APPLICATION NOTE
BEHIND-THE-METER ENERGY STORAGE SYSTEMS FOR RENEWABLES INTEGRATION

Sam Jaffe, Cairn Energy Research Advisors

October 2016

ECI Publication No Cu0242

Available from www.leonardo-energy.org

Document Issue Control Sheet

Document Title:	Behind-The-Meter Energy Storage Systems for Renewables Integration
Publication No:	Cu0242
Issue:	01
Release:	Public
Content provider(s)	Sam Jaffe (Cairn ERA); Shmuel De Leon (SDLE)
Author(s):	Sam Jaffe; Shmuel De Leon
Editorial and language review	Bruno De Wachter
Content review:	Jürgen Timpert

Document History

Issue	Date	Purpose
1	October 2016	Initial publication in the Good Practice Guide
2		
3		

Disclaimer

While this publication has been prepared with care, European Copper Institute and other contributors provide no warranty with regards to the content and shall not be liable for any direct, incidental or consequential damages that may result from the use of the information or the data contained.

CONTENTS

Acknowledgment(s)

I would like to thank Shmuel DeLeon of Shmuel DeLeon Energy for his help in conceiving and editing this paper.

SUMMARY

This paper explores renewables-linked behind-the-meter energy storage systems. It explores applications which can be performed with such systems, including the business model behind such applications and the duty cycle requirements of such applications. It also explores siting and technology choices, including battery types, inverter classifications and other purchasing and installation considerations.

Energy storage systems are becoming a more frequent component on electrical systems throughout the world, both on the utility side of the meter and on the customer side of the meter (also referred to as "behind-the-meter"). Behind-the-meter storage is most often integrated with renewables (usually photovoltaic systems) and can function as a flexible and powerful part of the electrical structure of a given site. Adding renewables and an energy storage system to a particular site can save money (by reducing peak electricity demand periods and by displacing grid electricity) and add resilience and functionality to a particular site's electrical circuits.

Evaluating combined renewables and energy storage systems is a complex task. Most vendors in this field are relatively new. Additionally, there are few choices of integrated systems that allow for a single purchasing decision. Instead, each component must be selected separately. And every site has its own unique qualities that will always require some amount of customization to each system.

Because batteries are relatively new to the grid, technology choices can seem overwhelming. Multiple battery chemistries are available, each offering its own unique capabilities and drawbacks. Even within the market leading technology, Lithium Ion, there are numerous electrode chemistry choices. Choosing the right battery for a system is the most crucial part of selecting an energy system and requires an in-depth knowledge of the strengths and weaknesses of the competing chemistries.

The difficult decisions don't end there. The other components of the system, including the inverters, charger/controllers and system enclosures present another dizzying array of choices. Understanding the underlying technologies (as well as the site-specific requirements) go a long way in determining the best components for the customer's needs.

The single most important part of the picture, however, is to understand what the batteries will be used for. There are dozens of applications for which batteries can be applied. Exactly how they will be used goes a long way in determining how they will be sized, deployed, charged and discharged. This paper explores most of the main battery applications, including peak shifting, ancillary services and self-consumption.

Choosing a battery system isn't one simple purchasing decision. Understanding the customer's requirements and appreciating the landscape of battery and other component technologies allows the right choice to be made.

INTRODUCTION

This paper is meant to explain the major elements of behind-the-meter energy storage systems (ESS) combined with a renewables generation system. A behind-the-meter energy storage system is defined as a energy storage device (usually an electrochemical battery) which is placed at the site where it is being used and is electrically connected to the site's electrical network, not to the grid itself. This paper does not aim to provide recommendations on particular brand names of batteries and components, but to explain the components and how they work together.

These combined ESS/renewables systems are quickly appearing throughout the globe and becoming an important part of the grid. Energy storage on its own is almost always an uneconomical opportunity. Renewables on their own don't provide the reliability that we traditionally expect from our electricity providers. ESS combined with renewables allow business-owners and residential customers for the first time to become their own utilities—to generate and dispatch energy for themselves when they need it.

To realize that vision, however, a host of technological and business decisions must be made. What will the system do? What battery should be used? Will the system last long enough to make all the payments on the loan that was taken out to purchase it? Will the system introduce unnecessary safety risks? And many more. This paper is meant to help potential purchasers and installers weave their way through all of these issues, find answers to their questions and help them to make the correct choices.

ENERGY STORAGE SYSTEM TECHNOLOGY CHOICES

Energy storage can be accomplished by many different types of technologies. For behind-the-meter systems, however, the only technology that is in wide deployment is the battery, which uses the potential energy of electrochemical reactions to store energy. The battery has won the struggle to provide stored energy over many other competing technologies thanks to its energy density, its safety profile and its cost. In some cases, there are other energy storage devices being used behind-the-meter, such as short-duration flywheels for reserve power and supercapacitors for voltage management of local circuits. Nevertheless, batteries consume the bulk of the market of the active energy storage device for behind-the-meter energy storage systems.

The technology choices don't end there. Within the overarching category of batteries, there are many battery chemistry types to choose from: lead acid, lithium ion, redox flow batteries, etc. And once the battery is chosen, there are still many other technology choices to be made, from the type of the inverter to the enclosure that contains the entire system. This section explores all of the technology choices that have to be made and how best to make them, starting with the proper sizing and specifications of the energy storage system and then moving into system components.

System Specifications

The easiest way to make a mistake in purchasing an energy storage system is to buy too little or too much of it. This section discusses how to size and prioritize system specifications required.

Ideal Sizing of ESS Energy Capacity

When contemplating the proper sizing of an ESS, there are two parameters that have to be considered: power and energy. Sizing a system by power requirements is relatively straightforward. If the ESS is providing reserve power, then the overall peak load of the site will indeed determine the power requirement. If the system is providing demand charge mitigation, then the economic value of each fifteen-minute reduction of peak load must be calculated and the intersection between the highest amount of peak reduction with the most affordable ESS will determine the power setting. Regardless of the power rating, it's important to note that any ESS is capable of providing almost any level of power below the peak setting. This is usually done by the power control system deciding to activate only a selected subgroup of strings or modules

