IRENA
International Renewable Energy Agency

Electricity Storage and Renewables for **Island Power**

A Guide for Decision Makers

May 2012

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation dedicated to renewable energy. In accordance with its Statute, IRENA's objective is to "promote the widespread and increased adoption and the sustainable use of all forms of renewable energy". This concerns all forms of energy produced from renewable sources in a sustainable manner and includes bioenergy, geothermal energy, hydropower, ocean, solar and wind energy.

As of April 2012, the membership of IRENA comprised 158 States and the European Union (EU), out of which 92 States and the EU have ratified the Statute.

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Foreword

Energy is a key issue for sustainable development. In island and remote communities, where grid extension is difficult and fuel transportation and logistics are challenging and costly, renewable energy is emerging as the energy supply solution for the 21st century, ensuring reliable and secure energy supply in such communities. The deployment of renewable energy technologies is increasing globally, supported by rapidly declining prices and government policies and strategies in many countries, resulting in renewable energy solutions being the most cost-effective option in many markets today. For example, in 2011 the Special Report of the IPCC (Intergovernmental Panel on Climate Change) on Renewable Energy Sources and Climate Change Mitigation showed that approximately 50% of new electricity generation capacity added globally between 2008 and 2009 came from renewable energy sources. Therefore, the future of renewables as the base energy source for islands and remote communities looks very bright.

However, as the share of renewables in power supply increases, the natural variability of some renewable energy sources must be tackled appropriately to ensure continuous availability and efficient use of the energy generated. Successful strategies to manage this variability can encompass a range of measures, such as a balanced supply technology portfolio, geographical spread of supply, better forecasting tools, demand-side management and appropriate storage solutions. Traditionally, large scale electricity storage systems were based on pumped hydropower installations. New solutions are emerging, including affordable and long-lasting batteries. This technology field is developing rapidly and prices are falling.

IRENA has developed this report as a practical guide to the available energy storage solutions and their successful applications in the context of islands communities The report also includes various best practice cases and different scenarios and strategies. It is part of the IRENA Renewables in Islands Initiative (IRII) and contributes to the sustainable energy for all initiative of the United Nations. We hope this report helps decision-makers and project developers in their daily work. We also hope to receive your feedback so that we can build upon and improve IRENA's work on the subject.

Dolf Gielen
Director, Innovation and Technology

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Executive Summary

Electricity systems in remote areas and on islands can use electricity storage to integrate renewable generation and help meet continually varying electricity demand. Electricity storage technologies vary widely in design, technological maturity and cost. There is no single best storage technology, and storage is not necessarily appropriate for all island electricity systems. This report will help electricity system planners, operators and managers to better understand what role storage can and should play in their electricity systems and to provide guidance on selecting and installing storage.

The mature technology of lead-acid batteries has moderate costs and high reliability. However, these batteries have a relatively short lifetime (typically, three to ten years) and must be disposed of or recycled properly. Lithium-ion batteries are common for mobile applications (such as cell phones and laptop computers) and may make their way into the electricity grid market in the next five years. They have higher first costs than lead-acid batteries but longer lifetimes and lower losses. Flow batteries (notably, vanadium-redox and zinc-bromine) hold the promise of long lifetimes and low operating costs. However, they are just entering the commercial market and thus do not have an established record of operation for electricity storage applications. Flywheels are best suited for short-duration storage (less than one minute), but they are still at an early stage of technical development. Compressed air energy storage (CAES) and pumped hydro are generally suitable only for large (500 MW+) electricity systems. There are numerous other storage technologies in earlier stages of technical development.

In addition to helping integrate renewables, storage can also contribute significant value by increasing the operating efficiency of diesel generators. These generators are much more efficient when operated at high load factors, and the addition of storage can significantly reduce the number of hours they operate at low or minimum load factors.

Storage can also be of value in systems that are transmission capacity–constrained or that suffer from low power quality at the end of the distribution system. Storage is generally not appropriate, in contrast, for solving problems such as chronic supply shortages or poorly performing transmission and distribution systems.

Detailed modeling of a typical diesel-based island electricity system shows that storage can be cost-effective even in the absence of renewables through its ability to increase diesel generator efficiency and thereby reduce diesel consumption. The rampant oversizing of diesel generators contributes to these potential savings. A combination of renewables, storage and diesel generators—all carefully sized and integrated—can yield the lowest cost solution (based on the levelised cost of electricity). However, such systems are complex. “Pure” renewable systems, such as photovoltaic (PV) plus storage, are relatively expensive due to the need for PV system and storage oversizing to meet loads during extended cloudy periods.

Acquiring storage for an electricity system has much in common with any large capital acquisition project. However, it does require that particular attention be paid to: (1) system integration, as storage must be carefully integrated with other electricity system components; (2) technical performance expectations, as many storage technologies are not yet technically mature; and (3) maintenance, as some storage options have critical maintenance needs.

Case studies of storage applications for island and remote locations point to several lessons learned from project experiences elsewhere, including:

- Pay close attention to system *design*, particularly ensuring that all system components are sized correctly and can work together.
- The more system components, the greater the complexity and challenge of system integration.
- Do not expect new technologies/pilots to be financially viable.
- Walk first, then run. Try to introduce one technical innovation at a time.
- Do not underestimate the transport costs, complexity and time requirements associated with getting equipment and expertise to rural/isolated locations.
- System monitoring and operation and maintenance (O&M) are critical to ensure system reliability/longevity.
- Test and debug system components *before* sending them out to rural/isolated locations.

- Diesel generator oversizing is rampant and contributes to high diesel consumption.
- It is critical to make systems financially sustainable. Even if subsidies cover first costs, operating costs (including battery replacement and O&M) will need to be covered by electricity sales/revenues or continuing subsidies.
- End-user buy-in (financially and politically) is critical.

The first step when considering storage is to conduct careful analyses of the costs and benefits of storage. Storage can help integrate renewables and reduce diesel use; however it comes at a cost that must be considered. If storage is desirable, further system design analysis is needed to determine the optimal type of storage. This can be done with free or low-cost system design and analysis tools, such as the HOMER modeling system.

1. Introduction

1.A Opportunities and Challenges

Dependable and reliable electricity service is critical to economic development and quality of life. Electricity systems—particularly those in remote areas or on islands without physical connections to other electricity grids—must therefore continually monitor electricity demand and produce exactly the quantity of electricity demanded by their customers. This is a technically challenging task.

Electricity generation is typically provided by fossil fuel–fired power plants. These plants' output is continually adjusted to meet electricity demand, and plants are turned on and off as needed. This can be expensive, as many power plants are less efficient when operated at part load, which in turn increases fuel consumption. In addition, continual adjustment of output increases operation and maintenance (O&M) costs and can decrease power plant life.

An alternative to fossil-fired power plants is the use of renewable electricity- generating technologies. Some of these technologies, notably wind and solar, have seen recent dramatic price decreases. Onshore wind turbines can produce electricity at a levelised cost[1] of 5¢ to 16¢/kWh (U.S. cents, 5% discount rate), while photovoltaic (PV) systems are at about 22¢/kWh and dropping (5% discount rate, 25% capacity factor), according to the Organization for Economic Co-operation and Development (2010). These technologies are rapidly moving closer to "grid parity", meaning that they may be able to produce electricity at a cost comparable to that of traditional, fossil-fired technologies. And, at current prices for diesel fuel, they may actually be less expensive in remote areas.

The advantages of renewable electricity are many, including reduced environmental impact, potential for lower costs and reduced dependence on imported fuels. However, some forms of renewable electricity—notably, wind and solar—can aggravate the operational challenge of meeting electricity demand. The output of wind and solar plants varies with the resource (the wind and the sun, respectively), and it is not possible to ramp these plants up to meet demand. Instead, electricity system operators must simply take what they can get from these plants, and use "dispatchable" fossil-fired power plants to fill in any gaps.

1.B Storage: A Potential Solution

The fundamental problem underlying the two challenges of meeting variable demand and integrating variable renewables resources is the difficulty in storing electricity. Until recently, electricity storage was feasible only for very large systems, via pumped hydro, or for very small amounts of electricity, with lead-acid batteries. Recent technical advances in storage technologies, however, suggest that storage *may* be able to play a greater role in electricity systems.

This report is intended to help electricity system planners, operators and managers better understand what role storage can and should play in their electricity systems and to provide guidance on selecting and installing storage. The focus is on smaller systems for remote electricity systems and islands, particularly those in developing countries.

1.C Report Structure

The rest of this report is organized as follows:

- ***Chapter 2*** *provides a detailed snapshot of electricity storage technologies*, with an emphasis on current costs and performance. It focuses on batteries, as they have seen significant cost decreases in recent years and may be appropriate for smaller electricity systems.
- ***Chapter 3*** *is a guide for determining what role, if any, storage should play in an electricity system*. It first clarifies the problems storage can and cannot solve and then explores the complex relationships among renewables, storage and costs.
- ***Chapter 4*** *outlines the process for getting storage installed in an electricity system*. It lays out what needs to happen in order for storage to go from an idea to a fully functional component of an electricity system.
- ***Chapter 5*** *describes case studies of storage in electricity systems*. These case studies provide tangible evidence of the benefits—and problems—of storage.
- ***The appendices*** provide a list of abbreviations, links for more information and other resources that can assist decision-makers with storage-related decisions.

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[1] *Levelised cost accounts for first (capital) costs, operation and maintenance (O&M) costs and fuel costs.*

2. Overview of Storage Technologies

Storage in electrical systems can take many forms. Energy can be stored in chemicals (e.g. batteries or hydrogen), as potential energy (e.g. pumped hydro or compressed air), as electrical energy (e.g. capacitors) or as mechanical energy (e.g. flywheels). Because of this diversity of technologies, the system of categorisation and metrics used to compare them is abstracted from the underlying storage medium. Further complicating an assessment of storage is the growth of new and novel technologies to store energy, which rapidly adds new and unproven products to the marketplace. These new technologies often make performance claims specific to their technology that can be difficult to compare to other technologies.

In this chapter the metrics by which one can compare storage technologies, such as capacity and discharge rate, are discussed. Then there is an overview of the many storage technologies with a focus on the technologies that are currently commercially viable. Particular consideration is given to those storage technologies that appear especially promising for isolated, island and remote electricity systems. Finally, a high-level survey of technologies that are currently in the pilot project phase and those that are still under early research and development is provided. These are included to give a view of what technologies are not yet ready but may be available in the near future.

2.A Understanding Storage Performance

The fundamental metrics used to define a storage technology for most electricity grid systems include:

- Energy storage capacity [kWh or Ah];
- Charge and discharge rates [kW or A];
- Lifetime [cycles, years, kWh_{life}];
- Roundtrip efficiency [%];
- Initial capital costs [$/kW, $\$/kWh_{cap}$, and $\$/kWh_{life}$];
- Operating costs [$/MWh, $/kW x yr]; and

For mobile systems and systems in which space is at a very high premium, the physical size (m^3) of the system may also be important:

- Energy density [Wh/kg and Wh/m^3] and power density [W/kg and Wh/m^3].

Energy Storage Capacity

Energy storage capacity is the amount of energy that can be stored at a given time [kWh]. Some batteries will assume an operating voltage [V] and provide energy capacity in a different form [Ah, where kWh = V × Ah / 1,000]. The useful energy capacity will often be less than the stated total capacity based on a number of factors described below. For some battery technologies, the capacity will appear less if power is pulled out quickly and greater if power is pulled out slowly. Many technologies also have restrictions on how much of the storable energy may be used. Overdischarging some technologies (in particular, lead-acid batteries) can shorten their lifetime.

Charge and Discharge Rates

Charge/discharge rates are measures of power (kW) indicating the rate at which energy is added/removed from a storage system. Some systems will assume an operating voltage (V) and provide the charge/discharge rates as a current in amperes (A) [where kW = V × A / 1,000]. For many technologies these rates will not be constant values at all times; in practice, they will change with how much energy is in storage and how long power has been continuously removed/added to storage. However, at a high level they can be discussed with nominal values that are representative. The charge rate is lower than the discharge rate for most technologies. Typically, a storage system will be described in terms of its discharge rate, as in Figure 1.

Lifetime

Every storage technology has a limited lifetime. Some technologies measure lifetime according to how much they are charged and discharged [cycles], while other technologies will lose functionality due to time passing [years] and yet others have lifetimes limited by total energy throughput [kWh_{life} or Ah_{life}]. As they age, most storage technologies will suffer from degraded performance.

