Role of Electrical Energy Storage in Virtual Power Plants and the Smart Grid

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Abstract: The emergence of renewable energy sources such as solar photovoltaic (PV), presents potential problems for the electrical grid. Peak supply of renewable energy occurs at midday when the sun is at the highest elevation, reducing nonrenewable energy demand for a short period of time. The lower midday demand results in a bimodal energy demand curve typically known as the 'Duck Curve'. The two peaks require coal- and gas-fired electrical plants to startup (at a significant fixed cost) to meet demand, these plants are commonly referred to as peaking power or peaker plants. The large costs associated with short term spikes in energy demand incentivize a solution that shifts energy demand or stores energy for use at other times. Various energy storage systems (ESS's) have emerged to reduce the demand for coal- and gas-fired peaker plants. Renewable energy generation and storage technologies require accommodations for the grid to utilize them properly. Virtual power plants (VPPs) are one option that can allow a utility to manage renewable energy generation and storage. This paper intends to give an overview of the structure and functionality of the 'Smart Grid' before introducing various ESS's with a focus on battery energy storage systems (BESS's). The paper will then cover what VPPs are and the role they play in the electric grid. The aim of the paper is to provide a broad understanding of the management systems within the electrical grid and what capabilities advanced battery management systems offer to improve security, reliability, and overall efficiency.

Introduction

Prior to the introduction of smart meters in 2006, utility companies had very limited knowledge on the electricity consumption of its customers. Electricity demand had to be manually measured and generation had to exceed that demand to prevent brownouts and power outages. All electricity was produced at a centralized power plant and distributed outwards to consumers over power lines. The excess energy had to be burnt off to maintain optimal voltage, current, and frequency. Switches and transformers were manually controlled by dispatched technicians during emergencies and power outages. Very few sensors were deployed along the distribution network and those that were provided very limited insight to grid managers.

Today's "Smart Grid" utilizes modern digital technology and communication networks to provide constant real-time monitoring and remote-control capabilities. Smart meters have been installed on almost every home in the United States, providing real-time usage data that can be aggregated to model total energy demand across large distribution networks. Electricity plants use demand data to adjust output or activate storage facilities to store excess energy in various forms. Remote terminal units (RTUs) provide real time data and remote control of grid elements to its operators, allowing them to make quick changes in the event of emergencies and outages. Sensors are deployed at almost every point of conversion throughout the grid to provide insight into present and future issues that may arise. Central plants, privately owned plants, and consumer owned generation can all be integrated into a single distribution network with new sensors and controls.

One of the most significant changes in recent years has been the broad adoption of distributed energy resources (DERs). Small modular energy generation and storage technologies such as solar panels, wind farms, and large batteries can be classified as DERs. Rooftop solar, home power walls, private solar farms, and gravitational energy storage systems include some of the many DER technologies that have been appearing all over the grid in recent years. Combined with smart home appliances and demand response programs that can be controlled by grid operators, modern technology has presented incredible opportunities for utility companies to create a more efficient and stable electricity grid.

Virtual power plants (VPPs) attempt to aggregate DERs into a single entity that can be controlled through a distributed energy resource management system (DERMS). VPPs can remove the need to individually monitor and control each DER by itself and instead manage the sum as a singular unit. VPPs can be especially useful for residential communities with rooftop solar and battery energy storage systems (BESS's), typically in the form of power walls. Energy storage systems (ESS's) play a significant role in VPP applications by allowing grid operators to "deposit" energy into them during low demand and "withdraw" energy during high demand. The ability to generate and store power creates an opportunity to look at the grid as a large group of small independent modules that cooperate with each other.

This paper will first give an in-depth review of the smart grid and recent advancements before reviewing various energy storage systems and discussing VPPs.

Smart Grid

The US government defined the Smart Grid in the [Energy Independence and Security Act of 2007, Title XIII]. In summary, the purpose of the Smart Grid is to improve grid reliability, security, and efficiency. Digital information and controls should be utilized to dynamically optimize grid operations to maximally utilize energy resources. The deployment of "smart" technologies and appliances such as meters, remote sensors, and scheduled consumer devices should be incentivized. The Smart Grid should incorporate DERs, especially renewable energy generation and storage technologies. The goals require a large communication infrastructure that has been realized through cellular networks such as 5G communication. Many technologies needed to be developed for the vision of a Smart Grid to be realized.