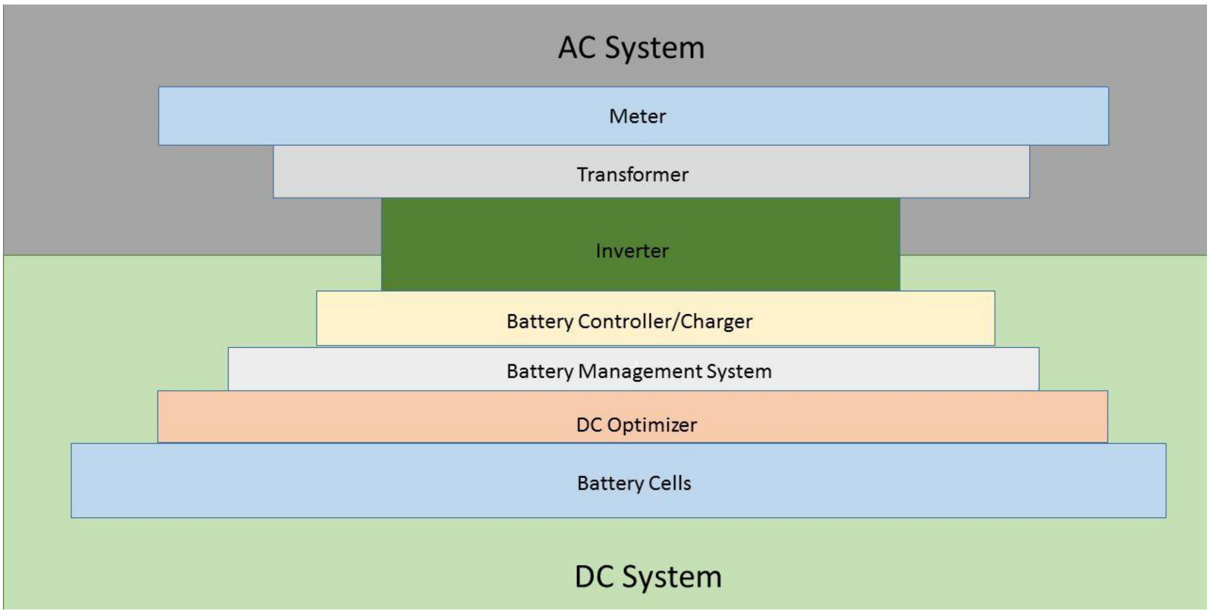

Figure 1 – Typical behind-the-meter energy storage system Technology stack.

Once the power rating has been selected, an energy duration level must be chosen. Like the power rating, the energy duration of the system is dependent on the particular application it will be performing. Most behind-the-meter ESS will vary in duration from between 30 minutes at peak power to 2 hours. For example, a typical residential self-consumption application might require a discharge time of 2 hours at peak power (with the capability to provide a much lower power output over a longer period of time when required), whereas a frequency regulation application would only need a 30-minute discharge time. A reserve power system will require a much shorter duration (usually 5-15 minutes at peak power). In most cases, an energy capacity that exceeds the expected needs of the application by 10-15% would be the optimal system sizing.

Inverter Choice and Architecture

An inverter transforms direct current (DC) power into alternating current (AC) power. Almost all appliances, from lightbulbs to air conditioners, require AC power input (even if that AC power is then rectified back into DC for use in the appliance's internal circuits, as is the case with computers and smartphones). Batteries can produce only DC power, hence the need for an inverter for any ESS. Likewise any electricity produced from photovoltaics is produced in DC.

There are four factors that influence the choice of a particular inverter: directionality, durability, ancillary features and costs. Those factors are further impacted by the conditions of the site and its interconnection, as well as the details of the application for which the ESS is being used.

Directionality refers to the direction of flow of the current in the system. A uni-directional inverter can take DC power from the batteries and/or photovoltaics and invert it into AC power for the site load or for net metering. A bi-directional inverter can also rectify AC power into DC power which can then be fed into the batteries during charge. A three-port inverter adds another port, such as the ability to bring DC power directly from photovoltaic panels, clean up the power quality and then send it into the batteries for charging them. A four-port inverter allows, for instance, a stream of AC power to flow directly into a particular appliance, as well as an output that goes into the general load circuit of the site.

Another parameter of inverters is the ability to insert power quality services in both directions, which is most commonly referred to as a four quadrant (or four zone) inverter. That term refers to an inverter that is capable of providing both positive and negative voltage and positive and negative current. This allows the inverter to serve as a voltage and power factor management device in addition to its primary task of inversion and rectification. A four quadrant inverter provides the most flexibility to the overall system.

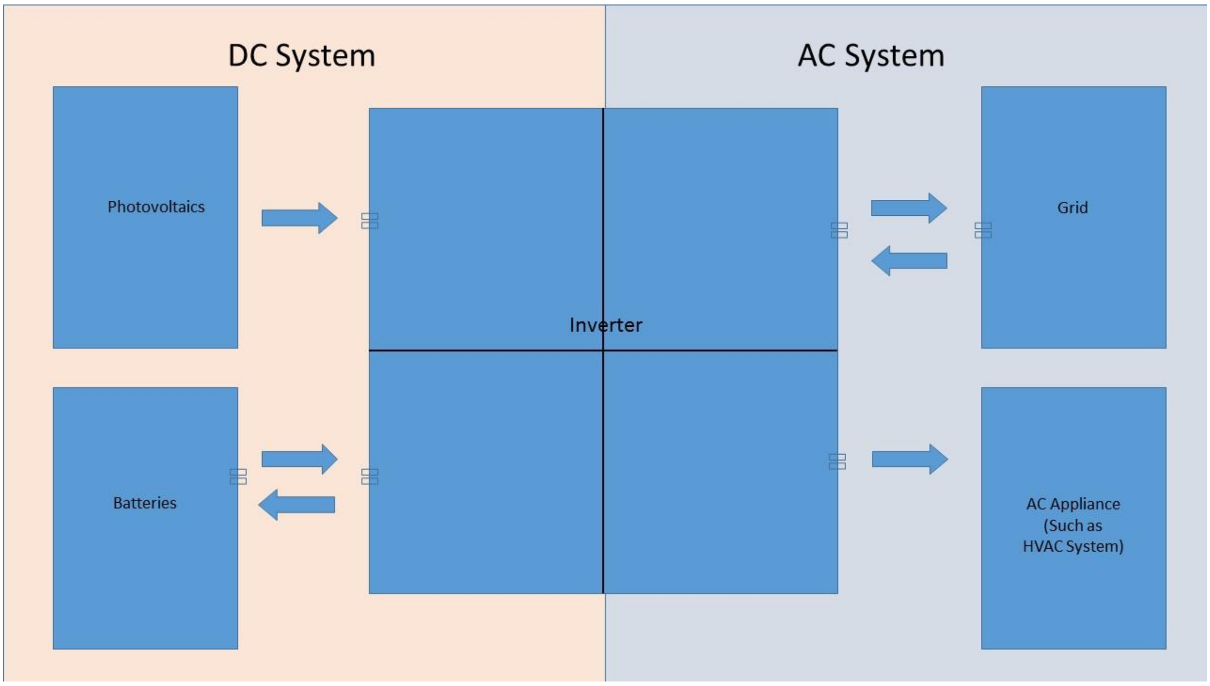

Figure 2 – Layout of a Four zone inverter.

When it comes to durability, inverters can have far-ranging differences, based on the quality of their components. Durability is most often directly translated into the length of warranty from the manufacturer. Most PV inverters have a ten-year warranty. If a ten-year warranty inverter is chosen, the financial impact of replacing the inverter after ten years should be integrated into the financial model of the system. If the warranty duration is found to be appropriate, the buyer's task doesn't stop there: warranty terms and conditions must also be suitable for the buyer. In some cases, warranties are invalidated if certain temperature, voltage or current parameters are exceeded.

Another key differentiator in ESS inverters are the various ancillary features that can be provided by the device beyond simple inversion from DC to AC. Many inverters are branded under the term "smart inverter" because they also have controls that allow them to insert reactive power (which can improve the power quality at any site that might have flicker due to engine starts or large appliances in the vicinity), voltage management, harmonics regulation or any other power quality services that can be provided. Another key feature that should be considered is telemetry and remote control of inverters, which can add an extra layer of control and security to the operation of the system.