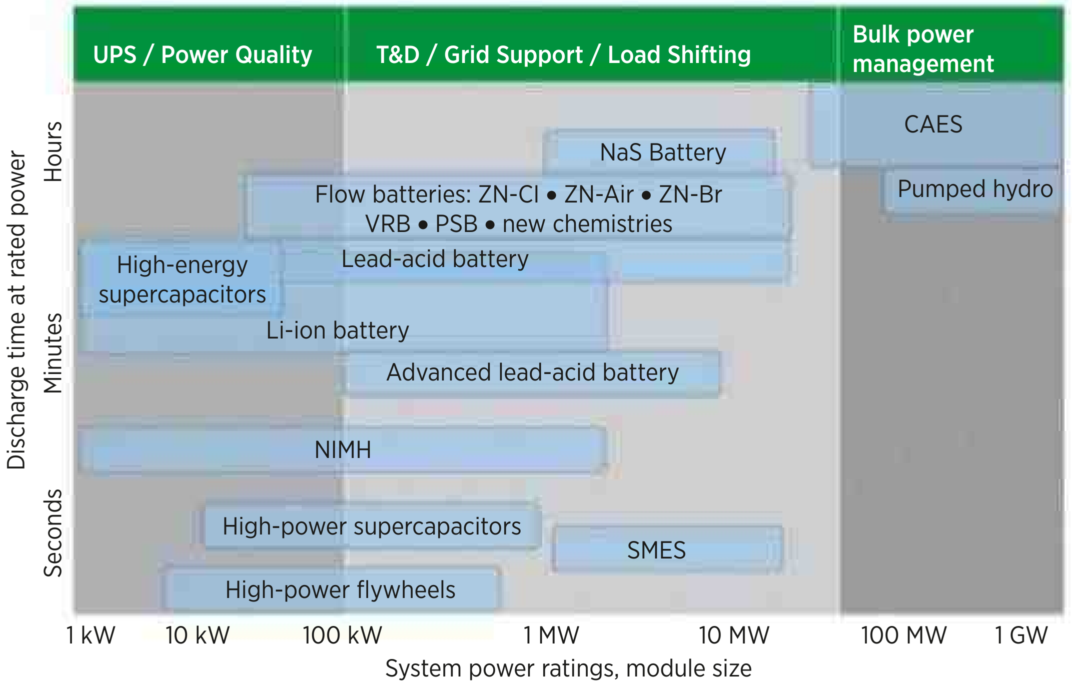

Figure 1: Summary of major storage technologies by discharge rate for different scales of application (adapted from Rastler, 2010)

Roundtrip Efficiency

Every storage technology will require more energy to charge than can be discharged. This loss of energy is typically expressed as a percentage known as roundtrip efficiency [%], which is the ratio of energy discharged from storage to the energy input into storage. There will be some energy losses during the process of storing the energy and some energy losses when converting the stored energy back into electricity. These both contribute to the roundtrip efficiency.

Roundtrip efficiency affects the costs of storage. A less efficient storage system will require more electricity to store the same amount of electricity supplied than a more efficient storage system. For example, if it costs $0.50/kWh to generate electricity and 20% of that is lost in the storage system, then the effective cost per delivered kWh is $0.625/kWh – plus the cost of the storage system (A more detailed sample calculation demonstrating the impact of roundtrip efficiency on costs is given in Appendix B).

Initial Capital Cost

The capital costs provided here are estimates based on professional experience and informal surveys of publicly available prices. They are intended to provide a high-level understanding of the issues and are not intended as cost inputs into a design. Costs for a specific system will vary across a wide range of factors. These factors include system size, location, local labor rates, market variability, intended use of the storage system, local climate, environmental considerations and transport/access issues.[2]

It is important to recognize that installing storage will impose additional costs, commonly called balance-of-system (abbreviated BoS) costs. These include safety equipment (e.g. fuses, current fault protection), inverters/rectifiers, system controllers, remote monitoring equipment and supplemental sensors. The needed equipment will vary considerably, depending on the specifics of the electricity system. BoS equipment can have a large impact on the total system cost, ranging anywhere from 100% to 400% more than the costs of the storage technology alone (See Appendix B for an example calculation that illustrates BoS costs).

The principal price bases for comparing technologies are the prices per amount of power that the storage can

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[2] *See Chapter 3 for a discussion of software that can estimate storage costs and performance for the electricity system.*

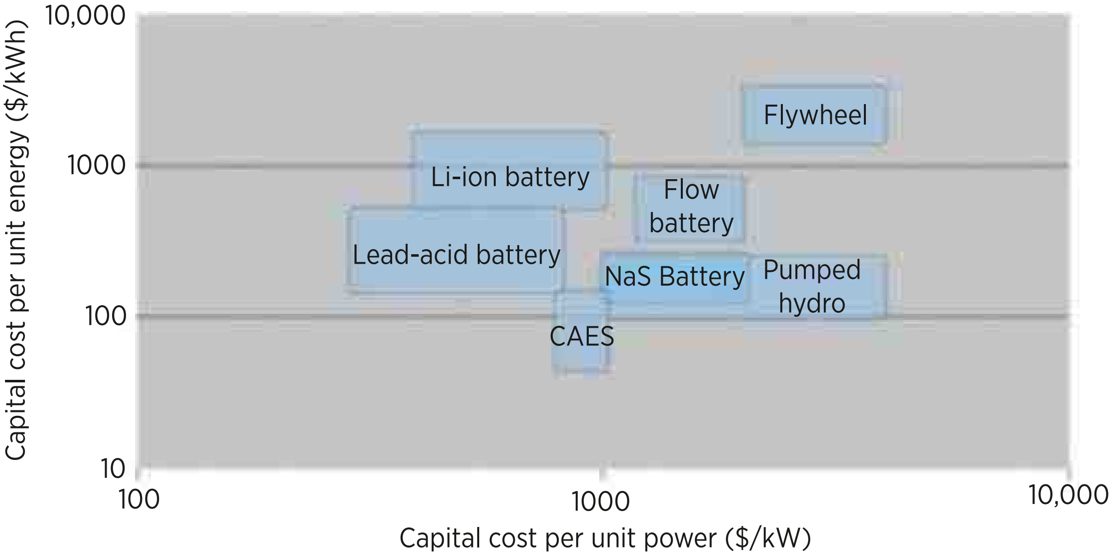

Figure 2: Initial capital cost per unit power versus capital cost per unit energy for selected storage technologies (Adapted from ESA, accessed 10 Dec. 2011)

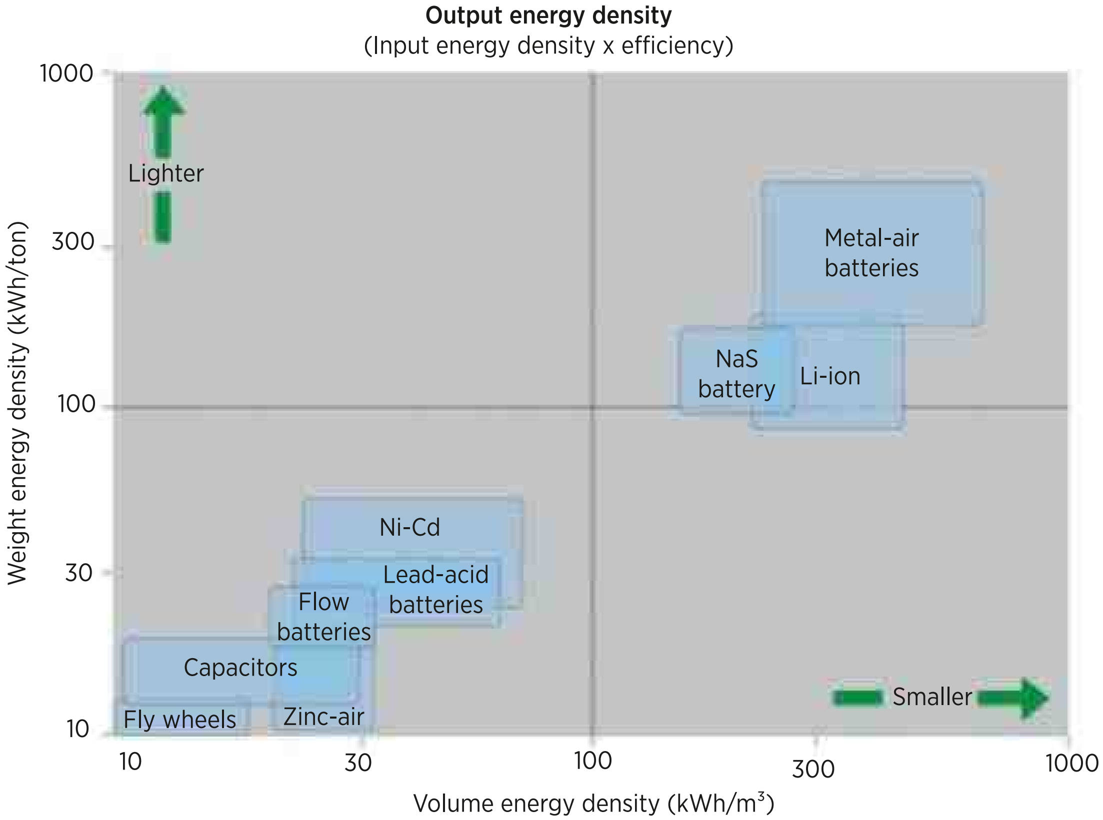

Figure 3: This plot shows a summary of major storage technologies by volume and weight energy densities (adapted from ESA, accessed 10 December 2011).

deliver [$/kW] and costs per amount of energy capacity [$/kWh$_{cap}$]. Figure 2 shows a graphical representation of costs for selected storage technologies.

When looking at costs, it is also important to consider the expected lifetime of the technology because frequent replacement will increase costs of the storage system. To capture the entire lifetime cost, the capital cost of the battery is divided by the total expected lifetime energy throughput [$/kWh$_{life}$]. The lifetime cost of storage provides insight into the cost of storing a kWh of electricity and indicates the expected additional cost for each unit of electricity stored (see Table 1 below). The costs presented here (in U.S. dollars) represent an average installation and do not include site-specific factors such as tariffs, taxes and shipping costs.

Operating Costs

Technologies require ongoing operation and maintenance to remain at peak performance. In reality, a number of factors will influence ongoing O&M costs, including how often the storage equipment is used, ambient temperatures, handling of the equipment, adherence to the recommended maintenance schedule, quality of installation, protection from overcharging, protection from overdischarging, the rate at which the equipment is cycled and the quality of the storage equipment. For simplicity, all of these factors are bundled in a typical annual cost based on the size of the equipment [$/kW x yr]. Estimates of these annual costs are provided in Table 1.

Energy and Power Density

In a stationary power system, the weight of the batteries is generally less important than their functionality. In some mobile applications and some site-specific locations, the size and weight of the storage technology is important. In these cases, it is useful to consider the capacity per weight [kWh/ton] or capacity per volume [kWh/m^3]. As these factors increase, the required size of the system decreases at equal energy storage; that is, storage technologies will be smaller and lighter if they have high weight and volume energy densities. These are summarized in Figure 3.

2.B Commercially Available Technologies

A number of storage technologies are commercially available and can be readily purchased from multiple vendors. Below is a review of commercially available storage technologies, which come in two basic size categories:

- *Small scale (up to 10 MW).* Lead-acid batteries are the most common storage technology in small-scale electrical systems. They are considered a mature technology. However, lithium-ion batteries are becoming more common, particularly if there are size or weight constraints. Zinc-bromine flow batteries are beginning to gain market acceptance at the small scale but are still considered an emerging technology.
- *Large scale (greater than 10 MW).* For larger electrical grids, pumped hydro storage is the dominant technology, accounting for over 99% of all storage worldwide. It is considered a mature technology. Compressed air energy storage (CAES) and sodium-sulfur batteries make up a much smaller, but still sizable, portion of the large-scale storage worldwide. However, pumped hydro storage and commercially viable CAES technologies must be located near sites with appropriate geology. Lead-acid batteries have been used traditionally, but they are being used less in recent large-scale installations. Flywheels, lithium-ion batteries and vanadium redox batteries (VRB) are gaining some market traction but are still emerging technologies at larger scales.

Technical and cost characteristics of these technologies are summarized in Table 1.

Batteries

Batteries are a very modular technology. The useful storage capacity will increase with each battery added to a battery bank and, depending on the architecture, the charge/discharge rate will also increase.

A battery is composed of a number of cells. Each of these cells contains a cathode (positive plate), anode (negative plate), positive electrolyte and negative electrolyte. Each cell typically has a voltage of around 1.5 to 2 volts although this will depend on the chemicals and materials used.

The life of batteries is dependent in part on how much of their storage capacity is used at any one time, which is known as the “depth of discharge” (DoD). The deeper a battery is cycled, the shorter its expected lifetime. For example, a battery cycled down to 80% of its full capacity (an 80% DoD) will, in general, have an order of magnitude shorter lifetime than a battery that is cycled only to a 10% DoD.

Deep-Cycle Lead-Acid Batteries. Lead-acid batteries are very common and are the *de facto* workhorse

Table 1: Summary of commercially available storage technologies. Source: Authors' estimates.

	Lead-acid batteries	Li-Ion batteries	NaS batteries	Flow batteries	Fly-wheels	Pumped hydro	Large-scale CAES
Applicable grid system size [kW/MW]	≤10 MW	≤10 MW	≥100 MW	25 kW–10 MW	100 kW–200 MW	Mostly ≥200 MW	≥500 MW
Lifetime [years]	3–10	10–15	15	Cell stack: 5–15; Electrolyte: 20+	20	25+	20+
Lifetime [cycles]	500–800	2,000–3,000	4,000–40,000	Cell stack: 1,500–15,000	>100,000	>50,000	>10,000
Roundtrip efficiency [%]	70%–90%	85%–95%	80%–90%	70%–85%	85%–95%	75%–85%	45%–60%
Capital cost per discharge power [$/kW]	$300–$800	$400–$1,000	$1,000–$2,000	$1,200–$2,000	$2,000–$4,000	$1,000–$4,000	$800–$1,000
Capital cost per capacity [$/kWh$_{cap}$]	$150–$500	$500–$1,500	$125–$250	$350–$800	$1,500–$3,000	$100–$250	$50–$150
Levelised cost of storage [$/kWh$_{life}$]	$0.25–$0.35	$0.30–$0.45	$0.05–$0.15	$0.15–$0.25	N/A	$0.05–$0.15	$0.10–$0.20
Annual operating costs [$/kW-yr]	$30	$25	$15	$30	$15	$5	$5

for industrial and commercial use. It is common to see lead-acid batteries in a range of applications, including in automobiles for starting and lighting, in small vehicles such as golf carts, at telecom centers for reliability and at facilities everywhere for emergency lighting. However, not all lead-acid batteries are appropriate for use in electricity supply systems. Batteries in electrical systems must be *deep-cycle* batteries, meaning that they must be able to discharge a large amount of energy in one cycle, which is made possible because they have a high useful energy capacity relative to their actual energy capacity. In particular, *automotive lead-acid batteries are not appropriate for use in electricity storage systems.*

Deep-cycle lead-acid batteries can be split into two common classes: *wet cell* and *valve regulated (VRLA)* batteries. A wet cell uses distilled water as part of its electrolyte, and the distilled water has to be replaced on a regular schedule (typically about twice a year). They must also be oriented upright to prevent spilling electrolyte. VRLA batteries require less maintenance and are less sensitive to non-upright orientations than wet cells. The primary distinctions between these types of batteries are the initial capital cost (wet cells are less expensive) and maintenance (VRLA batteries require less maintenance and will not spill). VRLAs can be either of the absorbed glass mat type or the gel type. Table 2 provides a summary of lead-acid batteries.