Consumer Technologies

The primary consumer technology during early days of the Smart Grid were smart appliances which offer digital controls that can be accessed by the owner or the electricity provider. The consumer's energy management system (EMS) can be accessed via a smartphone offering remote control of their appliances. Homeowners can turn up their heat from work right before their evening commute or monitor the energy savings from their new dishwasher. Additionally, smart meters provide a gateway into a home's home area network (HAN). The energy provider could delay appliance operations from peak demand hours to low demand hours to improve grid performance and save consumer's money. Advanced heating and air conditioning systems can extend cycle times to prevent usage spikes which can greatly increase efficiencies when implemented across thousands of buildings. Figure 1: Smart Energy Home System below presents an visual from a company that offers an EMS for homeowners. The management system aims to consolidate all the information and controls into a user friendly interface.

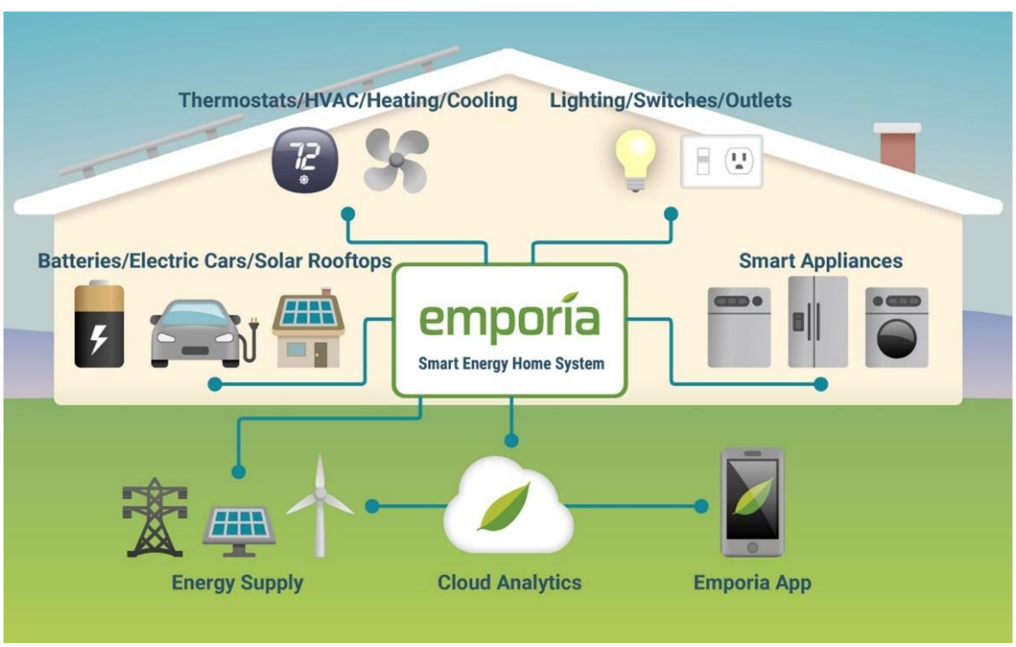

Figure 1: Smart Energy Home System

Early smart appliances could schedule their operations overnight when electricity demand and prices are low. For example, a homeowner loads the dishwasher after dinner and schedules it to run at 2 AM; the same could be done for washing and drying machines. However, as more sophisticated technologies are implemented, consumers can provide a set of constraints to a scheduler. Once the schedule is set, the utility's management systems can optimize the schedules across all households and reliably predict the amount of electricity that will need to be produced.

Traditional consumers have now gained the ability to produce and store their own electricity at scale, creating what are known as prosumers. Prosumers produce their own electricity, but still draw power from the grid when their generation does not meet their demand. A typical scenario involves a homeowner that pays to install solar panels on their roof and possibly a power wall to store some of that energy. These solar panels can meet their energy demands when the sun is out, storing the excess in the power wall. If the stored energy meets their total daily energy demand, the prosumer can sell the excess electricity to the grid to receive solar tax credits. Otherwise, energy will be purchased from the grid. Energy storage offers the opportunity to buy electricity overnight when prices are low and sell electricity during the day when prices are high. This scenario can apply to commercial buildings, farms, and any other entity with access to renewable resources that can generate or store electricity.