The final factor in inverter choice is the price of the device, which in turn is usually determined by the quality of the three other factors. For instance, a 4-quadrant inverter with reactive power capabilities and a fifteen-year warranty, for instance, will cost significantly more than a uni-directional inverter with a ten-year warranty.

The inverter is the key component of Power Control System (PCS), which usually consists of the inverter, a computing processor that gives the system its charging and discharging commands, and safety equipment such as circuit breakers and switches. The PCS is often sold as an integrated unit.

Another part of the power electronics of some systems are the DC optimizers built into the battery pack itself. DC optimizers ensure a smooth and pure flow of DC electricity from each module or module string, which in turns lowers the stress on the inverter by avoiding sudden bursts of power from one section of the battery pack. DC optimizers are usually built into the battery pack itself and are not considered to be part of the PCS.

Key Safety Elements of ESS

No ESS is worth anything to its owner if it fails or—even worse—creates a safety incident such as an exposed circuit or a fire. Safety engineering is the foundation of all other design and configuration elements in an ESS and must be understood by any prospective buyer.

Battery Pack Safety Engineering

At the heart of ESS safety engineering is the battery pack itself. The key risk of modern battery packs, especially large ones, is thermal runaway (a cascade of thermal events that starts from a battery overheating and ends—in the worst case scenario—with a fire). This condition is most prominent with some forms of Li-ion batteries, but can also occur in other battery chemistries, including Nickel Metal Hydride and Lead Acid.

Thermal runaway has two components: initiation and propagation. The initiation phase simply means that an individual cell has gone into thermal runaway. This is usually caused by physical damage somewhere inside the cell that causes heat to build up internally to dangerous levels. The propagation phase refers to the spreading of that thermal runaway state from a single cell to other cells in the pack. The majority of safety engineering tactics and design are focused on the elimination of the risk of propagation. In the end, any battery cell is capable of entering into thermal runaway. A well-designed battery pack, however, makes propagation of that thermal runaway to the rest of the pack very difficult, if not impossible.

The most important part of thermal runaway propagation mitigation is the use of current disruptors on individual cells. These can be simple circuit switches that physically deform and thereby break the circuit when exposed to high temperatures. Most modern batteries have some form of current disruptors built into them at the cell level.

Another important factor in thermal runaway propagation mitigation is the use of some form of fireproof insulation between cells and modules. How this material is designed and used can alter the cost of the pack, as well as the danger level in the case of a safety event. Many modern battery packs use phase-change materials (which can vary in composition from simple waxes to expensive graphene) that will quickly shed heat if an individual cell goes into thermal runaway.

Other safety devices that mitigate the risk of full-pack thermal runaway include controlled blow-off devices (which discharge gasses that build up inside the cells) and cell monitoring through the battery management system. The most important safety element, however, is to ensure that the cells that are being used in the system are being manufactured in an environment that has stringent quality control measures in place.

Fire Detection and Suppression System

In the worst case scenario, a battery pack that has entered thermal runaway propagation will lead to outgassing of toxic fumes, smoke generation and even fire. Therefore, an additional layer of safety engineering is the use of fire detection equipment (either a smoke alarm or a more sophisticated Internet-based monitoring system) and even fire suppression equipment. For large systems that are housed in steel trailers, fire suppression systems are often comprised of halon or CO_2-filled tanks that, when activated, immediately reduce the amount of oxygen available in the immediate atmosphere of the ESS. For smaller systems, such as wall-mounted units, fire-suppression systems are not feasible.

Manual Disconnect Switch

In most localities, an ESS system must have a manual disconnect switch, which usually consists of a red-handled lever that, when pulled, cuts the circuit to the entire system. The switch is usually prominently displayed and is easy to identify by nearby non-professionals and by first responders. Any ESS that is connected to a PV system will usually be required to have two manual disconnects: one for the battery pack and one for the PV system.

Battery Technology Considerations

Of all the components in an ESS, choosing the right battery is by far the most crucial technology choice. While all batteries are capable of electrochemically storing energy, they can differ dramatically in their voltage levels, energy duration, durability, cost and a host of other factors.

Cost

For most buyers, the single most important factor in battery technology choice is the cost of the battery. However it’s important to differentiate between the up-front capital cost and the total cost of ownership (TCO) of the battery over the lifetime of the system. To reach a fair and appropriate TCO measurement, one must factor in all costs incurred, including the loss of capacity over time due to degradation, the reduction in the state-of-charge (SOC) window (i.e. the amount of the battery capacity which the charge controller allows the system to use) over time, the efficiency of the battery and the residual value of the battery at the end of its life. A detailed discussion of such a calculation is beyond the scope of this paper, but buyers should definitely be aware of the differences between TCO and the up-front capital cost of the battery.

To keep things simple, up-front capital costs of batteries are most commonly measured in the metric of “Currency per kWh”, which divides the cost of the battery by the nameplate energy capacity of the battery. Battery pricing can also be expressed in power capacity, which would be “Currency per kW”.

One important caveat that should be considered by purchasers is that battery pricing is usually expressed by pure price, without factoring in the cost of a warranty. Warranty pricing is extremely important, because if a battery is going to be purchased with a loan and the loan repaid by money earned by the use of the battery, then the battery must be able to reach certain performance milestones in order to repay the loan. The difficulty in discussing battery warranty prices broadly is that every manufacturer has a different warranty price for each of its cell types and, sometimes, for every application for which the battery is being used. Thus any prospective buyer of a stationary ESS should be aware of the duty cycle of the application the system will be performing and ensure that the price quoted includes a warranty that covers that particular application’s expected duty cycle.

	Cell-Level $/KWh in 2015	Cell-Level $/KW in 2015	Expected Deep Discharge Cycle Life	Average Capital Cost per KWh Delivered Over Lifetime of System
Advanced Lead Acid	450-600	113-150	1200	0.44
Deep Cycle Lead Acid	280-400	70-100	400	0.85
LFP Lithium Ion	290-550	145-275	1500	0.28
LTO Lithium Ion	1280-2000	427-500	15000	0.11
NMC Lithium Ion	245-500	123-250	2000	0.19
Vanadium Redox Flow	800-1200	134-200	12000	0.08
Aqueous Zinc	220-250	55-63	2500	0.07
Zinc Bromine Flow	600-900	150-225	1500	0.50

Source: *Cairn ERA*

Figure 3 – Battery Chemistry Technology Choices and cell level pricing ranges. Prices are listed on a US Dollar per KWh range based on nameplate capacity. Prices are stated in $/kWh (energy capacity) and on $/KW (power capacity), based on maximum C-Rate capability of each battery. Average Capital Cost per KWh Delivered is based on the average capital cost for the battery on the cell level, divided by the expected number of cycles the battery cell will be able to perform in its lifetime before 20% of the energy capacity experiences degradation.

Figure 1 shows the range of battery pricing (without warranties) at the cell level for major chemistries in use today. In some cases, the term "cell-level" can be misleading as some battery technologies have a single "cell", no matter the scale of the system (such as flow batteries, which comprise a stack of cells all housed within the same enclosure, even in the MegaWatt-scale), while other chemistries consist of discrete battery made up of internal cells (such as a lead acid battery). However the data in Figure 1 has been equalized to represent all battery-only costs of the DC-bus portion of the system (i.e. no welding, connectors, fuses, battery management systems or cabling are represented in the cost).