Concisely conveying the capacity of a lead-acid battery system is complicated and challenging. A lead-acid battery should never be discharged below 20% of the stated capacity (i.e. an 80% DoD) and under normal operation should never fall below a 50% DoD. Another challenge is that the capacity of a lead-acid battery decreases if power is pulled out quickly. Manufacturers will report capacities based on the time that it took to deplete the battery, with the notation C/Time (so C/20 is the current draw at which the battery will last for 20 hours). Regardless, the useful storage capacity is much less than the nominal storage capacity reported by manufacturers. Many assumptions have been made to provide a concise, single-value approximation for this report.

The lifetime of a lead-acid battery depends on a number of factors. The positive plate inside a lead-acid battery is corroded each time the battery is cycled, and its thickness directly relates to battery life. The lifetime of a lead-acid battery also depends on how the battery is charged and discharged. Most manufacturers recom-

Table 2: Summary of deep-cycle lead-acid battery properties

Applicability		10 MW and smaller systems
Useful storage capacity		0.5–10 kWh per battery
Charge rate [a]		0.1–1.5 kW per battery
Discharge rate [a]		0.5–2.0 kW per battery
Lifetime	**Time**	3 to 10 years
	Cycles	500–800 cycles
	Energy	100–7,500 kWh
Roundtrip efficiency		70%–90%
Initial capital cost	**Cost/discharge power** [b]	\$300–\$800/kW
	Cost/capacity [c]	$\$150/\text{kWh}_{\text{cap}}$–$\$500/\text{kWh}_{\text{cap}}$
Operating costs		\$30/kW-yr

Notes:

a. Charge and discharge rate will heavily impact the apparent storage and are shown here only for high-level comparison.

b. The cost per discharge power is based upon a typical C/5 rate, which indicates the power output that a completely full battery would be able to sustain for five hours.

c. Cost per capacity is based upon the C/20 rate, which indicates the amount of energy that a completely full battery would put out over 20 hours of constant discharge. Many manufacturers prefer to specify the C/100 rate, but the C/20 is a more practical value in remote systems.

Table 3: Summary of lithium-ion battery properties

Applicability		10 MW and smaller systems
Useful storage capacity		0.5–10 kWh per battery
Charge rate		0.2–2 kW per battery
Discharge rate		0.5–10 kW per battery
Lifetime	**Time**	10–15 years
	Cycles	2,000–3,000 cycles
	Energy	1,000–30,000 kWh
Roundtrip efficiency		85%–95%
Initial capital cost	**Cost/discharge power**	\$400–\$1,000/kW
	Cost/capacity	$\$500$–$\$1{,}500/\text{kWh}_{\text{cap}}$
	Levelised cost of storage	$\$0.30$–$\$0.45/\text{kWh}_{\text{life}}$
Operating costs		\$25/kW·yr

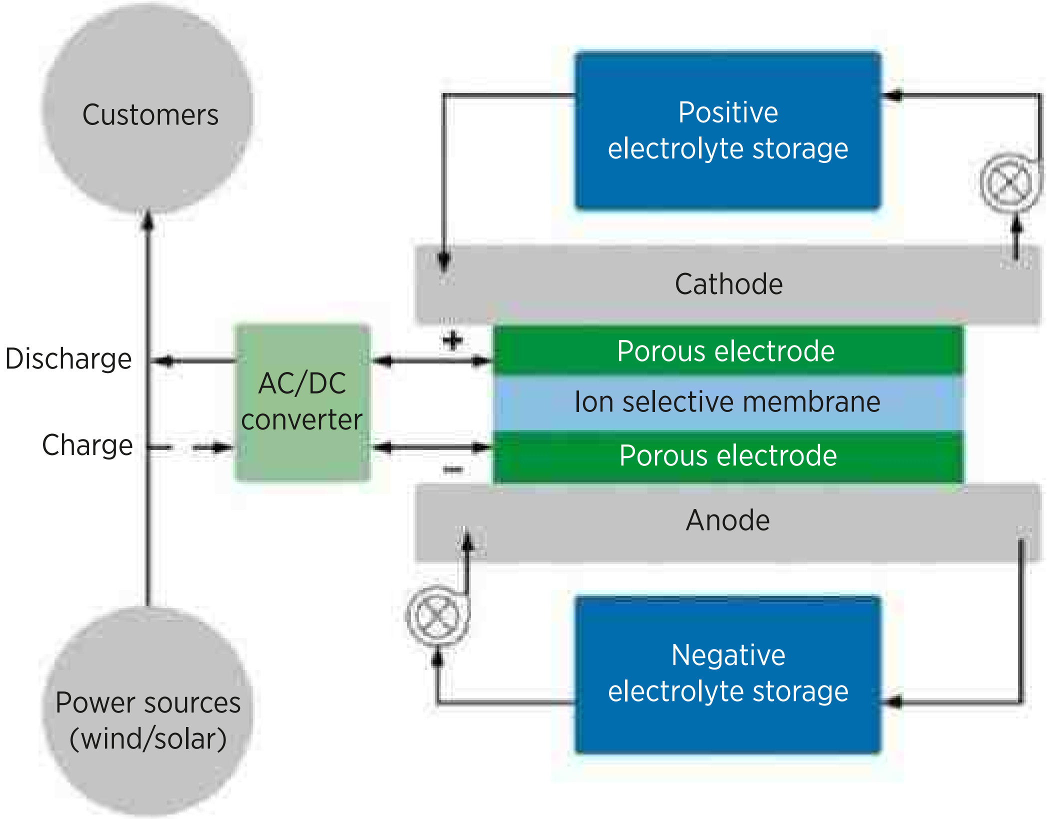

Figure 4: A schematic of a flow battery (adapted from Nguyen and Savinell, 2010)

mend that their lead-acid batteries not be discharged below about 30% to 50% of the specified battery capacity. Overcharging can shorten battery life. High ambient temperatures will also shorten battery life.

A lead-acid storage system requires a charge controller to properly manage the battery's state of charge. It is also important to employ a skilled technician who understands how to fill wet cell batteries, how to equalize the charge, how to clean the contact posts and how to perform other routine maintenance tasks.

Lithium-ion (Li-ion) Batteries. Lithium-ion technology has been steadily improving over the past decade. Driven by the use of Li-ion batteries in mobile applications (such as mobile phones and laptops), the technology has rapidly matured. For small mobile applications, Li-ion may be considered a mature technology; however, in electrical grid applications, Li-ion is still developing. Li-ion batteries are more commercially proven in applications in which size and weight need to be minimized.

Li-ion batteries have a number of different chemistries. Common examples include lithium-cobalt oxide ($LiCoO_2$), lithium-nickel oxide ($LiNiO_2$) and lithium-iron phosphate ($LiFePO_4$). Although there are some performance and lifetime differences among these technologies, at a high level they provide excellent weight-to-energy and weight-to-power ratios and slow self-discharge loss when not in use. Table 3 presents a summary of Li-ion batteries.

If overcharged or overheated, Li-ion batteries can rupture and, in some cases, explode. Both protective circuitry and fail-safe mechanical protections are typically included with a modern Li-ion system and have minimized these safety risks. Regardless, the ambient temperature where the battery will be used should be considered when using Li-ion storage in an application. Exposure to high temperatures can also shorten a Li-ion battery's expected lifetime.

Compared to lead-acid batteries, Li-ion batteries have more consistent charging and discharging characteristics and can handle deeper discharges from their stated capacities with less impact on lifetime. Li-ion batteries tend to cost more upfront but have longer lifetimes.

Sodium Sulfur Batteries. Sodium sulfur (NaS) batteries are based on the reaction between a sodium (Na) electrode and a sulfur (S) electrode. The most widely used NaS batteries require high temperatures (roughly

Table 4: Summary of sodium sulfur technology properties

Applicability		100 MW+
Useful storage capacity		400kWh/battery module
Charge rate		50kW/battery module
Discharge rate		50kW/battery module
Lifetime	**Time**	15 years
	Cycles	4,000–40,000 cycles
	Energy	1,000,000–1,500,000 kWh
Roundtrip efficiency		80%–90%
Initial capital cost	**Cost/discharge power**	\$1,000–\$2,000/kW
	Cost/capacity	\$125–\$250/kWh$_{cap}$
	Levelised cost of storage	\$0.05–\$0.15/kWh$_{life}$
Operating costs		\$15/kW·yr

300°C) for the reaction to take place, and the chemicals involved are corrosive. These factors make the battery suitable only for use in large grid applications. NaS batteries can be used to provide ancillary services (grid stabilization or support) to the grid. These ancillary services include preventing voltage fluctuations and momentary outages although they can also be used to stabilize intermittent renewable production in large mainland grids. A summary of properties of NaS batteries is presented in Table 4.

Flow Batteries

Flow batteries contain two major components: *electrolytes* and a *cell stack.* There are two electrolytes in a flow battery: a positive electrolyte and a negative electrolyte. The cell stack contains the anode and cathode that use the charge difference between the two electrolytes to produce power (see Figure 4).

The cell stack size roughly corresponds to the amount of power that the flow technology can supply or absorb at once, and the electrolyte volume roughly corresponds to the amount of energy that can be stored in the flow battery. The electrolyte and cell stack may be sized independently, which allows a system to have storage that precisely meets one's size needs. In many cases, the capacity can be increased if operational needs prove different from what was expected during the planning process.

Furthermore, most flow batteries can be fully discharged (to 100% DoD) without damaging the equipment, which expands the operational range of their storage capacity. This flexibility to independently size energy and power capacity is inherent in the technology, but manufacturers will often have a common configuration for marketing purposes.

One of the biggest challenges for flow batteries is their low energy density. The cell stack is roughly the size of a similarly sized traditional battery, but the electrolyte requires tanks, piping and pumps to hold and transport the fluid. Although flow batteries tend to have low lifetime costs of storage compared to other technologies, they also have high capital costs, which can become cost-effective due to the long expected lifetime and low operational costs.

Two prominent flow battery chemistries are commercially viable: vanadium redox batteries (VRB) and zinc-bromine batteries (ZBB). The VRB technology has more expensive cell stacks but less-expensive electrolyte than the ZBB. Additionally, the VRB electrolyte will, according to many estimates, last longer than 100 years. In general, ZBB is being marketed toward small-to-midsize systems, whereas VRB is being marketed to larger utility customers (See Table 5).

Table 5: Summary of flow battery properties

Applicability		25 kW to 10 MW systems
Useful storage capacity		20–50 kWh
Charge rate		5–20 kW
Discharge rate		5–25 kW
Lifetime	**Time**	5–15 years for cell stack 20+ years for electrolyte
	Cycles	1,500–15,000 cycles per cell stack
	Energy	75,000–300,000 kWh per cell stack
Roundtrip efficiency		70%–85%
Initial capital cost	**Cost/discharge power** [a]	\$1,200–\$2,000/kW
	Cost/capacity [a]	\$350–\$800/kWh_{cap}
	Levelised cost of storage [b]	\$0.15–\$0.25/kWh_{life}
Operating costs		\$30/kW·yr

Notes:

a. For flow batteries, the cost of discharge power and the cost of capacity are largely independent; storage cost will be the sum of these two factors. This is different than for most other batteries where the costs are very interrelated and only one should be used to determine storage cost.

b. The levelised cost of storage assumes that the system is used for at least 20 years and properly maintained. If the system is used for a shorter time, then the levelised cost will be higher.

Table 6: Summary of high-power flywheel properties

Applicability		Frequency and ramp rate reduction for 100 kW to 200+ MW systems
Useful storage capacity		1 kWh to 25 kWh
Charge rate		100 kW to 300 kW
Discharge rate		100 kW to 300 kW
Lifetime	**Time**	20 years
	Cycles	>100,000 cycles
	Energy	N/A
Roundtrip efficiency		85%–95%
Initial capital cost	**Cost/discharge power**	\$2.000–\$4.000/kW
	Cost/capacity	\$1.500–\$3.000/kWh_{cap}
	Levelised cost of storage	N/A
Operating costs		\$15/kW·yr

Table 7: Summary of pumped hydro technology properties

Applicability		Typically very large systems (200 MW+), although some applicability to small systems (5 MW+)
Useful storage capacity		Highly site dependent
Charge rate		5 MW to 4,000+ MW
Discharge rate		5 MW to 4,000+ MW
Lifetime	**Time**	25+ years
	Cycles	>50,000
	Energy	N/A
Roundtrip efficiency[a]		75%–85%
Initial capital cost	**Cost/discharge power**	\$1,000–\$4,000/kW
	Cost/capacity	\$100–\$250/ kWh_{cap} (highly site dependent)
	Levelised cost of storage	\$0.05–\$0.15/kWh_{life}
Operating costs		\$5/kW·yr

Note:
a. (Deutsche Physikalische Gesellschaft, 2011)

Flywheels

Flywheels use a large, heavy, rotating wheel to store energy. Electricity is converted into kinetic energy for storage, increasing the speed of the rotating wheel. The wheel slows when energy is discharged from it.

There are two types of flywheels: high-power flywheels and long-duration flywheels. Long-duration flywheels are still in early research and development and are not commercially viable. High-power flywheels store and release large amounts of power for very short periods of time—typically, about one minute. They are often used as part of an uninterrupted power supply to bridge between sudden power outages and starting a generator. They are also well-suited for reducing ramp rates from intermittent renewable technologies, such as solar and wind, improving system stability (see Table 6).