Consumers may soon be able to purchase small but economic wind turbines to place on their roofs or apartment buildings. Solar and battery technology continues to get cheaper as software applications improve their performance with the grid. Additionally, small communities and housing developments can work together to form a more cohesive energy system to benefit themselves and the grid. With the introduction of more sophisticated appliances and small energy generation devices, consumers in rural and urban settings can reduce their overall energy consumption and shift their energy usage to more renewable sources.

Utility Technologies

A major goal of the smart grid was establishing two-way communication with as many grid entities as possible. With government assistance, the responsibility of a Smart Grid was given to utility and power companies to integrate new technologies. Smart meters provide two-way communication with consumers; receiving demand data while providing real-time electricity prices and home appliance schedules. However, the traditional grid consisted of many more components that technicians manually monitored and interacted with decades ago.

Remote terminal units (RTUs) offer two-way communication with switches, transformers, and other points of interest in the distribution and generation networks. An RTU is a small computer with networking capabilities that offers remote control of the component it is attached to. RTUs generally have a power supply, a CPU, memory, analog inputs, and outputs, as well as digital inputs and outputs. The units can be as large as a server rack or small enough to fit on a telephone pole. Their broad adoption has laid the foundation for a digital map of electrical grid that can be managed by grid operators.

With RTUs deployed at most switches, transformers, and power converters throughout the grid, supervisory control and data acquisition (SCADA) systems were implemented to manage all of the new information and controls. The SCADA system collects data such as voltage, current, frequency, power demand, temperature, etc. This information can be processed and acted upon by the RTU if needed. Data is then sent to a control center to be combined with other RTUs, processed, and presented to a grid operator who can approve of grid-level operations. More complex systems, discussed later, can also utilize this data. If there is a power outage, the utility can use a SCADA system to identify exactly where and when this outage occurred. Switches can then be remotely controlled to shut off power to this area and redirect it to reduce total customer outages if possible. Overvoltage's can be identified throughout the grid and prevented by controlling switches and transformers to redirect, store, or burn off power when necessary. SCADA systems create a much more robust grid that can identify and fix issues faster.

Utilities have deployed technology that not only improves their customer's experience, but also improved their logistic capabilities. RTU's can reduce outages but also report real-time and detailed information that provides real insight into the grid's performance. The SCADA system not only allows remote control of the grid, but also collects and streams data to other management systems essential for grid operations.

Distributed Energy Resources

Renewable energy generation such as hydro, solar, and wind cannot be turned on and off because they generate electricity in real time as the water is flowing, sun is shining, and wind is blowing. Although weather forecasts can offer a way to predict how much electricity will be generated, the energy must be supplied directly to the grid without a way to store it. To utilize renewable energy sources efficiently (as mandated in the Energy Independence and Security Act of 2007), various management systems needed to be implemented since significant amounts of renewable energy come from DERs that are not operated by the utility.

Distributed energy resource management systems (DERMS's) aggregate weather, energy production, energy demand and other forecasts to make predictions that allow efficient utilization of DERs. For example, if tomorrow were a sunny day, solar farms would produce a lot of electricity that would reduce the demand for gas-fired power plants. Without managing these resources together, the gas-fired power plant would not reduce output as the solar farm generates large amounts of power. The excess energy would then have to be burnt off unless energy storage systems (ESS's) or other technologies were integrated. A DERMS can see that there will be low demand for nonrenewable energy tomorrow and communicate that with plant operators and ESS owners.

Figure 2: Grid Management Systems Overview below displays the location of a SCADA and DERMS in the grid. The advanced distribution management system (ADMS) is the primary interface that grid operators use. Its chief aim is to connect all systems below it and ensure grid operability under all conditions.