As can be seen from Figure 1, battery costs can vary widely both on a capital expense basis and on a cost-of-delivered-kWh over the lifetime of the battery. Additionally, they can vary dramatically on an energy capacity basis and on a power capacity basis. There is no one "correct" battery for all applications: the proper battery for a given system offers the capability to provide the application that is needed and comes at the lowest possible price.

In addition to analyzing the up-front cost of the battery, the end-of-life costs of disposing of the battery should also be considered. Lead acid batteries, for instance, require full recycling at the cost of the battery owner in most countries. The European Union will require, as of 2016, the provision of recycling services for any new Li-ion battery system, whether in a vehicle or in a stationary storage system. Such a service usually consists of transportation of the battery from the site to a recycling center. The recycling process itself is usually paid for by the re-sale of the recycled compounds.

C-Rate Capabilities

As mentioned above, a battery's power capacity (measured in kW) can vary significantly from its energy capacity (kWh). This is usually a function of the maximum C-Rate of the battery chemistry. C-Rate is the size of current at which the battery can be discharged safely and without inducing severe degradation. A 1 kW battery discharged over one hour would have a C-Rate of C1. A 1 KW battery that discharges its nominal capacity in 15 minutes would have a C-Rate of C3 Note that the charging rate of a battery is often non-symmetrical with its discharge C-Rate, meaning that some batteries must be charged more slowly than they can be discharged. A battery that is capable of handling a high C-Rate without damaging it is often referred to as a "power intensive" battery, and such batteries tend to have shorter duration of discharge. A power intensive battery is especially useful in applications that require short pulses of power, as opposed to long periods of energy discharge, such as frequency regulation and demand charge mitigation.

Cycle Life

A common end-of-life criterion (but certainly not the only one in use) is a battery that has a remaining charge capacity of less than 80% of its nominal capacity. Lead acid batteries, for instance, are not capable of handling more than a few hundred deep discharge cycles before they begin to fail. Some high cost chemistries, like Lithium-ion batteries with Lithium Titanate anodes, show the capability to endure more than ten thousand deep discharge cycles. The cycle life of the battery should be factored into the overall cost of the system. Such an analysis should always be done with the context of the particular application which the battery is performing.

Cycle life can play an important role in the financial model of a system when factoring the residual value of a system after the planned life of the system. If an ESS has performed its expected task and will be uninstalled, the residual value of the battery and the overall system should be considered as part of the total cost of ownership of the system. This is especially true for vanadium flow batteries, as the vanadium in the electrolyte will always have a high residual value due to the scarcity of vanadium.

Energy Density

Energy density can be measured two ways: gravimetric and volumetric. Gravimetric energy density refers to the energy density of the battery divided by weight. Volumetric energy density refers to the energy density of the battery divided by the volume of the cells. Gravimetric energy density, while extremely important in automotive applications, is usually not a significant factor in stationary storage systems. Volumetric energy density is usually a more significant factor, especially if there are space restraints at the site.

Battery Chemistry Type

Of all the technology choices to make in purchasing an ESS, the choice of the battery chemistry is by far the most important. Aligning the proper functionality at the right price is often a difficult process. A dizzying array of potential battery chemistries make it even harder. The vast majority of ESS utilize one of two battery chemistries: lead acid or Li-ion. And Li-ion can be further subdivided into three electrode chemistries which together account for almost all Li-ion installations. This section discusses those chemistries.

Lead Acid

For more than 100 years, the lead acid battery represented the only industrial battery choice. Lead acid batteries provided the starting power to turn on vehicle engines, reserve power in UPS systems and, in some rare cases, for shifting of peak loads at off-grid systems.

Lead acid batteries tend to be power-intensive batteries with high C-rates but very short term energy duration. In some cases, they are used for energy-intensive applications by discharging at much lower C-Rates (although these applications are headed mostly towards Li-ion batteries today). They also are highly prone to premature degradation when allowed to cycle deeply, lasting only a few dozen or a few hundred deep discharge cycles before they begin to suffer significant degradation. To avoid such premature degradation, lead acid batteries often maintain a very shallow depth-of discharge. Vehicle starter batteries, for instance, often cycle between a full charge at 65% of nominal capacity and a full discharge at 60% of nominal capacity.

	Cathode Material	Anode Material	Electrolyte	Energy Density (Wh/KG)	DC Efficiency	Maximum C-Rate	Expected Deep Discharge Cycles in	Potential for Thermal Runaway		Manufacturers
Deep-Discharge Lead Acid	Lead Dioxide	Lead	Sulfuric Acid	30	60%	4	100	None	None	Enersys, Exide, Furukawa, Leoch, Others
Advanced Carbon Lead Acid	Carbon-doped Lead Dioxide	Lead	Sulfuric Acid	40	75%	4	1,000	None	None	Axion, East Penn, Ecoult

Source: Cairn ERA

Figure4 – Characteristics of Lead acid Batteries.

For decades, lead acid batteries provided the only choice in stationary energy storage systems. With the advent of Li-ion and other new battery chemistries that are capable of more cycles at deeper discharges, some lead acid battery manufacturers countered with new technologies meant to increase the durability of the traditional batteries. Most of these solutions involved the addition of carbon layers to the lead electrodes, which increased the batteries resilience and also added to its energy capacity. These batteries, known as Advanced Lead Acid Batteries, have been installed in some stationary energy storage installations globally.

Nevertheless, the vast majority of lead acid installations in stationary storage systems is done for reserve power systems, usually in the form of an Uninterruptible Power Supply (UPS) system, which maintains power to a site in the rare occurrence of a grid disruption. Because UPS batteries are only used for a few times each year and require a very short duration, lead acid is still the battery chemistry of choice for these systems.

LITHIUM ION: NICKEL MANGANESE COBALT

Mass-produced Li-ion batteries first appeared in 1991, as an energy dense solution for high-end video cameras. They quickly took over the entire consumer electronics sector and are now the primary chemistry choice for smartphones, laptops, tablets and power tools. Additionally, they have become the default technology choice for electric vehicle traction batteries, as well as stationary storage applications.

	Cathode Material	Anode Material	Electrolyte	Energy Density (Wh/KG)	DC Efficiency	Maximum C-Rate	Expected Deep Discharge Cycles in	Potential for Thermal Runaway	Potential Fire Risk	Manufacturers
LNMC	Lithium Nickel Manganes e Cobalt	Graphite	Hydrocarbo n Solvents and Lithium Salts	210	87%	2	3,000	Moderate	Moderate	Panasonic, Samsung SDI, LG Chem, Others

Source: Cairn ERA

Figure5 – Characteristics of LNMC Batteries.

Of all the electrode chemistries used in stationary storage applications, the most common choice is NMC (sometimes referred to as NCM), which means that the primary active material in the cathode is a compound consisting of Lithium Nickel Manganese Cobalt. NMC is the most common electrode chemistry of choice today thanks to its superior safety profile (it is less prone to thermal runaway than its cousin compound LiNCA, or Lithium Nickel Cobalt Aluminum, which is used in some vehicle traction systems), its durability and its relatively low cost. Most major Li-ion manufacturers utilize NMC batteries for their ESS offerings, including Samsung SDI, LG Chem and Panasonic.