Flywheels are a low-maintenance storage technology with a long lifetime. However, they do not currently provide cost-competitive long-term storage. In some applications, they may be useful to improve short-term power stability (less than one minute) and improve delivered power quality (e.g. reduced reactive power).

Pumped Hydro

Pumped hydro storage involves pumping water from one reservoir to another reservoir at higher elevation. The water is then fed back to the lower reservoir through a turbine to capture the potential energy that was stored in the water. Pumped hydro installations are considered a mature technology.

A pumped hydro system is only cost-effective for very large amounts of storage. Existing pumped hydro systems have storage and production capacity typically more than 100 MW to 200 MW. This makes pumped hydro appropriate only for systems that have a large swing between peak electrical demand and low electrical demand, typically for large, mainland grids with demand greater than 1,000 MW (see Table 7). There are currently about 104,000 MW of pumped hydro storage capacity worldwide (U.S. Department of Energy, 2008).

Pumped hydro is not modular, and its appropriateness for an electrical grid is highly site-specific. There needs to be an available source of water, and the geology of the area will necessarily impact the capital expenditure. In addition, a number of highly trained consultants and engineers will be necessary to analyze, design and build

Table 8: Summary of compressed air energy storage technology properties

Applicability		Only very large systems (500 MW or greater)
Useful storage capacity		Highly site dependent
Charge rate		50–300 MW
Discharge rate		100–500 MW
Lifetime	**Time**	20 years
	Cycles	>10,000
	Energy	$50–$150/kWh [a]
Roundtrip efficiency [b]		45–60%
Initial capital cost	**Cost/discharge power** [c]	$800–$1,000/kW
	Cost/capacity	$\$50–\$150/\ \text{kWh}_{\text{cap}}$ (highly site dependent)
	Levelised cost of storage	$\$0.10–\$0.20/\text{kWh}_{\text{life}}$
Operating costs [d]		$5/kW·yr

Notes:

a. Costs are highly site-specific. Values based on ESA, 2002 are projected over ten years at 3% annual inflation.
b. Large-scale CAES improves the efficiency of a simple-cycle natural gas turbine rather than storing electricity directly. Roundtrip efficiency is defined here as the improvement in fuel efficiency from using the compressed air from CAES. The efficiency has been estimated against a modern simple-cycle turbine (assumed 40% efficient). For reference, one estimate is that the McIntosh CAES returns 1 kWh of electricity from 1.34 $\text{kWh}_{\text{thermal}}$ of input fuel and 0.80 kWh of compressed air energy (Pollak 1994).
c. The cost is roughly based on a 3% annual interest rate for 20 years to escalate the 1991 costs reported by Pollak, 1994.
d. Does not include fuel costs for the gas turbine.

the storage system. Civil, mechanical and electrical engineers will need to be involved in all stages of the process. Furthermore, the permitting process will likely be lengthy and involve a consultation process with local residents and other affected stakeholders.

Large-Scale Compressed Air Energy Storage (CAES)

There have only been two successful large-scale CAES projects (McIntosh, Alabama, USA in 1991 and Huntorf, Germany in 1978), but because the underlying technologies are based upon traditional equipment, it is generally considered a mature technology. The particular challenge with large-scale CAES is finding an appropriate location. The two existing projects are located near underground salt caverns although other underground formations could be suitable.

These two proven CAES projects are *diabatic*, meaning that when the air is compressed, the heat generated is lost as waste heat. *Adiabatic* CAES technologies (currently under development) would capture and use this waste heat to improve the efficiency of expanding the compressed air. This could improve storage efficiency substantially.

Conventional large-scale CAES differs from many other storage technologies in that the stored energy is not converted directly to electricity but rather used to improve the efficiency of fossil fuel–based electrical production. This CAES technology requires extensive geologic surveys, and costs will be site-specific. CAES is appropriate for electricity systems 500 MW or larger (see Table 8).

2.C Technologies Under Development

The technologies presented here are not currently cost-competitive with the storage technologies discussed above. However, they are under development and may someday become mainstream technologies. Since the research and development (R&D) focuses on improving technical performance rather than cost reduction and there are few or no full-scale installations of these technologies, reliable cost data are generally not available for these technologies.

Hydrogen Storage

Hydrogen storage for grid applications is expensive, due largely to the roundtrip efficiency of storage. Typical roundtrip efficiency values in pilot projects are in the range of 20% to 30%.[3] It will be very difficult for hydrogen storage to overcome this fundamental hurdle, and some argue that it cannot be done (Bossel 2006).

Despite its efficiency challenges, there has been strong interest in hydrogen storage for off-grid applications. There have been several pilot projects worldwide—including in Ramea, Newfoundland, Canada and Utsira, Norway; however, the reported efficiencies have been very low.[4]

A hydrogen storage system consists of three major pieces of equipment: an electrolyzer, which uses electricity to remove hydrogen from water; a storage tank, which captures and stores the hydrogen; and a fuel cell (or generator), which uses hydrogen to generate electricity (see Table 9).

Table 9: Summary of hydrogen storage technology properties

Applicability		100 kW–10 MW
Useful storage capacity		Highly variable
Charge rate		10 kW–5 MW
Discharge rate		Highly customizable
Lifetime	**Time**	20 years
	Cycles	N/A
	Energy	N/A
Roundtrip efficiency		20%–30%

Dry Cell Batteries

Dry cell batteries are based on a technology from the 1990s and use metal-coated fiber mesh as part of the storage element. Recently, these batteries have gained a much higher profile internationally with several major installations in the Hawaiian Islands. These are considered by some to be a variant of advanced lead-acid batteries, but some industry members disagree with that characterisation[5] (see Table 10).

There is very little public data about these batteries due to non-disclosure agreements that have been required of all persons involved with these projects. Despite indications that dry cell batteries may be technically viable, without additional price data, it is unclear if they are commercially viable beyond pilot projects.

Table 10: Summary of dry cell battery technology properties

Applicability		50 MW+
Useful storage capacity		1,000 kWh_{cap}
Charge rate		1,500 kW
Discharge rate		1,500 kW
Lifetime	**Time**	20 years
	Cycles	250,000 cycles at 10% DoD 20,000 cycles at 50% DoD 1,000 cycles at 100% DoD
	Energy	~10,000,000 kWh_{life}
Roundtrip efficiency		90%

2.D Technologies in Early Development

Storage technologies are in rapid transition. There are a number of technologies that have potential but are currently in a relatively early stage of commercial development. These include, but are not limited to:[6]

- *Supercapacitors and ultracapacitors.* These are capable of charging and discharging very rapidly and have extremely long lives. Although they can put out large amounts of power, they do not store large amounts of energy. They are currently being considered as a bridging technology (similar to a flywheel) that provides power when an intermittent renewable resource drops suddenly.
- *Vehicle-grid integration.* Plug-in electric vehicles have the potential to provide peak capacity and

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[3] Assuming an efficiency of 25%, this would mean that the cost of electricity from hydrogen storage is 400% what it would be if the electricity were used directly, and the cost would be even less favorable if the capital costs were included. This is in contrast to a lead-acid battery, which, at an approximate roundtrip efficiency of 75%, only incurs a 33% price increase over directly delivered electricity. See Example 2 of Appendix B for a more detailed sample calculation.

[4] For example, see the case study on Ramea in Chapter 5.

[5] The Electric Power Research Institute (EPRI) and industry analyst Energy Insights consider these a variant of advanced lead-acid batteries.

[6] This list is not exhaustive; rather, it is intended to highlight some of the many new storage technologies currently under development.

load leveling for the grid when they are parked and connected to the grid.

- *Metal-air batteries.* Current technology rechargeable metal-air batteries are inefficient and have a relatively short lifetime of a few hundred cycles. However, as with all these technologies, technical performance will likely improve with further R&D investment.
- *New Li-ion chemistries.* Li-ion batteries are being developed to reduce costs, improve safety and increase lifetime while maintaining energy/power density benefits.
- *New types of NaS cells.* There are a number of alternate NaS technologies that can operate at low temperatures and can produce more power.
- *Ultra-batteries.* Ultra-batteries are hybrid energy storage devices that combine VRLA batteries with electrochemical capacitors.
- *Superconducting magnetic energy storage (SMES).* Energy is stored in the magnetic field induced when a current is passed into a superconducting coil at very low temperatures. The low temperatures create a conductor with very little resistance and losses.
- *New flow batteries.* Promising new chemistries include iron-chromium (Fe/Cl) and zinc-chlorine (Zn/Cl)
- *Improved (adiabatic) CAES.* This variant of existing compressed air energy storage would capture the heat generated when compressing air and use it to heat the air when it is expanded, potentially improving the storage efficiency to about 70%.
- *Above-ground CAES and mini-CAES.* These CAES technologies are similar to traditional CAES technologies except that compressed air is stored in smaller, above-ground tanks.
- *Long-duration flywheels.* These flywheels would be able to store electricity for longer periods of time than current high-power flywheels.

2.E Storage Technologies – Summary

Storage technologies are undergoing rapid advancement, and there is as yet no clear winning technology. However, as experience with these technologies grows, their advantages and constraints are becoming clear. Those advantages and constraints are summarized in Table 11 for those technologies that are commercially available (section 2.B) and under development (section 2.C).

Table 11: Advantages and Constraints of Storage Technologies

Storage Technology	Advantages	Constraints
Lead-acid batteries	Widely available, moderate costs, modular	Limited lifetime, must be disposed of properly, must be maintained properly
Li-Ion batteries	Rapid technological improvement, compact in size	Rupture risk, little experience with use in electric grids
Na-S batteries	Can be used for ancillary services, high roundtrip efficiency	Suitable only for larger electricity systems, corrosive chemicals
Flow batteries	Can be fully discharged, somewhat modular	Still under development, higher capital costs
Flywheels	Modular, low maintenance	Expensive
Pumped Hydro	Technically proven, low costs	Very large scale, significant environmental impacts of construction
CAES	Moderate costs	Very large scale, uses natural gas
Hydrogen	Can be used as a transportation fuel, compatible with fuel cells	Low roundtrip efficiency, expensive

3. Does Storage Make Sense for My System?

When considering whether storage might be an appropriate addition to an electricity system, the first question to ask is: what is the problem that I am trying to solve? Storage, like any technology, works best when properly applied and is good at some tasks but not so good at others. Here several situations for which storage might be a promising solution are identified—and several for which it probably is not. It is then shown, using a model of a typical island electricity system, how renewables, storage and costs all relate.

3.A Problems Storage Can Solve

Here are a few examples of useful applications of energy storage.

I want to install significant variable renewables (wind and solar) and am concerned about maintaining reliability. Or I have already installed significant variable renewables, and my existing generators cannot keep up with the renewables' rapidly changing output.

If an electricity system has, or plans to have, significant amounts of variable renewables (such as wind and solar), then storage can help integrate those resources into the system. Storage can fill in the gaps when renewables have reduced output and thus allow for renewables to provide a greater fraction of total electricity while maintaining system reliability.

There is no hard-and-fast rule about how much renewable energy can be added before storage becomes attractive. However, as a starting point, the following rough rules can be considered:

- For variable renewables penetrations (defined as percent of generation, not capacity) of 0% to 20%, storage is probably not necessary.[7] Some additional controls and equipment may, however, be helpful for maintaining reliability.
- At variable renewables penetrations of 20% to 50%, it is likely that some actions will be necessary to maintain reliability. These will probably include storage but could also include demand response, use of emergency-only generators or contracts with neighboring utilities (if physical links exist) to supply power as needed.
- At variable renewables penetrations over 50%, storage or one of the other options listed above will almost certainly be required.

My diesel fuel consumption is high, and my diesel generators often operate at partial load.

Most power plants, particularly those fueled by diesel, are much more efficient at full load, and efficiency drops off rapidly at lower loads (Figure 5). A related problem is that many diesel generators cannot operate below about 30% of their rated capacity, meaning that they must operate at 30% even if demand is lower than that. Diesel fuel can be expensive and, for remote locations, diesel fuel deliveries can be unreliable. Storage can help reduce diesel consumption by shifting the diesel generators' operating characteristics such that they operate at optimum efficiency, which is typically at or near peak load. When load drops, the diesel generator simply shuts off and allows the storage to meet the load.

My generating resources are poorly matched with my loads, resulting in frequent outages and low power quality.

If generating resources are sufficient to meet average demand but struggle to meet peak demand, then storage can help by filling in the gap between average and peak demand—as long as demand does fall below average sufficiently often to recharge the storage. Here again, storage can be thought of as a "matchmaker" between generation and demand.

My system is transmission-constrained—I have a transmission bottleneck.

If an electricity system is transmission-constrained (for example, due to an inability to site additional transmission), then distributed storage (that is, storage located downstream of the transmission constraint) can post-

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[7] An exception is a system with one oversized diesel generator, which might be able to benefit from storage even without any renewables. See Chapter 3.

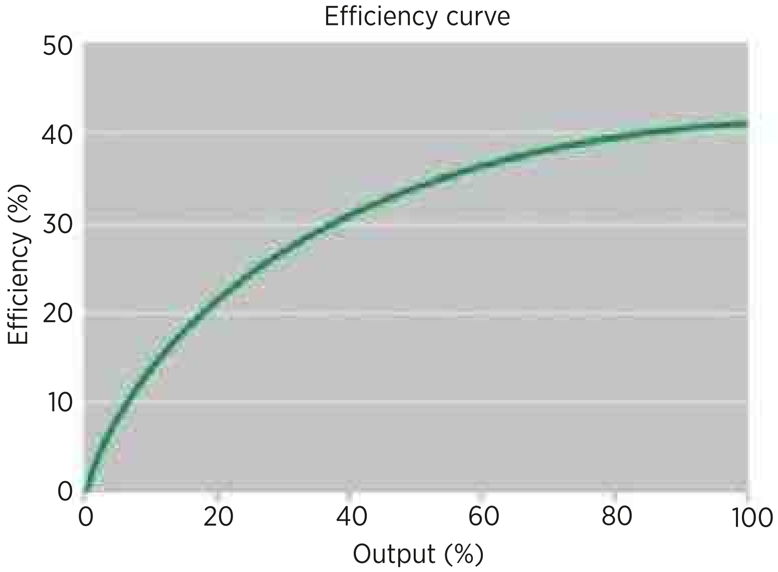

Figure 5: Diesel generator efficiency as a function of output (HOMER software system)

pone or eliminate the need for transmission capacity upgrades. The storage would typically be charged at night when system demand is lower and then tapped to fill in unmet demand during the day.