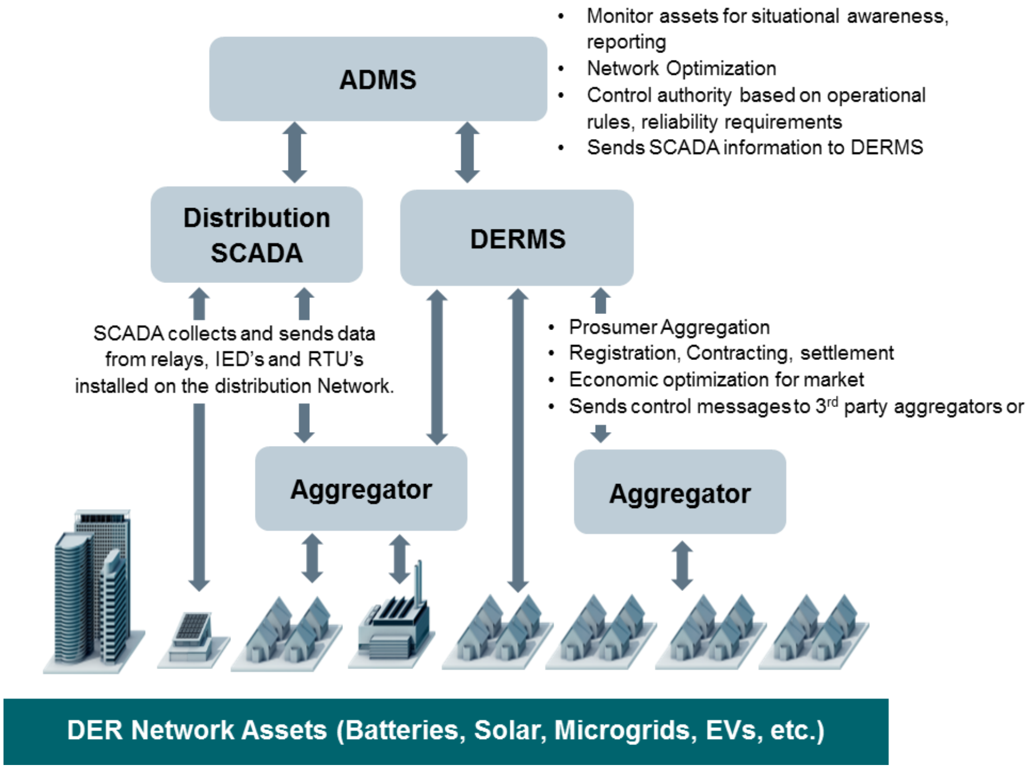

Figure 2: Grid Management Systems Overview

Demand Response Programs

The integration of sensors, communication networks, RTU's and other technologies into the electrical grid permits unprecedented insight into demand and control over consumption. Utilities can predict when consumers will use how much power and can influence their actual usage ahead of time. The most common demand response program offers electricity prices that mirror the demand for electricity. Generally, electricity prices are low overnight and high during the day. However, renewable energy generation creates a bimodal energy demand curve that is sometimes referred to as the duck curve.

Figure 3: Duck Curve below displays the effect that increased solar installations have had on the net load on the grid. Overall energy demand starts low in the morning and steadily rises until the evening before beginning the overnight descent. However, if you subtract renewable energy production from the total demand, you get the net load which requires nonrenewable energy production such as coal- and gas-fired power plants to meet demand. The severe drop in the afternoon net load requires power plants to shut down and then quickly ramp back up to meet evening demand.