LITHIUM ION: LITHIUM TITANATE OXIDE

A less common Li-ion chemistry that is only used in stationary storage applications is Lithium Titanate Oxide (LTO). In this case, the term LTO refers to the anode (most other Li-ion batteries use a graphite anode). LTO anodes are often paired with a Lithium Iron Phosphate or a Lithium Manganese Oxide cathode.

	Cathode Material	Anode Material	Electrolyte	Energy Density (Wh/KG)	DC Efficiency	Maximum C-Rate	Expected Deep Discharge Cycles in	Potential for Thermal Runaway		Manufacturers
LTO	LFP or Lithium Manganese Oxide	Lithium Titanate Oxide	Hydrocarbon Solvents and Lithium Salts	85	89%	6	10,000+	Mild	Moderate	Toshiba, Leclanche, Liacon, Microvast, Others

Source: Cairn ERA

Figure6 – Characteristics of LTO Batteries.

LTO batteries are significantly more expensive, thanks to a more difficult and demanding manufacturing process as well as the higher priced Titanate material in the anode. But they also tend to be extremely durable (in most cases lasting 10,000 cycles or more) and also are capable of very high C-Rates, making them an excellent choice for applications that require high pulses of power with frequent cycling, such as frequency regulation. Major LTO manufacturers include Toshiba, Microvast, Leclanche and Liacon.

Lithium Ion: Lithium Iron Phosphate

Another major player in the stationary energy storage space is the Lithium Iron Phosphate (LFP) battery. The LFP cathode provides an excellent safety profile (less propensity for thermal runaway than most other cathode chemistries), excellent power capabilities and reasonably good energy density. The LFP battery is the primary technology produced by Chinese battery manufacturers for vehicle traction and for stationary storage applications. LFP also has the added advantage of having low-cost material inputs (iron and phosphate are two of the most common and cheapest industrial commodities), thus opening up the possibility to eventually becoming a cheaper option than other Lithium batteries. LFP batteries today, however, are not significantly cheaper than other options because the technology requires a more difficult and expensive manufacturing process than some other chemistries. The major Chinese battery manufacturers (including BYD, Lishen, BAK and ATL) all offer large format LFP batteries for stationary storage applications.

	Cathode Material	Anode Material	Electrolyte	Energy Density (Wh/KG)	DC Efficiency	Maximum C-Rate	Expected Deep Discharge Cycles in	Potential for Thermal Runaway	Fire Risk	Manufacturers
LFP	Lithium Iron Phosphate	Graphite	Hydrocarbon Solvents and Lithium Salts	105	85%	4	2,000	Mild	Moderate	ATL, BYD, Lishen, A123, Others

Figure7 – Characteristics of LFP Batteries.

Other Battery Chemistries

While most behind-the-meter stationary storage ESS utilize either lead acid or lithium ion batteries, there are many other technology options. The one with the largest installed base is the Vanadium Redox flow Battery (VRB). Unlike self-contained batteries like Li-ion or lead acid, flow batteries consist of a central stack past which charged electrolyte flows. As the electrolyte runs along the stack, electrons are shed and an electric current is created. The discharged electrolyte is then stored in a separate set of tanks. To charge the system, the discharged electrolyte is pumped past the same membrane stack to which now a current is applied, resulting in newly charged electrolyte. A flow battery always maintains a constant voltage and current. The energy capacity of the system is determined by how much liquid electrolyte is stored. Despite its inherent advantage of lower cost for long-duration applications, flow batteries are rarely used in behind-the-meter applications due to the fact that very few such systems require long duration energy flows.

In addition to VRB's, other flow battery chemistries include Hydrogen Bromine flow Redox batteries (HBR) and Zinc Bromine flow redox Batteries (ZBB). All utilize the same fundamental concept of a liquid electrolyte flowing past a membrane stack. Most flow batteries provide excellent durability over a very long cycle life.

Prominent manufacturers of flow battery systems include Uni-Energy Technologies, Imergy and Prudent Power.

	Cathode Material	Anode Material	Electrolyte	Energy Density (Wh/KG)	DC Efficiency	Maximum C-Rate	Expected Deep Discharge Cycles in	Potential for Thermal Runaway		Manufacturers
Vanadium Oxide Redox Flow B	Carbon	Carbon	Vanadium Oxide	75	70%	NA	10,000+	None	None	UniEnergy Technologies, Imergy, Gildemeister, Rongke Power, Others
Zinc Bromine Flow Battery	Carbon	Carbon	Zinc Bromine	80	70%	NA	2,000	None	None	ZBB, Redflow, Primus Power
Aqueous Zinc Battery	Zinc	Titanium	Water-based	75	70%	NA	10,000+	None	None	Eos Energy Storage
Source: Cairn ERA										

Figure 8 – Characteristics of flow and aqueous zinc batteries.

Another emerging battery chemistry of note is the zinc-based battery system produced by startup Eos Energy Storage. The Eos battery is comprised of zinc and titanium-based electrodes bathed in an aqueous electrolyte. The Eos battery is renowned for being significantly lower-cost than most other battery chemistries.

SITE-SPECIFIC CONSIDERATIONS

In addition to the choices surrounding the technology to be used in an ESS, proper sizing and selection also require a full understanding of several site-specific factors. These factors, ranging from the physical restraints to the electric load profile, will also influence the type of ESS to be installed.

PHYSICAL CONSIDERATIONS

Almost every potential installation site has some sort of physical constraints. In some cases, it is the volumetric amount of space that is available for the device. This will lead to the choice of a high-energy density battery chemistry, such as Li-NMC, which has nearly twice the energy density of LFP or LTO and nearly 4 times the energy density of Lead Acid batteries. The more energy that can be packed into a given battery cell, the less physical space the system will require.

The primary site considerations for the placement of an energy storage system are:

- Beyond the reach of the general public
- Location must be capable of bearing the weight of the system
- Adequate protection against the elements and extreme temperatures
- Theft/vandalism protection
- An area that is capable of harboring noise producing equipment (i.e. fans or air conditioners) without impacting the business operations of the site
- An area that won't be impacted by the extra safety precautions that might be necessary (such as fencing, extra containment zones, fire suppression systems, etc.)

ELECTRICITY DEMAND CONSIDERATIONS

ESS installations must also take into account the condition and characteristics of the site's electrical system and use patterns. Worn or undersized circuit breakers can lead to short circuits that could potentially propagate back to the ESS and cause damage, for instance, so a thorough inspection of all the power equipment on the building's circuit should be conducted. Another aspect to be taken into consideration is the potential presence of feeder circuits that forbid reverse power flow. Sufficient circuit switches can prevent such a reverse power flow from happening. However, if sending power onto the grid is a part of the business model, this might represent a significant loss of income.