My system produces excess electricity, which I can't use; therefore, it is being wasted.

Storage can help capture excess electricity—such as that produced by wind turbines at night when the load is low—and make it available at peak times when it is needed.

I have some weak spots at the end of distribution lines.

If a system has difficulty meeting demand or maintaining power quality at the ends of the distribution system, then relatively small amounts of distributed storage can be a less expensive alternative than distribution system upgrades.

I want to move from part-time operation to 24-hour electricity availability.

Because night time load will likely be low, storage combined with diesel and renewables can help avoid operating the diesel generator at inefficient low or minimum load levels.

3.B Problems Storage Cannot Solve

As the following examples show, storage is not an appropriate solution to all electricity system problems.

Electricity demand on my system frequently exceeds my generating capacity.

Electricity storage is not electricity generation; in fact, storage is a net electricity *consumer*. If an electricity system frequently runs short—that is, if there is often insufficient electricity to meet demand—then storage will likely worsen the situation. Similarly, if load growth is high, then new generation (combined with end-use efficiency, such as high-efficiency new appliances)—not new storage—is the answer. Storage can fill in for short time periods when generating capacity is insufficient, but storage is not a long-term answer to fundamental capacity shortages.

I have frequent outages and/or low power quality due to my transmission and distribution (T&D) network being in poor condition or being inadequately maintained or underinvestment.

Storage cannot fix problems elsewhere in the system. Storage may be able to reduce peak loads on the T&D system or even improve underlying voltage and frequency issues. However, it is not the best option for responding to fundamental problems on the T&D network.

My electricity system suffers from high maintenance costs, breaks down frequently and is generally unreliable.

As discussed in Chapter 2, storage technologies are improving, but they still generally require frequent monitoring, attention and adjustment. It is possible that storage will exacerbate, rather than improve, underlying maintenance issues.

I have a part-time electricity system (not operating 24 hours/day)

Storage typically only makes sense for 24-hour/day electricity systems.

3.C Storage, Renewables, Reliability and Cost: How Do They Fit Together?

In this section, it is shown how storage can be used as a tool to allow one to integrate higher levels of variable renewables while maintaining system reliability and keeping costs down.

To show how these variables—renewables penetration, reliability, storage and cost—interact, a model of an electricity system that starts as a pure fossil-fueled system, to which we add varying amounts of renewables and storage, is used. Key model outputs are reliability and costs. In other words, it is shown how increased use of renewables can be combined with storage to maintain reliability and show the overall cost impacts of doing so.

The HOMER modeling system, which is emerging as the international standard for modeling of smaller and distributed renewable electricity systems, is used. HOMER is an electricity system design tool that chooses an optimal mix of generation resources from a user-defined set of choices and provides as outputs capital and operating expenses. A free version of HOMER software can be downloaded at ***www.homerenergy.com.*** The software is relatively easy to use and well-supported via an active and engaged online community.

The results shown here are for a typical, or representative, small island electricity system. However, these results may not be applicable to *all such systems*. Costs, insolation (sunlight) levels, electricity demand, load shape and other variables vary across systems, and their values affect how renewables and storage interact and perform. Fortunately, it is not too difficult to do a com-

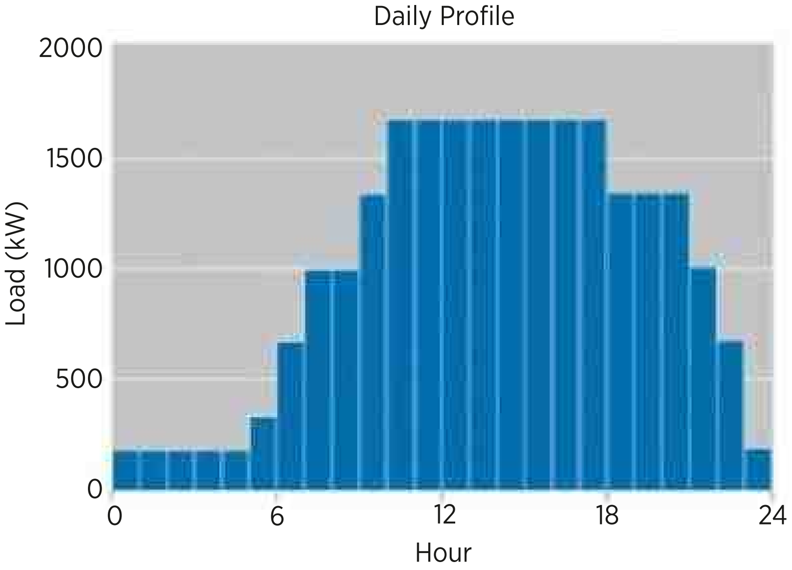

Figure 6: Assumed daily load shape

parable analysis for any system. The process of getting started is illustrated at the end of this section.

The Model Island and the Base Case: Diesel Generator Only

For this analysis, we created a fictional island located in the Caribbean, near Puerto Rico. The electricity system on this island serves 1,000 households, each with an average electricity demand of 500 watts, totaling 500 kW residential average demand. The island also has a comparably sized commercial and industrial average demand of 500 kW. The load factor is 0.37, meaning that the total *peak* demand is 2.7 MW.[8] The daily load shape follows typical working hours with a midday peak (Figure 6).

For a base case, it is assumed that a single diesel generator serves the island, with a peak rated output of 3.5 MW. Such oversizing is quite common, motivated in part by a desire to provide reliable electricity even if demand exceeds predicted levels and to accommodate future demand growth. However, as shown below, such oversizing has a significant penalty in the form of high diesel consumption.

It is assumed that this diesel generator costs $250/kW, or $875,000 (first cost only). Furthermore, it is assumed that diesel fuel is available at a price of $1/litre. (All prices and costs in this report are in U.S. dollars, unless noted otherwise). The efficiency (defined as the percentage of energy in the consumed fuel that is converted into electricity) of this diesel generator rises sharply with load, which is typical of diesel generators.

The final critical assumption is that electricity supply always equals or exceeds demand. In other words, there is a requirement that there is always sufficient capacity to meet demand. It is important to note, however, that since transmission and distribution (T&D) issues, such as downed power lines, are a significant cause of outages, this requirement does not translate into 100% reliability.

The costs and other performance characteristics of this base case system are summarized in Table 12. Note that the levelised cost of electricity, which accounts for both the first cost of the diesel generator and the ongoing costs of the diesel fuel, is 53.9¢/kWh. (This assumes a 6% real interest rate and reflects only generation costs; it does not include T&D, operations or other electricity system costs.)

Table 12: Base case: diesel generator only

Indicator/measure	Value	Units
Initial (first) cost	875,000	US$
Diesel consumption	4,016,700	Liters/year
Levelised cost of electricity	53.9	¢/kWh

Adding Storage and Renewables to the Model Island

To demonstrate the potential roles of storage and renewables, the island is then modeled with several alternative electricity generation scenarios:

- Generator plus storage;
- Generator plus PV;
- Generator plus PV plus storage; and
- PV plus storage (100% renewables).

The results of these scenarios are summarized in Table 13.

Note: "Renewables fraction" is defined as the fraction of annual electricity consumption that is provided by renewable sources. Storage is 7.6 kWh capacity lead-acid batteries, $2,000 each. The storage cost estimate includes balance-of-system costs.

There are several interesting implications of these results. These are best explained by discussing each scenario individually.

Generator + Storage. Adding storage increases the first cost significantly (i.e. an additional $2 million in this example). However, it also allows for a 25% reduction in diesel use. It does so largely by allowing the diesel generator to operate at higher loads (and thus higher efficiencies) and to switch off entirely when loads are low. In this scenario, the generator was able to reduce its run time from 8,760 hours/year (24 hours/day, 365 days/year) to 5,568 hours/year (an average of about 15 hours/day). Note that the levelised cost of electricity for this scenario is quite a bit lower than for the base case because the diesel savings more than outweigh the additional first cost of storage.

Generator + PV. This relatively small PV system did reduce generator run time, but mostly during midday, when demand was high, thus aggravating the inefficient-at-part-load problem with diesel generators. Diesel savings were modest and levelised cost increased. PV as a supplement to a diesel generator without accompanying storage is unlikely to be a financially attrac-

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[8] The load includes some random variability, which is why the 2.7 MW annual peak exceeds the 1.6 MW peak shown in Figure 6.

Table 13. Costs and other characteristics of alternative system designs

Scenario	Generator (kW)	PV (kW)	Storage (kW)	First cost ($1000)	Diesel use (mill. liters/yr)	Levelised elec. cost (¢/kWh)	Re-newables fraction
Gen Only	3,500	0	0	875	4.0	53.9	0
Gen+Strg	3,500	0	1,000	2,875	3.0	42.6	0
Gen+PV	3,500	500	0	3,375	3.9	55.0	0.10
Gen+PV+Strg	3,500	2,000	2,000	14,875	2.0	42.4	0.28
PV+Strg	0	7,000	12,000	59,000	0.0	68.4	1.00

tive choice although it may be worth considering as an interim step to become familiar with the PV technology.

Generator + PV + Storage. This scenario has a very high first cost, but it cut diesel consumption by 50% and thus had the lowest levelised electricity cost. This is because the PV and the storage were able to work together such that the generator operated either at high output levels or shut off entirely. This is a technologically complex system, as it would require a sophisticated controller and software to optimize operation of the PC and storage. Nevertheless, as shown in Table 13, it can be cost-effective from a long-term financial perspective.

PV + Storage. This system has both the highest first cost *and* the highest levelised cost. This is because a very large PV system (7 MW) and storage system (12 MW) is required to ensure system reliability. (Relaxing the reliability requirement would allow for a smaller PV system and thus lower costs.) This nicely points out the challenges in going to a 100% renewable system. One needs to oversize the system significantly or allow for the possibility of occasional generation shortfall.

Implications for Renewable Energy Generation and Storage

The results summarized above lead to several key findings:

- Diesel generators have very low first costs but high operating costs. Although alternative systems using storage and/or renewables can have lower levelised costs, as discussed above, implementing these systems requires finding the up-front capital to cover the higher first costs.
- Storage should be considered as a supplement to pure diesel systems, even without renewables. As discussed above, storage can allow diesel generators to operate at much higher efficiencies and to switch off entirely when appropriate. The higher first costs of the storage can be more than outweighed by the diesel savings. It also prepares the system for integrating renewables later.
- Small amounts of renewables added to diesel-based systems are generally not a cost-effective option. This is because some renewables, notably PV, aggravate the low-load inefficiency of diesel generators.
- Combining diesel generators, renewables and storage can be the lowest cost option, based on levelised cost. However, such systems are complex and technologically sophisticated. It is suggested to add new technologies one at a time, rather than all at once.
- Pure renewable systems, particularly based on PV, can be very expensive, and they will need to be oversized to meet electrical needs throughout the year.

When to Add Storage

Use of the HOMER modeling system is strongly recommend to assess the feasibility and economic attractiveness of storage and renewables for a given electricity system. This modeling system:

- Helps to model a wide range of storage technologies, including hydrogen, batteries, flow batteries, flywheels and more.
- Uses a chronological analysis, which is critical for understanding the impacts of adding storage to a system. Without this sort of analysis, one must rely on rules of thumb to select storage, which can be inaccurate.
- Allows one to do sensitivity analyses and answer questions, such as: Which system is least expensive if the cost of fuel doubles? How much can be paid for PV panels and still cost-effectively add them to the system? If electricity demand goes

up, will the system be able to supply enough electricity? If so, how much would it cost?

- Includes tools to do a quick PV analysis by specifying the location. It connects to an online database of solar radiation worldwide to determine how much electricity can be expected from the PV array.
- Creates a wide range of outputs and graphs that can be used to better understand the system. There will be many goals , and the available analysis tools are diverse enough to support many of them.
- Helps to not only identify the best system to supply electricity but also helps one understand *why* it is the best system.

As noted earlier, a free version of HOMER can be downloaded from the Internet and there is an active, friendly online community of users that can provide advice and support. Individual consulting and professional support is available for a fee. A free Getting Started guide is available for download at the HOMER website ***(www.homerenergy.com).***

4. I Want Storage on my System. Now What do I do?

In many ways, storage is similar to any other major capital acquisition. However, the highly integrated role of storage in an electrical system leads to several critical distinctions. This chapter provides an overview of equipment acquisition and then describes the key considerations that are specific to storage planning and acquisition.

4.A Summary of Major Electrical Equipment Acquisition Process

Investing in equipment for an electrical system is a challenging task. There is no single proven technology that always works, and local considerations will often dominate the process. Electricity systems, like any other infrastructure, require clear planning, thoughtful design, competent installation and consistent maintenance. The process for acquiring major infrastructure equipment is summarized in Table 14.

4.B Key Considerations for Storage

The four key distinctions when considering storage are:

- *Integration.* A successful storage system requires a very high level of integration with other system components.
- *Technological maturity.* Storage technologies are typically less mature than many other types of equipment that will be installed in an electricity system.
- *Preliminary design.* The preliminary design phase, although important for all major equipment acquisitions, is particularly critical for storage.
- *Maintenance.* Electrical equipment requires a strong maintenance plan, but storage requires an even more robust and thorough approach to maintenance.