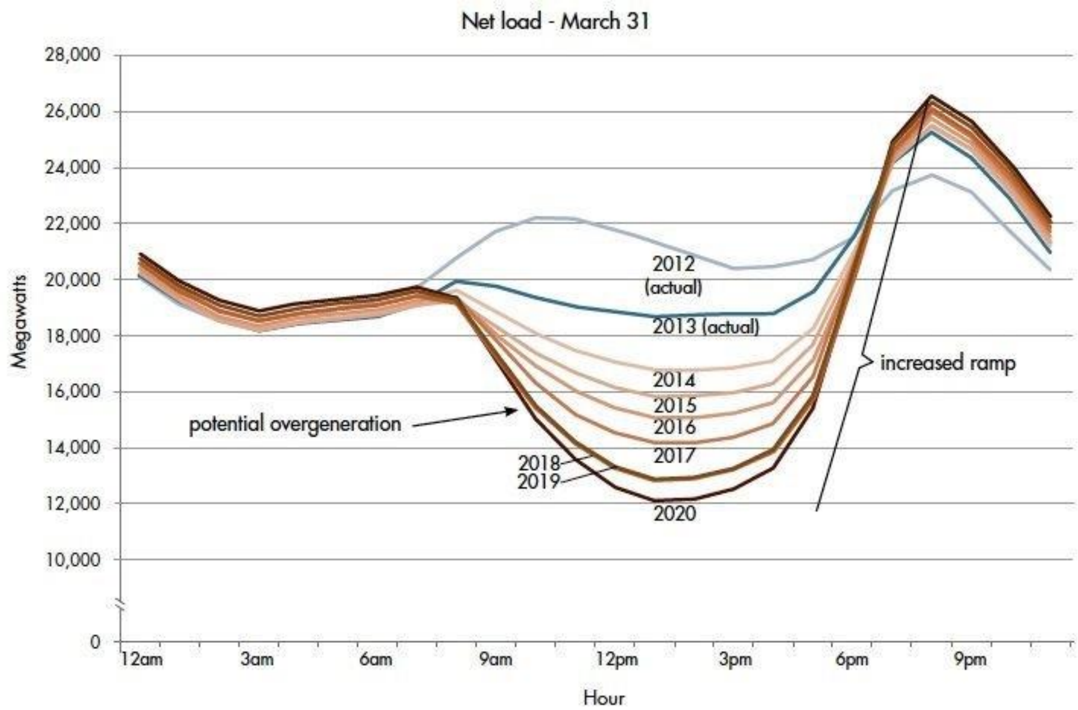

Figure 3: Duck Curve

Meeting Peak Demand

Peaking power plants, or peaker plants, sit idle for most of their 24/7 operation ready to ramp up to meet spikes in energy demand. The cost of activating New York City's peaker plants for only a few hundred hours each year has amounted to approximately $4.5 billion from 2010 to 2020. A significant amount of this cost goes into keeping the power stations on standby in case there is an extraneous peak in demand. The number and cost of these peaker plants will increase as energy demand increases and the grid receives more solar energy, further exaggerating the duck curve.

The new technologies that have built the smart grid enable unique solutions to the duck curve problem. All the data and remote controls can allow the utility company to work with the consumers to create a cheaper and more balanced electricity grid. Smart appliances enable overnight scheduling, smart meters provide extensive consumption data, and remote-controlled heating and cooling systems allow utilities to smooth overall demand by preventing too many systems from running at the same time.

Two primary techniques have been used to lower peak energy demand, sometimes called 'peak shaving'. The first technique involves shifting energy demand to other times of day. For example, a household can schedule their dishwasher to run at 3am rather than during peak demand at 8pm. The same house could also store additional hot water in their tanks overnight rather than heat water during the morning peak. The second technique involves storing electricity in an energy storage system (ESS) during low demand and drawing electricity during peak demand.

Energy Storage Systems

The imbalance between renewable power generation and overall energy demand prevents the electricity grid from being completely powered by renewable sources. Additionally, the unpredictable nature of renewable power generation cannot guarantee a steady supply of energy every day. To effectively utilize renewable energy, an ESS can store excess energy during generation and provide energy whenever renewable energy generation is not available. ESS's can consist of many different technologies such as electrochemical batteries, heat storage, pumped hydro storage, and many more.

Battery Energy Storage Systems

Batteries store the energy that power most portable consumer products. However, they can have a place in the electrical grid as well. Battery energy storage systems (BESS) require a high energy efficiency, long cycle life, and relatively high energy density to be cost-effective grid solutions. BESS's allow the grid to integrate renewable technologies, perform frequency regulation, shift peak demand, and assist in power management. Although there are many types of batteries, only a select few can fulfill the requirements of grid operation. Lithium-ion batteries have been integrated into residential homes as well as large grid-level installations. Flow batteries can offer aggregated communities a reliable alternative to traditional batteries. Grid-level storage has seen new technologies involving gravitational storage and solar-based generation that utilizes mirrors rather than electronic-grade panels.