Assuming that the local electrical circuits are up to code and safely protected, then power quality issues should be taken into consideration. Any site that has a lot of motor-driven equipment is prone to motor-start issues. When a typical motor starts to operate, it causes a brief imbalance between reactive power and real power. This imbalance can cause power quality issues in the connected circuits, which can lead to voltage irregularities and light flicker, among other things. An ESS with a smart inverter that is capable of handling reactive power imbalances on its own is capable of protecting the ESS while also improving the power quality for all circuits at the affected site. However the downside of utilizing a high-end smart inverter is its higher cost. Additionally, if the ESS is designed to solve local power quality issues, then the power electronics need to be sized for the overall circuit, not just the maximum load of the ESS.

Any attempt to solve energy problems at a site requires a lot of meter data (at the very least a year's worth of fifteen-minute interval data). This will allow the ESS buyers to choose the right application and to determine the proper settings of the control system of the unit. If such interval data is not available, installation of a smart meter that is capable of collecting and transmitting such data should be strongly considered. Additionally, in some cases, sub-metering might be recommended. This refers to the placement of meters on individual circuits within a building (such as on the HVAC circuit).

BUSINESS USE MODELS FOR BEHIND-THE-METER ENERGY STORAGE SYSTEMS

INTRODUCTION

On the surface, the use of energy storage systems (ESS) for grid management seems like a relatively simple process. Batteries charge when the grid has excess supply of power and then they discharge when demand outstrips supply. The actual implementation of such systems, however, is much more complicated. For an entity—whether it be an electric utility or a building owner—to invest in an energy device there has to be a clear means to earn revenue (or offset costs). This section explores the major applications of behind-the-meter ESS/Renewables systems and how they can produce an income stream that can pay for the system. For the purposes of clarity, these applications are described individually, but it's important to note that any ESS can combine multiple applications with the same equipment.

COMMERCIAL RESERVE POWER

All commercial endeavors require electricity to function. Large-scale manufacturers use it to power their equipment. Office buildings use it to keep the lights on and IT equipment online. Small retailers use it for their cash registers and accent lighting. In many cases, the provision of electricity is considered a mission critical function, meaning that if power were to be cut off, the company's existential mission would be at risk. And although power blackouts are uncommon in modern grids, they still sometimes happen. Therefore, many commercial entities invest in Uninterruptable Power Supply (UPS) systems to ensure that critical tasks can still be performed even when the power goes down.

A UPS system usually consists of three main components: a battery pack that will take on a building or site electrical load when the mains power is disrupted, a generator (either powered by natural gas or by diesel fuel) to pick up the load from the batteries for longer-term disruptions, and the power electronics that are needed to manage the system's operation and to ensure high-quality power generation from the system. UPS systems are common in high-security installations such as telecommunications network datacenters, health care sites and emergency responder command centers. In the last decade, they have started to proliferate to other sites, such as sporting event venues, large retailers and shopping malls.

Another emerging trend is the linkage of onsite renewables, usually solar photovoltaics (PV) to UPS systems as a means to charge the battery element of the system. The technical requirements for such a system are relatively modest and include the creation of a circuit link between the PV system and the battery pack, as well as some extra disconnect switches for safety purposes.

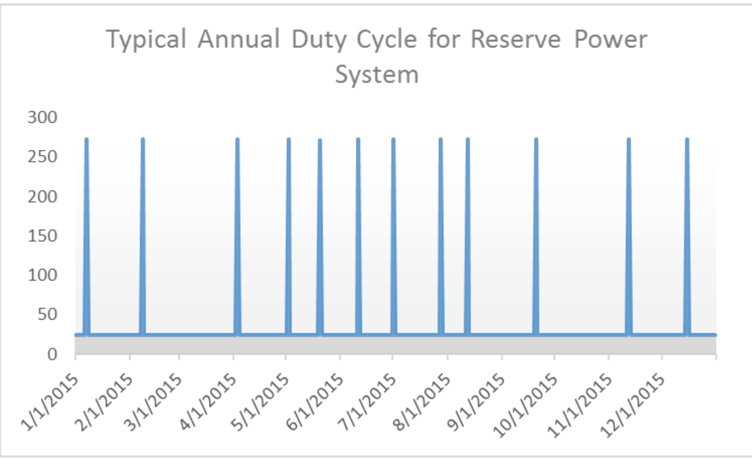

Figure 9 – A typical annual duty cycle for a reserve power system, in KW , with sudden bursts of discharge (blue spikes) when the grid goes down, and relatively constant low-level charging on a float charge basis (gray bar).

The duty cycle of a typical reserve power is shown in Figure 1. The blue spikes represent discharge at 250 KW for five minutes for each cycle. In most cases, a reserve power system has a diesel generator that, once switched on, takes up the building's load. The battery pack need only to provide a power discharge for approximately five to fifteen minutes until the generator takes over. Reserve power systems require a high-power capability battery that will only cycle 10-30 times per year. When the system is not being used for actual reserve power it usually maintains constant float charging, which means it is in a low level trickle charge or low level discharge from current leakage throughout all hours of the day. Many reserve power battery packs use this float charging time to provide power quality services to the building load, such as flicker control, voltage surge protection and reactive power.

Commercial Demand Charge Mitigation

Most commercial ratepayers have a two-tiered system of metering. Like residential ratepayers, they pay a set amount of money for each Kilo-Watt-Hour (kWh) consumed. They also pay a second rate, called a demand charge, that is set based upon the peak 15-minute usage period for the entire month. Electric utilities use demand charges as a method to incentivize commercial customers to reduce peaks in electricity demand. And commercial ratepayers do what they can to lower peaks in electricity consumption in order to lower their demand charges.

There is only so much a company can do to reduce peaks in demand while still concentrating on fulfilling their primary business mission. Thus there is always interest in new technologies that can allow them to lower their demand charges. One emerging trend is the use of electricity generation from PV to offset peaks in demands. This is an especially powerful tool in cases where air conditioning is often the cause of dramatic spikes in electricity usage. The correlation between PV output and air conditioning, however, is not perfect: sometimes the sun isn't shining brightly when it's hot outside.

Enter a battery-based energy storage system. With a relatively small amount of energy capacity, a PV/Energy Storage integrated system can be used to match the air-conditioning related demand spikes with output from either the PV system or the battery pack. Such a system requires only an energy storage system, a PV system and a controller/software package that optimizes the charging and discharging of the system for demand charge mitigation.

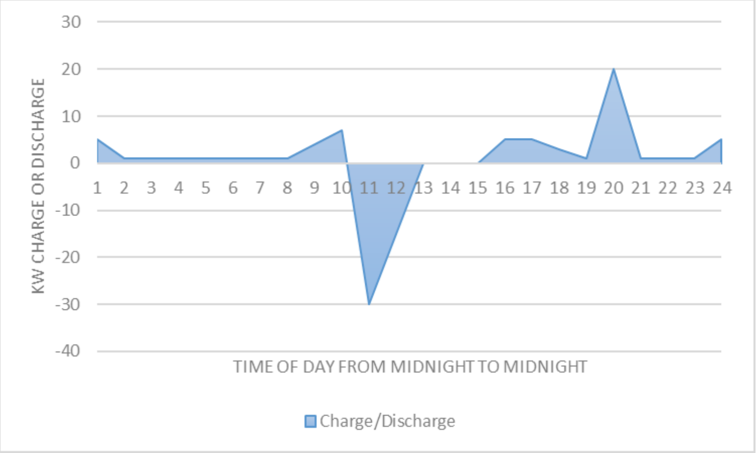

Figure 10 – Typical Daily Duty Cycle in KW for a Demand Charge Mitigation Application, with charging denoted in red line and discharging denoted in green lines.