Integration

The biggest distinction that separates storage equipment from others in an electricity system is that the primary function of storage is to improve the performance of supply equipment to meet the users' electrical needs. Storage is used to integrate higher levels of variable renewables while still maintaining users' electrical reliability. It can store electricity and supply it later, it can improve power quality in a number of ways, and it can provide reliability. These unique roles mean that changing any equipment will have implications for the storage system.

Integrating storage and renewables into a remote electrical system increases the technological complexity of the system. However, there are a number of readily available, robust system integration technologies that can help to manage the complexity of generation operation. In smaller systems (on the order of a few hundred kilowatts), the majority of this sophistication can be managed almost exclusively by the inverter/rectifier equipment.

Integrating storage into a grid requires additional balance-of-system equipment, although which equipment depends on the selected storage technology and how much automation is desired. In addition to safety equipment,such as fuses, current fault protection, etc., the equipment for integration will include a storage controller (e.g. charge controller) and may include inverters/rectifiers, system controllers, remote monitoring equipment and supplemental sensors.

The inverter/rectifier will convert between AC and DC electricity if the grid demand is AC and the storage is DC. There are three major types of inverter/rectifiers: stand-alone; grid-interactive; and dual-mode. These are summarized in Table 15.

The storage controller will manage storage levels and provide feedback to the rest of the system about when to turn the generators off and on, making dispatch decisions. It is preferable to automate the dispatch process but doing so requires additional equipment and more specialized technical expertise. Particularly in smaller systems, the system inverter/rectifier may include most of the necessary controls although supplemental equipment will still likely be necessary.

In larger systems, it is likely that more of the dispatch decisions will be automated. Smaller systems may employ a person who manually turns generators off and on although this is changing as technology improves and the need for faster, more reliable responses increases.

Table 14: General summary of stages in major capital acquisitions for electrical systems

Stage	Description
Goal development and planning	The project goals need to be established to evaluate the design, and high-level planning should ensure that these goals are relevant and reasonable for the stakeholders involved. Examples of common goals include lowering the overall cost of electricity, lowering the operational cost of the system, improving the reliability of electricity or reducing pollutant emissions. The goals at this stage should be, in general, indifferent to the underlying technology.
Preliminary design	The preliminary design phase should be based on a high-level analysis of systems that meet the goals specified. This stage should provide a short list of technologies that are likely to help achieve these goals.
Detailed design	The detailed design will provide firmer costs and will verify or reject the assumptions from the preliminary design phase. Detailed quotes and specifications should be obtained for all major equipment. The detailed design should determine the equipment needed for the project. The design should consider operation and maintenance needs and should include plans for the equipment at the project's end.
Funding and financing	Electrical infrastructure is very capital intensive, and therefore funding requires particular consideration. Banks, governments and other agencies may all offer support to obtain the necessary funding.
Acquisition and installation	Once the design and funding are in place, the equipment needs to be purchased and installed.
Operation and maintenance (O&M)	The O&M plan should include sufficient financing, staff and logistical considerations to run the electrical system. After installation, the O&M plan will begin and continue throughout the life of the project.
Project closure	The project closes only when the equipment has ceased to provide adequate functionality to the system. The project end will include plans for repowering, recycling/re-using equipment and safe disposal for equipment that can no longer be used.

Regardless, storage can be more beneficially used if the controls are automated with a properly selected control strategy.

A charge controller will provide storage-specific controls and management. In the case of batteries, the charge controller will help prevent the system from pulling too much charge from the batteries (which can shorten battery life) or prevent the system from overcharging the batteries (which can both shorten battery life and cause overheating, which can lead to fires).

A particular system may benefit from additional equipment. For example, many wind turbine systems may work better with a dump load to accept any excess electricity. In smaller systems, one may need additional wiring; in larger systems, one may need additional T&D capacity.

The overarching goal of storage is to maximize its usefulness to the system. Most forms of storage can provide many different services (including load and supply shifting, bridging power between generators and increasing power reliability). The more each system component can be automated, connected and controlled in response to system needs, the greater the value to be gotten out of storage.

The level of integration needed has cascading effects on the project stages presented in Table 14. It will increase the funding and financing necessary and require more consideration when planning the system O&M. It will also increase the importance of a strong preliminary and detailed design.

Technological Maturity

In contrast to many other electrical technologies, most large scale electricity storage technologies are less commercially proven. Lead-acid batteries have been used extensively in small, isolated systems. Pumped hydro

Table 15: Summary of major inverter/rectifier types

Stand-alone inverter/rectifier	Produces the necessary AC electrical frequency (i.e. 50 or 60 Hz sine wave) to invert DC electricity. It should never be connected to large mainland grids because it does not include the appropriate safety equipment to prevent electrocutions when the grid goes down.
Grid-interactive inverter/rectifier	Relies on the attached grid to produce an AC frequency that it follows when it inverts DC electricity. It cannot operate without a grid and is typically used only in grid-tied renewable applications.
Dual-mode inverter/rectifier	It can operate in both stand-alone and grid-interactive modes. It is the most appropriate choice for use in micro-grids that can either operate independently or in conjunction with another electrical grid.

has been widely used in mid-size to very large systems. However, with these notable exceptions, storage is still a young technology.

The relatively recent widespread deployment of variable technologies, such as solar PV and wind turbines, has increased the importance of storage, with the goal of a storage technology that is both highly efficient and affordable. The field is changing rapidly and is filled with new and novel technologies striving to fill this need. The rapid changes are exciting, but they make it more challenging for consumers to select the best technology for their system.

It is also true that each technology has different strengths and weaknesses. There is currently no single accepted method for characterising them; each manufacturer reports the characteristics that are most favorable to its technology. This increases the upfront burden necessary to fully characterise each technology and understand its impacts on the system.

In terms of the project flow, the fact that storage technologies are still rapidly maturing means that the goal development, preliminary design and detailed design stages of the project will require more effort and time. It may be necessary to cyclically run through these phases before actually installing storage in the system. It may also be helpful to hire an energy consultant or storage specialist to help during preliminary design and detailed design phases.

Preliminary Design

As demonstrated throughout this report, there are a number of novel and promising storage technologies but no clear technology that is always preferred. The best technology will depend on what a given system needs. This reality, coupled with the technical complexity of comparing storage performance in a system, makes selecting the proper technology a critical task. After all, it is likely that storage will form a very large portion of the capital investment for the system, so it is important to have a strong preliminary design to get a strong return on investment.

The preliminary design stage is more important in a project with storage because of the high level of component interdependence. A strong preliminary design can help to optimize the system design, reducing long-term costs and preventing overcapitalizing of other equipment. It can also maximize the value that storage provides to the electrical system.

Chronological simulation[9] is helpful in hybrid systems (systems with multiple generation sources, including storage). Although there are many rules of thumb that technical specialists use to size a battery bank in simple systems, when the system is complicated with multiple technologies, these rule-of-thumb shortcuts often yield poor system designs. A simulation will help to determine how the system will behave under a wide range of likely scenarios and lead to both a better understanding of the system dynamics and a strong overall design. For example, there are times when the peak electrical demand can occur when there is little charge in the battery. If reliability is important, then a simulation would determine if this situation is likely to occur and would provide guidance about adjusting the design.

Maintenance

Maintenance is critical to getting the most out of storage technologies. Storage technologies tend to have high upfront capital costs, and poor maintenance can

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[9] A chronological simulation will model the behavior of the system over a period of time, often a year. This simulation enables one to know if the proposed storage will properly support the rest of the system under typical operation, particularly when a system includes variable renewable resources, such as solar and wind.

lead to catastrophic failure. For example, batteries that are poorly maintained will require much more frequent replacement. Therefore, when deciding to invest in storage, it is critical to ensure that funding is allocated for the necessary ongoing routine and preventative maintenance tasks.

There can also be unexpected system behavior that can lead to failures. A remote monitoring system will enable system technicians to closely monitor the equipment and respond quickly if there is a problem. Similarly, if possible, a locally available technician who can respond quickly can help keep a small failure from becoming a large failure. However, in remote areas, a qualified technician may not be readily available. In that situation, a local resident can be trained in routine maintenance and instructed on how to properly manage a system fault until a specialist can travel to the site.

Many types of storage have a relatively short lifetime in comparison to other components. For example, a PV array has an expected 20-year life, while a lead-acid battery is expected to last only five to ten years. This should be considered in the planning stages and included as part of the O&M stage of the project process. There should be a plan for replacing the storage while the rest of the system is still operational. A smooth transition plan will help ensure that any electrical interruption is very brief.

5. Case Studies

Some storage technologies—notably, lead-acid batteries—have been available for several years, and there is a growing body of real-world experience with them. In this chapter, ten case studies of storage are detailed. These case studies were selected to illustrate how remote/island/innovative electricity storage technologies fare in real-world applications. The focus is on systems that have been installed and operating and for which clear lessons can be drawn about how to make storage successful. The case studies are summarized in Table 16.

Table 16: Ten case studies

Name	Description
Apolima	PV/lead-acid batteries
Bella Coola	Hydro/diesel/hydrogen fuel cell/ flow battery system
Bonaire	Wind/diesel/nickel-based battery system
King Island	Wind/diesel/vanadium-redox battery system
Kiribati	Household-sized PV/lead-acid batteries
Metlakatla	Hydro/diesel/lead-acid batteries
Osmussaare	Wind/diesel/lead-acid batteries
Padre Cocha	PV/diesel/lead-acid batteries
Ramea	Wind/diesel/hydrogen storage
San Juanico	PV/wind/diesel/lead-acid batteries

The case studies illustrate diverse technologies and applications. Nevertheless, they do point to key lessons learned, including the following:

- Pay close attention to system *design*, particularly ensuring that all system components are sized correctly and can work together.[10]
- The more system components there are, the greater the complexity and challenge of system integration.
- Do not expect new technologies or pilots to be financially viable.
- Walk first, then run: Try to introduce one technical innovation at a time.
- Do not underestimate the transport costs, complexity and time requirements associated with getting equipment and expertise to rural or isolated locations.
- System monitoring and O&M are critical to ensure system reliability and longevity.
- Test and debug system components *before* sending them out to rural or isolated locations.
- Lead-acid batteries, if monitored and maintained, can last up to eight years.
- Diesel generator oversizing is rampant and contributes to high diesel consumption.
- It is critical to make a system financially sustainable. Even if subsidies cover first costs, operating costs (including battery replacement and O&M) should be covered by electricity sales/revenues.
- End-user buy-in (financially and politically) is critical.

5.A Apolima Island

Storage technology: Lead-acid batteries

Location: Apolima Island, Samoa

Electricity system type: PV with battery storage

Electricity system size: 13.5 kW PV system

Population served: 100 residents

Apolima Island is one of the four islands that make up the nation of Samoa. The island is accessible only by small boats. Electricity in Samoa is provided by the Electric Power Corporation (EPC), a government agency. Electricity was first provided to the small community on Apolima in 1997, with a 15 kVA diesel generator that typically operated five hours per day. However, the lack of 24-hour power, the high noise and emissions of the diesel generator and the costs and logistical challenge of ensuring a reliable supply of diesel fuel led to a search for alternatives.

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[10] See Chapter 4 for further information on software for system design.

In 2005/2006, a 100% renewable electricity system was installed. This system consists of a 13.5 kW photovoltaic array, lead-acid batteries, inverters and the necessary buildings and wiring systems. The system was oversized in order to meet the demand growth expected to arise due to the availability of 24-hour power. In addition, the system was sized to provide reliable power through February, which is typically the cloudiest month. System users agreed not to use high-current-draw equipment (such as electric kettles and cookers) during cloudy periods and to purchase only energy-efficient refrigerators and other equipment.

Preliminary analysis of the system found that it did meet its primary goals of providing 24-hour electricity and reducing diesel consumption. The use of "stacked" inverters, rather than one large inverter, increased system flexibility, as more inverters could be added later if necessary, and reduced system losses, as unused inverters could switch off during low electricity demand periods. The system has operated for five years with only minor technical issues. One analysis credits consistent routine maintenance by EPC as a key factor in the system's reliability and longevity.

A challenge with this system was its first cost, which was $223,500 or approximately 70¢/kWh (assuming a 15-year life, 4% discount rate and 30% capacity factor). The system serves a rural community whose residents have little opportunity for earning income so recovering all these costs directly from users may not be realistic.

References for this case study: Clay, Bruce (not dated); Clay, Bruce (2011), UNDP (not dated), UNDP (2004).

5.B Bella Coola

Storage technology: 100 kW fuel cell, 125 kW flow battery

Location: Bella Coola, B.C., Canada

Electricity system type: Hydro/diesel/hydrogen/fuel cell/battery storage

Electricity system size: 8 MW (diesel and hydro)

Population served: ~1,900

This innovative and technologically advanced system is intended to increase utilization of a run-of-river hydropower facility and reduce diesel fuel consumption. Historically, the bulk of electricity for this remote region, which is unconnected to any other electricity systems, came from the Clayton Falls hydro facility. When electricity demand fell below hydro output, water bypassed the turbine. When demand exceeded hydro output, a diesel generator filled in.

Although this system did provide electricity to the rural community, it resulted in both high diesel consumption and wasted hydropower when water bypassed the turbine. So the decision was made to add two electricity storage systems to better match demand and supply: an electrolyzer to produce H_2, which could then be used to power a fuel cell; and an advanced battery. Specifically, a 60 Nm^3/hr H_2 electrolyzer[11] was specified, along with a 100 kW fuel cell. A 125 kW flow battery system was specified as well.

The concept behind the two distinct storage technologies was to use the flow battery for shorter-term transients and grid support (less than five minutes) and the H_2 fuel cell for longer-time-period support (as it takes about five minutes to come up to peak power).