Lithium-ion batteries have been the focus of many BESS's in recent years. Most notably, Tesla has installed one of the largest BESS's (189 MWh) in Australia which has resulted in over $150 million in savings for consumers. PG&E has begun building a 1.1 GWh Lithium-ion battery installation in California with the help of Tesla as well. Additionally, as of second quarter of 2020, Tesla has installed over 100,000 Powerwall's in households with a total energy capacity of 260 MWh. Despite the increased scale of production bringing significant cost savings to high-capacity systems, the cost and performance of Lithium-ion batteries has not been improving at the rate it once was. The current lithium-ion cost structure cannot support a 100% renewable grid in developing nations due to the high costs and relatively short lifespan.

Vanadium redox flow batteries (VRFB) offer an alternative for large lithium-ion BESS's. The positive cell holds a V^4+/ V^5+ solution and the negative cell holds a V^2+/ V^3+ solution. A proton-permeable membrane sits between the two solutions with metal electrodes on the outside. Energy is stored by running a current through the system that causes the positive cell to release electrons that flow to the negative cell. During discharge, the negative cell releases electrons that then recombine with ions in the positive cell. Chlorine and water molecules are also present in the cells to assist in the chemical reactions. See Figure 4: Vanadium Redox Flow Battery Diagram below for an illustration.

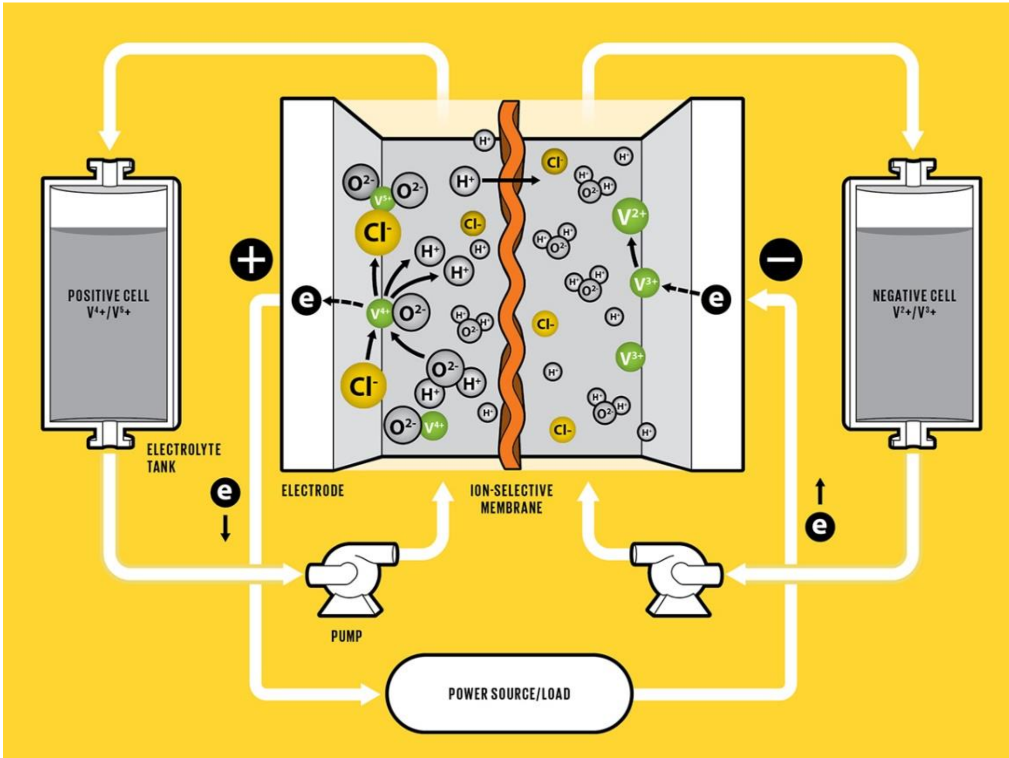

Figure 4: Vanadium Redox Flow Battery Diagram

VRFB systems currently reach 75-85% efficiency at a power rating of 2-kW while Lithium-ion systems can reach 90-95%. Additionally, Vanadium can be very expensive due to the lack of commercial interest, although the element is much more abundant on Earth than Lithium. Despite numerous home and community storage systems utilizing a VRFB systems, Lithium-ion systems remain more cost-effective than VRFB systems at 2- and 5-kW power ratings. Early adopters of the technology have been experimental and commercial applications are slim.