The duty cycle of a typical daily duty cycle for a demand charge mitigation energy storage system is shown in figure 2. The system modeled here is a 45 KW energy storage system linked with a 100 KW PV system that is charged and discharged for a small commercial business, primarily to offset air-conditioning peaks. Note the large and short-lived spikes in both charging and discharging, which correspond in this case to air conditioning compressors running at full power at mid-day (charging) and to availability of low time-of-use rates in the middle of the night. Because of this pattern, a relatively small duration high-power capability battery pack should be chosen.

Commercial Time-of-Use Rate Optimization

Time-of-Use (TOU) rates are a schedule-based rate regime that charges lower prices for energy during certain low-demand periods in the day (e.g. 10 PM to 7 AM) and higher rates during high-demand hours (e.g. 7 AM to 10 PM). For a time-of-use rate to be administered, a smart meter must be installed at the site location. Electric utilities use smart meters as a method to lower electricity demand during peak demand periods and to encourage commercial customers to shift some parts of their electricity consumption to periods of low systemic demand. In almost all cases, TOU rates are available to commercial customers, not to residential customers.

Commercial entities with on-site renewables generation—In most cases PV systems—can impact the amount of money they pay for grid electricity during higher-priced periods of the TOU rate structure. The PV alone, however, can't be optimized for TOU optimization, as it generates electricity only during daylight and can't be otherwise modulated. Combining the on-site PV with an energy storage system provides an element of control for the facility-owner that allows them to optimize their energy consumption and generation for TOU rates.

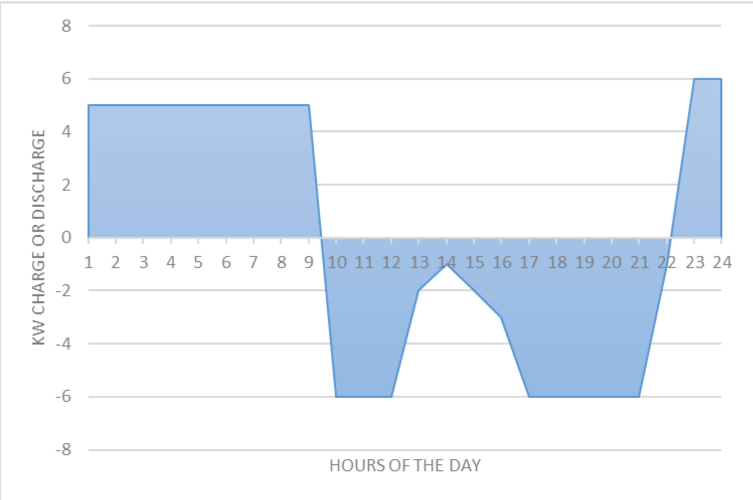

Figure 11 – Typical Daily Duty Cycle for a Time-of-Use Optimization Application with Renewables + ESS, in KW. Charging is denoted with the blue line and discharging with the gold line.

TOU rate optimization requires frequent cycling of the battery system, in coordination with the PV system. Figure 3 shows a typical monthly duty cycle for a 10 KW, 45 KWH integrated ESS/Renewables system that is programmed to optimize for TOU rates. Charging is relatively constant during night-time hours. Discharging is done during the daytime hours of 9 AM to 10 PM, assuming that the TOU rate increases electricity prices during those hours. Note that discharging sometimes drops off during the mid-day when PV generation is at its height. Although not shown, the ESS system would be completely inactive during weekend hours, as the TOU rates are usually not in effect during the weekend.

TOU rate optimization would require a relatively low-power capable battery with a significant amount of energy duration. The Power Control System would be sized on the relative low end because of the low power requirements of the system.

COMMERCIAL DEMAND RESPONSE OPTIMIZATION

Demand response is a process of voluntary electricity consumption curtailment during hours of peak demand or crisis events when grid function is impaired. A commercial business will enroll in a demand response program in order to get paid capacity payments even when the demand response process isn't active and also to get payments for curtailment during demand response events. Demand response originated as an option for large manufacturers who were willing to idle factory lines in order to prevent grid-wide blackouts during periods of extreme demand/supply imbalance. At most, conventional demand response events were only called a few hours per year. However, it has transformed over the last few decades into a much more integrated and frequently used part of grid management that can be called dozens and in a few cases hundreds of hours per year. Many grid managers and electric utilities expect demand response to continue to transform into an extremely complex system of connected devices distributed throughout the grid that can respond to DR calls on a frequent basis. (See also the LE Application Note "Load Management").

Energy storage systems can easily be used for the DR process. Instead of load curtailment, an energy storage DR responder would simply discharge electricity from the energy storage device. Integrated PV/Energy Storage systems can provide DR services as one of the menu of options that the system can perform, and thus provide an extra stream of revenue to the site owner without requiring load curtailment that might otherwise interfere with business processes. An ESS and PV system that participates in DR would require a communications gateway with the DR aggregator as well as an advanced metering capability that confirms and validates the reduction in energy usage during DR events.

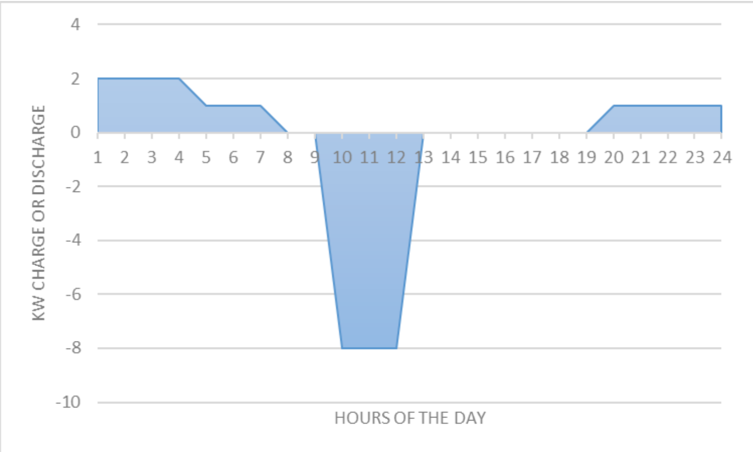

Figure 12 – Typical weekly duty cycle for a demand response ESS application. Batteries are discharged upon a demand response call by the grid operator. Batteries are then charged at night (when electricity cost is lowest, assuming a TOU rate is in force).

COMMERCIAL ON-SITE ANCILLARY SERVICES PROVISION

Managing a grid requires the right amount of power to be delivered at exactly the right time. Imbalance between power generation and consumption leads to deviations in the grid frequency (50 Hz in Europe and many parts of the world, 60 Hz in North America). A deviation of even one Hertz could potentially damage grid equipment, leading to outages and, in extreme cases, fires. By pulsing the right amount of power onto and off the grid to compensate for imbalances between generation and consumption, frequency regulation providers keep the frequency of the grid within safe parameters.