As of 2011, the system was operating, albeit with some start-up challenges. Diesel fuel consumption had been reduced about 15%—just under the predicted savings of 17%. Overall system control and operation has been a challenge, and getting the various components to link and optimize their operation has taken some time. The system is not yet fully automated. In addition, there has been a frequent need for a highly trained operations staffer, which is not readily available in this very rural area.

The H_2 system, according to those involved, is not cost-effective. This is clearly a pilot/technology evaluation project with a focus on evaluating technical, not economic, performance so it comes as no surprise that costs are high. Nonetheless, results to date for this project suggest that H_2 system costs need to come down before these systems can compete economically.

Another lesson learned is the importance of testing and fine-tuning innovative technologies *before* sending them out into the field. Particularly for remote applications, the availability of trained personnel, spare parts and technical support is limited, so time spent ensuring that everything is working properly before it is sent out is well spent.

References for this case study: BC Hydro 2010, Miles and Gillie (accessed 11 April 2012).

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[11] Nm^3/hr is "normal cubic meters per hour," where normal is defined as 0°C and 1 atmosphere.

5.C Bonaire

Storage technology: 3 MW nickel-based battery

Location: Bonaire, Venezuela

Electricity system type: Wind/diesel/battery storage

Electricity system size: 25 MW

Population served: 14,000

Bonaire—an island near the coast of Venezuela, with a permanent population of about 14,000 and a peak electricity demand of about 12 MW—turned a disaster into an opportunity when, in 2004, the island's sole power plant burned down. The government decided to put in place a plan to move the island toward using 100% renewable sources for electricity.

In the interim, rented container diesel generators were installed. In 2010, however, a new system consisting of 14 MW of diesel generators, 11 MW of wind and 3 MW of battery storage was installed. The plant became operational in late 2010. The wind farm produces 3,500 full load hours annually and is stabilized by 3 MW of battery storage backup system produced by Saft. According to a Saft press release statement for this project, "...Saft's new nickel-based SMRX block battery … [is a] … 640V battery with a nominal capacity of 1320Ah (~845 kWh) that can fit into three standard transportation containers for … installation and commissioning." The "Saft energy storage system is to provide backup power to ensure that the main frequency of the Bonaire grid remains under constant control at the steady 50 Hz required for grid stability. So if the frequency should start to drop—which might happen due either to a sudden increase in load or a loss of generation—the battery will supply just over 3 MW for well over two minutes."

References for this case study: Johnstone, H., 2010; Saft (accessed 12 April 2012).

5.D King Island

Storage technology: Vanadium redox batteries, 400 kW peak output

Location: King Island, Tasmania, Australia

Electricity system type: Wind/diesel/battery storage

Electricity system size: 8.5 MW installed capacity

Population served: ~1,700

King Island is one of the islands of the Australian state of Tasmania and has a population of about 1,700 people. The King Island electricity system is owned and maintained by a government-owned generator/retailer, Hydro Tasmania and supplies a mixture of residential, commercial and industrial customers.

The electricity system was originally designed as an all-diesel system. However, high diesel fuel costs led to the installation of three 250 kW wind turbines in 1998, followed by two 850 kW wind turbines in 2003. At that time, a vanadium redox battery (VRB) energy storage system was installed "to increase the recoverable portion of renewable energy and to smooth the variable output of the wind farm to enhance the use of wind power to displace diesel generation" (Hydro Tasmania, undated).

The VRB storage system had "68,000 litres of electrolyte contained in four plastic tanks, 6 Sumitomo cell stacks, energy storage of 200 kW for four hours (800 kWh) and peak short-term output of 400 kW" (Hydro Tasmania, undated). The combination of wind turbines and the VRB storage system allowed for an approximately 35% reduction in diesel fuel use. In addition, a 100 kW solar PV system was added in 2010.

An overcharging event led to overheating of the electrolyte, which in turn damaged the cell stack membrane. The damage was found to be unrepairable, and as of 2011 the VRB system was still out of service.

There is much to be learned from King Island's experience. Simon Gamble, project manager for Hydro Tasmania, points to three distinct lessons:

- *Understand the challenges that island locations face, particularly for emerging technologies.* The simplest advice is to understand the nature of the remote location and what this means for logistics and support. This drives a focus on robust technical solutions that are tried and tested. One must strike the right balance between islands being excellent test beds for emerging technologies and the risk of an asset failure and the impact this can have on system performance.
- *Understand the technologies as a system.* Do not just focus on the storage technology but consider the full delivery system, including power and, of course, a fully scenario-tested control system with adequate interlocks. Invariably, there will always be a single point of failure that cannot be avoided. One needs to identify these points and ensure that they are all equally robust. Too much focus on chemistry and not enough on inverter cooling (as an example) can still lead to a failed venture.

- *Work with an experienced supplier.* Wind developers like to see 1,000 units in the group before they make a wind turbine order. This is not possible with island systems, and particularly storage. But one would ideally want a supplier who has worked in this space before and solved remote area location issues before.

References for this case study: Hydro Tasmania, undated; Gamble, S., accessed 11 April 2012.

5.E Kiribati

Storage technology: 140 Ah lead-acid batteries

Location: Outer islands of Kiribati, Republic of Kiribati, central tropical Pacific Ocean

Electricity system type: Household-size 100 W PV with batteries

Electricity system size: N/A

Population served: N/A

High diesel prices and unreliable fuel delivery have sharpened interest in photovoltaics (PV) in Kiribati, particularly on the smaller and more remote islands. An ambitious PV project in the 1980s led to the installation of 270 distributed PV lighting systems with lead-acid batteries. However, surveys found that only 10% of those systems were fully operational after just three years. Short battery life due to lack of maintenance was a major cause of failure.

In the 1990s, an alternative business model was introduced that allowed consumers to rent rather than buy the PV/storage system. This was more effective. The cost of the PV/battery systems was lower than that of a diesel system, 1,700 systems had been installed as of 2005, and the initial price point (7 euros/month) was expected to provide sufficient cash flow to allow for battery replacements as needed.

The systems use 100 W PV panels coupled with 140 Ah lead-acid batteries. However, there was continued tension between the social and political desire to charge a low price that end users could afford and the need to bring in sufficient income to cover the costs of battery replacement.

Terubentau Akura, from the Kiribati Solar Energy Company, reports, "Already 20 percent of rural households across the country are using solar photovoltaic technology for lighting and other energy needs. … Some of our islands in Kiribati now have a very high take-up of solar energy. … In Marakai, Nonutai and North Tarawa between 50–80 percent of households use solar photovoltaic technology for basic lighting and power."

It's clear that this technological approach can provide basic services in remote areas.

References for this case study: Akura, T. et al, 2005; Akura T., 2011; Maclellan, N., 2007.

5.F Metlakatla

Storage technology: 1 MW lead-acid battery system

Location: Metlakatla, Alaska

Electricity system type: Hydro/diesel/battery storage

Electricity system size: 8.2 MW installed capacity with 3.5 MW peak load

Population served: ~1,400

Metlakatla, Alaska is a small and isolated native coastal community located in the rural Alaskan panhandle. Electricity is provided largely by a 4.9 MW hydroelectric system, supplemented with a 3.3 MW diesel generator and a 1 MW battery storage system. The storage system has been in operation since 1997; thus there is sufficient data to evaluate the system for both technical and economic performance.

The system originally was served only by the 4.9 MW hydro system. However, fluctuations in demand—due mostly to a large sawmill that was a highly variable load—led to low power quality and low system reliability. The hydro system was more than sufficient to meet average load, but it could not follow erratic load fluctuations. In response, a 3.3 MW diesel generator was installed. That did support the grid, but at a considerable cost: Diesel fuel and generator maintenance costs were approximately $1.1 million/year, plus generator maintenance and scheduled overhaul costs. There were, in addition, environmental risks and logistical challenges in getting diesel fuel to the community.

So the decision was made to add electricity storage. A 1 MW lead-acid battery bank was installed in 1997. As a result, the diesel generator is used largely for emergency standby, and net cost savings (reduced diesel fuel use and reduced diesel generator maintenance, partially offset by battery costs) are estimated at $550,000/year.

The batteries were replaced in 2008 at an estimated cost of $690,000. The original batteries operated for nearly 12 years (longer than the expected lifetime of eight years), and replacement took only six days once work commenced. Analysis of the replaced batteries found that, "they were in excellent condition and may have been able to operate even longer with appropriate conditioning charging."

References for this case study: Alaska state government 2008; Hunt, G. and J. Szymborski, 2009; Murphy et al. 2009; Szymborski et al. 2001.

5.G Osmussaare

Storage technology: 408 V (nominal), 250 AH lead-acid battery bank

Location: Osmusssaare, island off the Estonian coast

Electricity system type: Wind/diesel/battery

Electricity system size: 94 kW

Population served: N/A

This remote radar facility was originally powered solely by a diesel generator. However, the high costs of delivering fuel drove interest in renewables, particularly wind. A 30 kW wind turbine, coupled to two 32 kW diesel generators, was installed, along with a 408 V (nominal), 250 Ah (~102 kWh) lead-acid battery bank. Evaluation of the system showed that 85% of the electricity generation was from wind, which resulted in a sharp reduction in diesel consumption. The original battery system lasted for seven years before requiring replacement.

Those involved with the system note two important lessons learned:

- Remote monitoring of the system was found to be critical for identifying operational problems before they led to a system shutdown.
- A new hybrid power system must be designed and optimized with consideration for wind speed, average load power, load power profile, diesel generator output and battery bank capacity.

References for this case study: Ruin, S.,; Ruin, S., 2003, accessed 11 April 2012.

5.H Padre Cocha

Storage technology: Lead-acid battery system

Location: Padre Cocha Village, Amazonian jungle, Peru

Electricity system type: PV/diesel/battery

Electricity system size: 30.2 kW PV, 128 kW diesel generator

Population served: 2,467 residents

Padre Cocha village is a small Peruvian village on the Nanay River, accessible only by boat. Most of the population is of native indigenous origin, and the village does not have clean drinking water or wastewater systems. Production and sale of handcrafts and ceramics, mainly for sale to tourists, is the main economic activity.

In 2003, a PV/diesel/battery system was installed, consisting of:

- Two sets of 120 2-volt lead-acid batteries with a total storage capacity of 312 kWh;
- 378 80-watt PV panels, with a total rated peak power output of 30.2 kW;
- 128 kW diesel generator; and
- Inverter, control and monitoring system and other related balance-of-system components.

The PV modules cost $128,000, the batteries $58,000, the generator $41,000 and the control and power conditioning components $123,000 (Costs are in US$ and exclude project management, administration and related expenses).

On a typical day, demand peaks at 22 kW at 2000 hours, and the diesel generator turns on from 1900 to 2200 (three hours per day total run time). The generator typically operates at a load factor of 60% and hence is oversized for this application. Users are charged 21¢/kWh for electricity, plus a fixed charge of $1.51/month.

A financial analysis of the system showed that revenues cover only 22% of total costs (including first costs) and only 59% of operational costs (O&M, fuel and equipment replacement). This, of course, makes the system financially unsustainable. Even if one considers that PV costs have dropped considerably since 2003 when this system was installed, lower capital costs would not resolve the mismatch between revenues and operational costs.

References for this case study: Moseley, P., 2006; ESMAP 2005; ESMAP 2007.

5.I Ramea Island

Storage technology: Hydrogen electrolyser/storage/250 kW hydrogen generator

Location: Ramea Island, Newfoundland, Canada

Electricity system type: Wind/diesel/hydrogen storage

Electricity system size: 1.1 MW peak load

Population served: 631 residents

Ramea Island is located off the southwest coast of Newfoundland and is accessible only by boat. There is no electricity connection to the mainland. Until recently, electricity was provided by three 925 kW diesel generators, which consumed about one million liters/year of diesel. In an effort to reduce diesel fuel consumption, reduce associated carbon emissions and move toward renewable fuels, Nalcor Energy has implemented several innovative electricity technologies on Ramea Island.

In 2004, six 65 KW wind turbines were installed, which reduced diesel consumption by about 10%. However, high wind periods did not match high load (demand) periods, with the result that excess wind had to be "dumped". In 2005, for example, only 41% of the wind turbines' output was used; the remainder was lost. This led to consideration of storage to capture that "lost" wind, and ultimately it was decided to specify and install a hydrogen-based storage system, as well as additional wind capacity.

The new system components include:

- Three 100 kW Northwind wind turbines;
- Hydrogen electrolyzer, with a rated power input of 162 kW;
- Hydrogen storage, three tanks with a total capacity of 1,000 m^3 at 235 psi;
- Hydrogen-fueled generators (total rated power output of 250 kW); and
- Energy management system to provide automated monitoring and control.

As of fall 2011, the electrolyzer and the new wind turbines were installed and operating well. Complete system operation is very close. However, there have been some challenges with the hydrogen generators. Debugging is under way, but it appears that two technical issues are the likely culprits:

- The five individual hydrogen-fueled generators have a common exhaust, and when one or two are operating, moisture from the exhaust condenses on oxygen sensors in the other units' exhaust manifolds.
- The fuel injectors stick occasionally, resulting in poor running and overheating.

These issues are expected to be resolved soon. Once they are, testing and evaluation of the energy management system will begin.

References for this case study: Nalcor Energy, 2010;

Parsons, W., 2010.

5.J. San Juanico

Storage technology: Lead-acid battery system

Location: Baja California Sur, Mexico

Electricity system type: PV/wind/diesel/battery

Electricity system size: 167 kW

Population served: ~400

San Juanico is a small fishing village on Baja California Sur in Mexico. It is also known as Scorpion Bay and is a well-known surfing destination. The village had a 205 kW diesel generator installed in 1980, which provided electricity for three to four hours/day. Those taking electricity from the generator paid a flat rate of US$5/month. In 1999, a consortium of utilities and other organizations installed a hybrid electricity system consisting of:

- 17 kW PV array;
- A flooded lead-acid battery bank;
- Ten wind turbines, with a total rated capacity of 70 kW; and
- 80 kW diesel generator.