Industry experts hope to see VRFB play an important role in grid-level ESS's. The nature of VRFB systems allows more electrolyte to be added or tanks/cells to be expanded at any point. The 20-year lifetime of a VRFB system can perform over 10,000 cycles without significant damage. Lithium-ion battery capacity would degrade by approximately 20% over 20 years and only sustain up to 5,000 cycles. VRFB systems could see the dramatic improvement seen by lithium-ion batteries given the same level of economic interest.

Alternative Energy Storage Systems

Alternative ESS technologies that have been used in private and public applications include flywheels, pumped hydro storage, supercapacitors, and others. More recent technologies include solid gravity batteries and solar power towers.

A gravity battery stores electricity in the form of gravitational energy; expending energy to raise a substance and harvesting energy while lowering the same substance. Nearly all the grid's electrical energy is stored as pumped hydro which charges through pumping water up to an elevated pool and discharges by letting that pool drain through a turbine. Alternative gravity batteries suspend a heavy weight connected to a winch in a vertical cavity such as a mine shaft. The weights can range from tens to hundreds of tons which require special winches that can output tremendous amount of torque. Another method suggests raising a large piston (the weight) by building water pressure beneath it with a high-power pump. The companies constructing prototypes expect to build their first systems sometime in 2021 and expect future projects to provide hundreds of MWh in storage capacity. These systems can be very attractive to landowners of abandoned mines or other industrial operations. The vertical cavities offer the optimal environment (no wind or rain) and sufficient height to raise and lower massive weights. An abandoned mine would be safe and cannot be used for many other use cases. The ideal locations tend to be in rural areas where solar and wind farms would be located or industrial applications that draw consistent energy all day. Gravity batteries may offer opportunities for underused land to operate large scale ESS's that contend with traditional BESS's and pumped hydro.

Another energy storage method utilizes hundreds of sun-tracking mirrors called heliostats to focus solar energy onto a receiver. The solar power tower contains a working fluid such as water or sodium that can be pumped out and used to power a turbine. Water-based systems typically pump out the fluid and use the Rankine cycle to generate power with a steam turbine. Sodium-based systems must pump the salt to a steam generator before harvesting the energy with a steam turbine. Sodium is used because of its ability to store large amounts of heat for extended periods of time. A water-based solar tower would produce electricity in real time like a solar farm, requiring that the energy be sent directly to the grid or stored in an ESS. A sodium-based solar tower could heat the sodium during the day and produce steam as needed or wait until night to produce steam and generate electricity. In short, the solar tower could operate as both a power plant and an ESS. However, few systems have been implemented due to the lack of suitable environments for this technology. Some oppose the adoption since the concentrated solar radiation can kill significant amounts of wildlife. Systems have been implemented in deserts across California, Nevada, Israel, and Saudi Arabia.

New technologies constantly emerge that offer better methods to store energy for the grid. But not all the energy storage needs to be owned and operated by utility companies. Although utilities have a significant interest in ESS's, consumers and private corporations have a growing interest in where and how they get their energy. Additionally, privately owned DERs need to be integrated with the grid.

Virtual Power Plants

The widespread adoption of DERs, such as solar panels and battery storage, presents an opportunity to utilize smart grid technology to increase grid efficiency. Solar panels produce a significant amount of energy during sunny days which can be stored for use at other times. Although excess energy is typically dissipated in large plants, the same energy can be stored given enough storage capacity. The energy storage has always been done at large centralized plants. With rooftop solar and home power walls, energy generation and storage are more distributed than ever before. Virtual power plants (VPPs) aggregate large areas into a single entity, that mirrors a large centralized plant, that a grid operator can control and optimize separately from the entire grid.

Large housing developments or commercial parks with rooftop solar and ESS's are ideal settings for VPPs. Such settings generate a large amount of their own power during sunny days while simultaneously storing large amounts power. The individual solar panels and ESS's can be aggregated into a single system that provides a large amount of energy generation or storage to the grid. The VPP can manage the internal energy supply and demand before excess solar energy is sent to the grid, simplifying the integration of DERs into the grid. Additionally, a grid operator can direct excess energy into a VPP during low demand for later use when demand is high, reducing overall energy costs and thus providing savings to the consumers and utilities.