Most frequency regulation throughout the world is provided by traditional generation plants (natural gas, coal and hydropower being the most common) which keep a small portion of their capacity ready for the provision of frequency regulation in response to the grid operator's call. This process, however, usually takes more than a minute and, in some cases up to fifteen minutes. Battery-based energy storage could represent a means to provide ancillary services provision, usually in a faster and more efficient manner than with traditional generation.

To allow behind-the-meter ESS to participate in frequency regulation and other ancillary services markets multiple distributed behind-the-meter systems have to be aggregated into a virtual power plant that has sufficient power magnitude to be able to impact grid-wide frequency regulation (a lower bound of 2 MW's, for instance, is set in one U.S. market). Such aggregation concepts require sophisticated and secure control systems with communications pathways to aggregator's network operating centers.

This concept of aggregation of behind-the-meter ESS for ancillary services provision is still a hypothetical construct today in many regions of the world, but it represents a potential future source of revenue for behind-the-meter ESS owners throughout the world.

The vast majority of ESS used today for ancillary services is done in in the U.S. Today, more than 130 MW of frequency regulation ESS systems are in operation in the U.S. and there are multiple projects under design today. Several hundred MW's of frequency regulation ESS projects are planned in Germany, the U.K., South Korea and China.

Commercial and Residential Self Consumption

A self-consumption duty cycle refers to the combination of an onsite renewables generation source and an onsite ESS to displace all or the vast majority of electricity consumption from the grid. Most onsite renewables send any excess electricity generation that is not consumed by the system owner directly onto the grid. The system owner is compensated for this by having this reverse flow of electricity turn the buildings electricity meter backwards. This arrangement is referred to as net metering (because in most cases, the electricity consumption of the host site can only be brought to net zero—in other words a system owner can't create a surplus of electricity and thereby make a profit from selling it onto the grid).

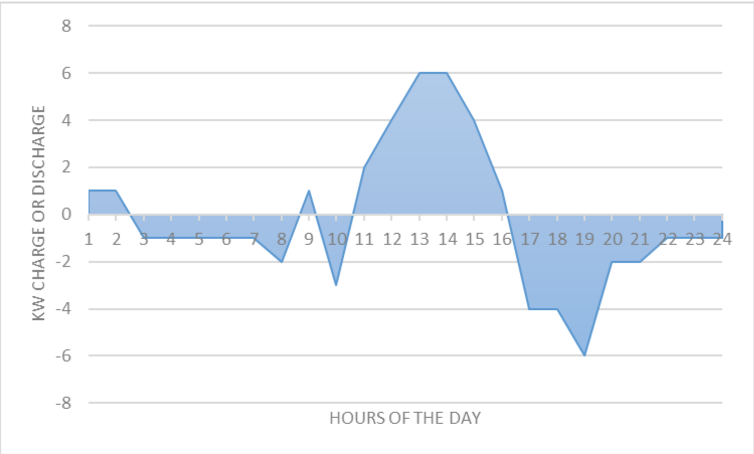

Figure 13 – Daily charge and discharge duty cycle of a 7 KW, 30 kWh self-consumption ESS. Note that charge occurs at night, using grid power, and then again during mid-day using power from the PV system. The discharge curve sees two distinct shoulders: one during the early morning and a second in the evening.

Net metering is an effective solution to the problem of operating a distributed generation device with a variable production profile, such as PV. It has societal limitations, however, because it can lead to over-penetration of localized distributed generation resources which can in turn lead to an unbalanced grid. In some cases in the United States, for instance, net metering programs are being made less effective by electric utilities by the imposition of extra charges and fees on net metering customers.

Commercial and Residential Off-Grid Microgrid

Off-grid systems are significantly less complex circuits, thanks to the lack of any anti-islanding requirements. Any grid-connected self-generation system must shut down in the case of a grid disruption so that it is not feeding electricity back into the grid (and thereby endangering maintenance personnel who are working on the lines). Off-grid systems do not require such a feature (since there is no grid into which the system can feed electricity) and are therefore significantly less complex when it comes to system design and safety features.

Prior to the last few years, the majority of renewables/ESS systems were used for off-grid purposes. It provides functioning electricity for a specific site that is not able to be hooked up to mains power. Most such installations are done in remote rural locations that don't have a grid or where the grid is poorly developed.

The majority of these types of off-grid systems are for residential purposes, but there are also some examples of commercial operations being run off the grid with an integrated renewables/ESS system. The largest such systems are large mining operations in remote areas, but such systems are also seen quite frequently in telecommunications networks.

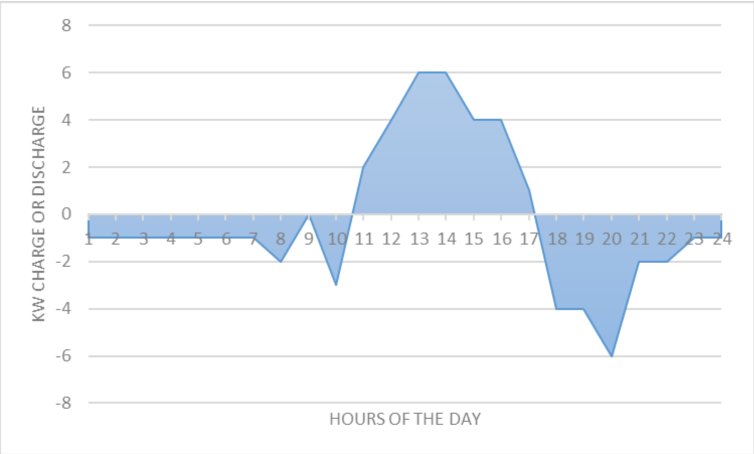

Figure 14 – Daily charge and discharge duty cycle of an off-grid 7 KW 45 kWh ESS paired with a 12 KW PV system. The off-grid curves look nearly identical to a self-consumption load profile, with the exception that charging only occurs during the hours of PV production.

CONCLUSIONS AND RECOMMENDATIONS

ESS technology continues to improve in cost-reduction, capabilities and safety engineering, making an integrated ESS/renewables system a viable business decision in many parts of the world. For those considering the purchase of an ESS/renewables system, there is no simple answer to the question "What should I buy?" Keeping the following guidelines in mind, however, will ensure a rational and sensible decision:

- **Choose the battery to fit the application**. Different batteries have different strengths and weaknesses. Lead acid batteries, for instance, are usually the optimal choice for reserve power UPS systems, as their low cost makes sense considering that their low durability isn't a concern when the batteries are discharged only a few times a year. Likewise, li-ion batteries often make the most sense in applications that require frequent cycling.
- **Know the installation site**. Know its history by studying its meter data for the previous twelve months. Know the activity that takes place there and how an ESS/renewables system will fit in with that. Know the safety concerns of the owner/inhabitants/employees. And know the specifics of the electrical circuits and power quality on them.
- **Only buy the batteries you need**. Size the system for the least amount of batteries for the application you expect to perform with the system. Any extra batteries that aren't being used will not be producing any revenue.
- **Understand the battery warranty**. Batteries will degrade and fail. Manufacturer warranties in the stationary storage industry are extremely complex contracts that ensure that the risk of such degradation and failure falls on the battery manufacturer, not the site owner.