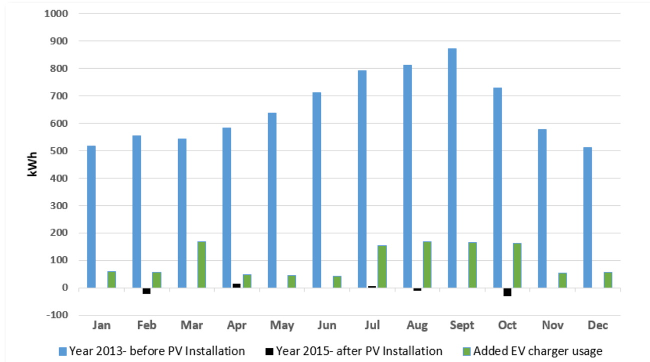

Fig. 6. Net zero demonstration: CE-CERT Administration Building daily average electricity usage from grid before and after PV installation

Figure 6 shows the comparison of daily average loads for the months of a year before and after the PV system was installed. Within the figure, the blue bar represents Administration Building usage without solar during 2013. After solar PV was installed on-site, the black bar is a representation of the building's net usage from the grid. Black bars which are very small in some months are not clearly visible in the plot. The green bars represent additional pass-through energy for four Level II and one Level III EV chargers connected to the building.

The PV installation in Administration building offers beneficial impact to the environment. This helped reduce the carbon dioxide emission by a large factor. After installing the solar the imported energy from the grid was significantly decreased. The local utility company reports that the carbon dioxide emission is 0.879 lbs for each kilowatt-hour energy they produce. The daily average energy consumption over a year was calculated before and after the PV was installed and associated carbon dioxide emission was estimated. The results are presented in table III shown below. An 85% reduction of carbon dioxide emission was achieved through the installed PV of Administration building.

TABLE III Carbon Dioxide Emission Reduction Due to PV Installation in Administration Building

PV Installation State	**Daily average Energy Consumption (kWh)**	**Daily Average CO_2 emission (lbs)**
Before	653.08	574.06
After	98.5	86.58

VII. Helping Existing Grid Operations on Critical Days

In September 14, 2014, triple digit temperatures led to Riverside Public Utilities (RPU) reaching a new all-time high electricity demand of 610 megawatts (MW). In the days to follow RPU send out an appeal to larger customers to conserve electrical energy, specifically between 2 pm to 5 pm. In response, CE-CERT's SIGI Testbed provided the flexibility to not only curtail the nominal power consumption of 365 kW from the three CE-CERT buildings, but also provided 225 kW back to the grid, resulting in a 590kW swing for three hours, as shown in figure 7.

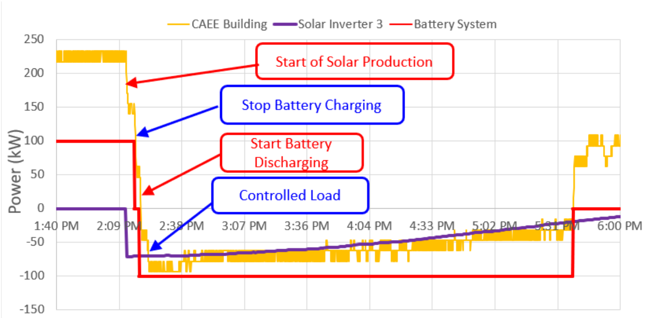

Fig. 7. CAEE Building demand deduction and net power fed back to the grid on RPU's voluntary load shedding request

Similarly, on July 23, 2018, a heat wave caused RPU's system to reach another new all-time high electricity demand of 642 megawatts (MW). This time RPU's request to larger customers was to conserve electrical energy, between 5 pm to 9 pm. UCR's Main Campus chiller cooling system which is a bigger version of CE-CERT's microgrids energy storage, provided the flexibility to shift compressor load operation resulting in a peak of 21 MW to occur at 10 pm instead of 8 pm. The peak during the requested time period was only 13 MW, avoiding a 61% higher peak. Figure 8 shows the operation of chillers in one of UCR campus's main meter on those instances.

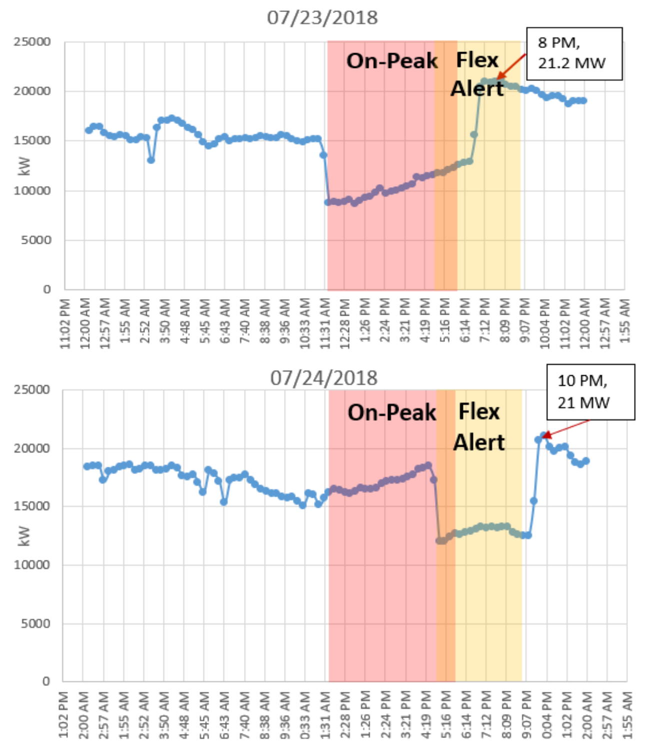

Fig. 8. UCR campus load before and after Flex alert actions

VIII. Conclusion

Sustainable future requires integration of more renewable energy. However, electricity from solar PV and wind are intermittent in nature. High penetration of solar and wind are creating imbalance between timing of production and use. This has manifested itself in California in the form of Duck Curve. A possible solution of a green grid of the future is a sustainable integrated grid incorporating solar PV, battery energy storage, electric vehicles and optimal controllers. At UCR multiple distribution utility scale testbeds were developed to study the challenges faced by a grid of the future. Limitation of available resources presented infeasible challenges while the other challenges were meticulously addressed and solved. Results were presented and discussed from three microgrids composed of the above components. Two prominent features presented are: (1) a zero net energy (ZNE) building, and (2) significant help provided to the local grid operator during their annual peak demand day. The impact of these two were demonstrated through the reduction of carbon dioxide emission by 85 percent and a net load reduction of 590 kW by supplying 225 kW to grid, respectively. This practical demonstration and implementation of distribution level microgrid will surely help to address and overcome challenges associated with green grid activation.

Acknowledgment

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