A Tesla VPP was implemented in Australia across numerous Powerwall customers, reducing overall electricity rates by 20%. Besides cooperating with the utility to manage excess demand and supply, the VPP controlled household appliances and climate control systems. The VPP took away the need for the energy provider to monitor and access each customer's systems by themselves. Although it is not impossible for a utility to manage all the DERs together, it requires a significant investment into the software and technology to do so. A VPP implements a DERMS into a much smaller scope, creating a hierarchical structure that would otherwise not exist.

The VPP creates an independent component of the grid where all internal operations are abstracted away from the energy provider. During a large-scale outage, the VPP generation and storage can provide enough electricity to power all prosumers within the accessible area. An energy provider can view the VPP and see the capacity it will be able to run at and if it can power neighboring areas as well. The utility would utilize a SCADA system to separate this area from the rest of the grid. Additionally, this interconnectedness can help in optimizing appliance scheduling and shifting the internal demand to present a steadier load to the external grid. With a large enough storage capacity, the VPP can provide significant peak shaving and overall load leveling, reducing the need for a utility to own large centralized ESS's. The abstraction of a portion of the grid's DERs to a single unit provides an excellent interface for the utility's existing DERMS.

The wholesale electricity market (WEM) strongly influences how VPPs operate. The WEM offers information on the cost to consume electricity from the grid as well as the profit from selling electricity to the grid. When a VPP attempts to optimize the ESS and energy demand of its consumers, it uses real time electricity prices provided by the energy market operator. Artificial intelligence can be utilized to make decisions that would maximize the profit made by the VPP. Such a system utilizes the daily irradiation, temperature, and relative humidity from local weather forecasts to model solar energy production. Combined with calculating price elasticity of electricity, loads can be shifted to and electricity can be sold at the optimal times. A VPP application for a residential community of 67 households in Western Australia utilized an 810-kW rooftop solar PV system and a 700-kWh VRFB storage system. The application saw a 24% reduction in electricity prices. Another VPP at the Huazhong University of Science and Technology utilized a 15-kW PV power system with a 13.5-kWh storage system. The Chinese research team utilized a more advanced neural network with decisions made at 5-minute intervals to obtain profits of 6 to 30 Yuan (~$1 to $5). It should be noted that the Australian households each had 12-kW PV and 10.4-kWh ESS's despite a similar load profile as the Chinese application. The smaller Australian application would have a much harder time producing any sort of profit under such conditions. The cost of electricity and seasonal patterns also greatly differ between the geographical locations. Please refer to sources 23 and 24 for more information.

Generally, consumers do not interact with the VPP operations besides coordinating the appropriate schedules and operating ranges for their appliances. But Tesla provides an interactive interface for customers to monitor the performance of their solar panels and power walls. A utility may also control the solar panel system and power wall through a smart meter and provide monthly data to the owner. Some electricity markets provide solar tax credits to be paid out in the form of yearly tax savings rather than a monthly payment. Alternatively, a VPP may provide direct savings to their electricity bills or provide free services to construct and maintain the solar panels and BESS.

In existing DERMS applications, utilities use powerful AI systems to monitor all grid components and look ahead to make predictions. These predictions often find issues such as overvoltage's that would damage grid components. The same systems can construct an alternative management plan and present the results to a grid operator to ensure its efficacy. The grid operator then approves or disapproves of the plan. Requiring the system to iterate the process across every household in a town or county can be extremely expensive. VPP's ease this computational requirement by internally managing the DERs and presenting limited controls to the DERMS.

Conclusion

The introduction of new and more efficient renewable technologies will increase DER adoption and enhance the need for VPPs. New solar technology could provide a more cost-effective model for universal adoption of rooftop solar and local solar farms. Advanced battery, supercapacitor, and other ESS technology could introduce cost-effective methods of long-term energy storage and high cycle lifetimes to enhance consumer access to electricity during outages and assist in daily grid operations. VPP modeling techniques allow the grid operators to optimize the usage of these new and existing technologies beyond a traditional DERMS.

Government incentives have fueled significant growth in renewable smart grid technology. Much more work needs to be done in developing energy resources, but it can be just as important to develop the software that manages these resources. Significant progress has been made by utilities and private corporations in developing comprehensive management systems. However, many systems still lack the broadly available artificial intelligence to optimize operations and reduce energy supply and demand requirements.

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