The project's implementation costs were ~$950,000. The system was designed such that users would pay a tariff that would cover the O&M costs. That tariff varied from about 16¢ to 27¢/kWh, depending on usage (the tariff used an increasing block structure). The average residential bill after system installation, including a $5/month flat fee, was $18/month.

Evaluation of the system found that wind and solar supplied 26% of the electricity, with the diesel generator providing the remainder. Several of the wind turbines suffered from failed alternator bearings, which may have been due to the corrosive seawater and desert dust. The inverter also suffered from several minor issues, which led to extended downtimes, as the onsite maintenance staff did not have the technical expertise to fix the inverter. The original batteries lasted only 2.5

years before their capacity degraded to less than 80%, at which point they were replaced.

Surveys and interviews with residents found a sharp increase in the number of electric appliances after the system was installed. Refrigerators, floor fans and televisions were the most popular new appliances. Load grew about 10%/year after the system was installed. In general, it appears that the residents appreciate the system, as it provides 24-hour power (usually), but they would like greater reliability. For example, the system went without 24-hour power for six to seven weeks at one point due to a minor problem with the inverter, which was easily fixed once appropriately trained technical personnel arrived.

References for this case study: Corbus, D. et al. 2004; UNFCCC 2000.

References

Akura, T., "Renewable Energy Solutions," presentation at IRENA Workshop on Accelerated Renewable Energy Deployment on Islands with Emphasis on the Pacific Islands, October 26-28, 2011, Sydney, Australia. See IRENA.org.

Akura, T., J. Merten, X. Vallve and D. Satue, "Sustainable Electrification of the Outer Islands of Kiribati," in C. Marin, L. Alves and A. Zervos (editors), *100% RES, A Challenge for Island Sustainable Development,* published by UNESCO Center of the Canary Islands, 2005.

Alaska State government, Metlakatla—Emergency Battery Energy Storage System Replacement, grant request to Commerce, Community and Economic Development Agency, dated April 29, 2008.

BC Hydro, "Hydrogen Assisted Renewable Power (HARP)," presentation, January 2010.

Bossel, U., "Does a Hydrogen Economy Make Sense?" Proceedings of the IEEE 94, no. 10 (2006): 1826–1837.

Clay, Bruce, "Apolima Island PV Project, Final Commissioning Report," not dated.

Clay, Bruce, presentation at IRENA Workshop on Accelerated Renewable Energy Deployment on Islands with Emphasis on the Pacific Islands, October 26–28, 2011, Sydney, Australia. See IRENA.org and clayenergy.com.fj.

Corbus, D., C. Newcomb and Z. Yewdall, "San Juanico Hybrid Power System Technical and Institutional Assessment," NREL/CP-500-36270, July 2004.

Deutsche Physikalische Gesellschaft, "Electricity: The Key to a Sustainable and Climate-Compatible Energy System" (Bad Honnef, Germany: Deutsche Physikalische Gesellschaft, December 2011), http://www.dpg-physik.de/veroeffentlichung/broschueren/studien/energy_2011.pdf.

Electricity Storage Association (ESA), "Capital Costs, Technology Comparison," 2002, http://www.electricitystorage.org. Accessed 10 December 2011.

ESA, "Per-cycle Cost, Technology Comparison," April 2009, www.electricitystorage.org.

ESA, "Size and Weight, Technology Comparison," not dated, www.electricitystorage.org. Accessed 10 December 2011.

Energy Sector Management Assistance Program (ESMAP), Independent Evaluation of the ILZRO/RAPS Diesel/PV Hybrid System in Padre Cocha, the Amazon Region of Peru, Consolidated Summary, December 2005.

ESMAP, "Solar-Diesel Hybrid Options for the Peruvian Amazon—Lessons Learned from Padre Cocha," ESMAP Technical Paper 111/07, 2007.

Gamble, S., "King Island Renewable Energy Integration Project," Hydro Tasmania, Available at www.kingislandrenewableenergy.com.au/ (accessed 11 April 2012).

Hunt G. and J. Szymborski, "Achievements of an ABSOLYTE Valve-Regulated Lead-Acid Battery Operating in a Utility Battery Energy Storage System for 12 Years," Exide Technologies, 2009.

Hydro Tasmania, "King Island—Towards a Sustainable Renewable Energy Future," undated.

Johnstone, H., "Bonaire: Island of Green Dreams," *Power Engineering International,* Vol.18, No. 5, January 2010.

Maclellan, N., "Energy: Wind and Solar," *Islands Business* magazine, 2007.

Miles, S. and M. Gillie, "Benefits and Barriers of the Development of Renewable/Hydrogen Systems in Remote and Island Communities," not dated. Available at http://ieahia.org/pdfs/RemoteIslandBenefits.pdf (accessed 11 April 2012).

Moseley, P., "Energy Storage in Remote Area Power Supply Systems," *Journal of Power Sources*, 2006.

Murphy, J., G. Holdmann and D. Witmer, Alaska Center for Energy and Power, *Energy Storage for Alaskan Communities Technology Summary*, prepared for the Alaska Energy Authority, July 2009.

Nalcor Energy, *Ramea Report*, January 2010.

Nguyen, T. and R Savinell, "Flow Batteries," *Electrochemical Society Interface* 19, no. 3 (2010): pp. 54–56.

Organization for Economic Co-operation and Development (OECD), International Energy Agency (IEA) and Nuclear Energy Agency (NEA), *Projected Costs of Generating Electricity—2010 Edition*, 2010.

Parsons, W., Nalcor Energy, "Wind-Hydrogen-Diesel Energy Project," presentation, November 23, 2010.

Pollak, R., "History of First U.S. Compressed-Air Energy Storage (CAES) Plant (110 MW 26h): Volume 2: Construction" (EPRI, May 1994), http://my.epri.com/.

Rastler, D., "Electricity Energy Storage Technology Options: A White Paper Primer on Applications, Costs and Benefits," Technical Update, 2010 Energy Storage (EPRI, December 23, 2010), http://my.epri.com/.

Ruin, S., "New Wind-Diesel System on Osmussaare," *Wind Engineering,* Vol. 27, No. 1, 2003.

Ruin, S., "Wind-Diesel Systems on Two Estonian Islands," undated presentation. Available at www.windpoweringamerica.gov/winddiesel/pdfs/2004_wind_diesel/operational/osmussaar_vaindloo.pdf (accessed 11 April 2012).

Saft, 'Saft energy storage system to support Caribbean island of Bonaire power grid in switch to eco-friendly generation,' Press Release No. 08-10, available at www.saftbatteries.com/SAFT/UploadedFiles/PressOffice/2010/CP_08-10_en.pdf (accessed 12 April 2012).

Szymborski, J., G. Hunt and R. Jungst, "Examination of VRLA Battery Cells Sampled From The Metlakatla Battery Energy Storage System," IEEE, 2001.

United Nations Development Program (UNDP), "A Photovoltaic Mini-Grid System for Apolima Island," not dated, www.undp.org. Accessed 10 December 2011.

UNDP, "Energy for Sustainable Development in Asia and the Pacific Region," 2004, www.undp.org.

United Nations Framework Convention on Climate Change (UNFCCC), Activities Administered Jointly (AIJ), USIJI Reporting Document on the "APS/CFE Renewable Energy Mini Grid Project, San Juanico, Baja California Sur," 2000, http://unfccc.int/.

United States Department of Energy (DOE), Energy Information Administration (EIA), "International Energy Statistics—Pumped Storage," 2008, www.eia.gov.

Appendices

Appendix A: Abbreviations

A	Ampere
AC	Alternating Current
Ah	Ampere-hour
BoS	Balance of System
CAES	Compressed Air Energy Storage
DC	Direct Current
DoD	Depth of Discharge
EPC	Electric Power Corporation
H2	Hydrogen
Kg	Kilogram
kW	KiloWatt
kWh	KiloWatt-hour
Li-Ion	Lithium-Ion
m^3	Cubic Meter
MW	MegaWatt
NaS	Sodium Sulfur
Ni-Cd	Nickel Cadmium
O&M	Operations and Maintenance
PV	Photovoltaic
R&D	Research and Development
SMES	Superconducting Magnetic Energy Storage
T&D	Transmission and Distribution
U.S.	United States
V	Volt
VRB	Vanadium Redox Battery
VRLA	Valve Regulated Lead Acid
Wh	Watt-hour
Yr	Year
ZBB	Zinc Bromine Battery
°C	Degrees Celsius

Appendix B: Sample Storage Calculations

The costs presented in Chapter 2 of this report are intended to allow for cost comparisons across storage technologies and thus are for the storage technologies alone. Installing storage into an electricity system will have additional costs for the balance-of-system (BoS) components[12] and for the electricity lost in the storage process. This appendix provides sample calculations illustrating these additional costs.

Example 1. Sample Calculation of Storage Capital Costs for a Small PV/Diesel Hybrid System

The total system costs of storage vary substantially, depending on the specific application, and determining these costs requires a system- and site-specific calculation. However, at a high level, there are some overarching themes that can clarify the total system costs of storage.

Suppose one wanted to build a PV/diesel hybrid system that produces a peak power of 1 kW. The system, without storage, would include a small 1.2 kW diesel generator, a 0.5 kW PV array, a maximum powerpoint tracker (MPPT) to optimize the electricity from the PV array and an inverter/rectifer to convert the DC electricity from the PV system to AC electricity. The inverter/rectifier would likely include some controls to switch the generator off and on and perform basic equipment integration. See Figure B.1 for a diagram of this system.

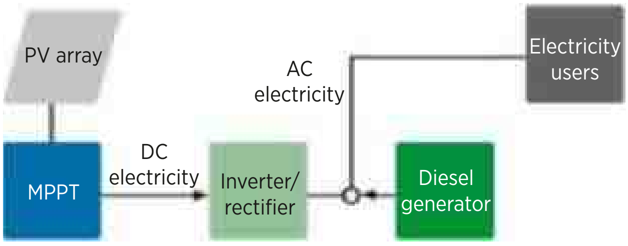

Figure B.1: Simplified diagram of a small hybrid electrical system without storage

After running the system, it is realized that the system performance is not particularly strong—the electrical output from the PV array is exceeding demand at times, and the diesel generator is having trouble responding quickly enough to the variable output from the PV array. In response, it is decided to add some deep-cycle lead-acid batteries to the system. In addition to the batteries (the costs for these may be found in Chapter 2), a charge controller will also need to be purchased. It may also be necessary to upgrade the inverter/rectifier, add additional sensors, upgrade the user interface to simplify system monitoring for maintenance, add wiring and install other BoS equipment. See Figure B.2 for a diagram of the new system.

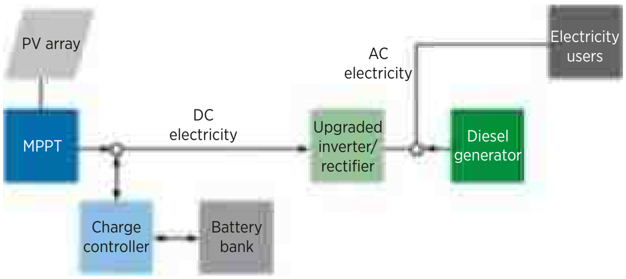

Figure B.2: Simplified diagram of a small hybrid system with storage and BoS equipment

Let us assume that the system needs 500 W of storage, based on an analysis including load demand, solar resource and the operational characteristics of the diesel generator. Let us also assume that these batteries can be bought for $500/kW (from Chapter 2), so the battery cost is $250. The BoS equipment also needs to be purchased. After consulting with BoS equipment suppliers, it is determined that this will increase the costs by about 150% on top of the storage costs, for an additional $375. The total cost is then $625. From this, one can estimate the total expected costs.

Different systems will need different BoS equipment, and the technology to be considered will also vary. A large mainland grid operator, for example, may opt to install sodium sulfur batteries. The BoS in this case may include substation upgrades, new transmission lines and new smart grid sensing technologies. Regardless of size, the system will require BoS equipment, and those costs

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[12] In this context, the BoS equipment is all equipment that is not explicitly part of the electrical generation equipment or the storage technology. Examples of BoS equipment are charge controllers, inverters, rectifiers, sensors and wiring.

will be a significant investment in addition to the storage technology itself. However, the equipment needed is highly specific to the system architecture and difficult to quantify.

Example 2. Sample Calculation to Understand the Cost of Electricity from Storage

The cost of electricity from storage includes more than the cost of the storage and BoS equipment. It also includes the cost of lost electricity due to inefficiency. Suppose there is a simple system that can be represented as shown in Figure B.3.

As can be seen in the diagram, the cost of generation is $0.50/kWh. If it is not stored, the cost of electricity is simply $0.50/kWh. However, if it must be stored before it is used, the cost increases substantially. The roundtrip efficiency of the storage (80% in this example) leads to electrical losses, which increases the cost of the underlying electricity to $0.625/kWh.

However, the storage technology also suffers from wear and tear with each kWh of electricity. The levelised cost of storage (LCOS) is assumed to be $0.20/kWh to account for this (see Table 1). In addition, the BoS equipment will also suffer wear and tear and is taken to cost 200% of the LCOS or $0.40/kWh. The equipment wear costs are then $0.20/kWh + $0.40/kWh = $0.60/kWh. Adding the cost of the stored electricity to the LCOS and BoS costs yields $0.625/kWh + $0.60/kWh = $1.225/kWh.

As can be seen, the underlying cost of electricity, efficiency losses and equipment degradation all contribute to the cost of storage. Ideally, only electricity that will not be used (that can be considered free or inexpensive) should be stored. It is also helpful to select efficient storage technologies that are inexpensive.

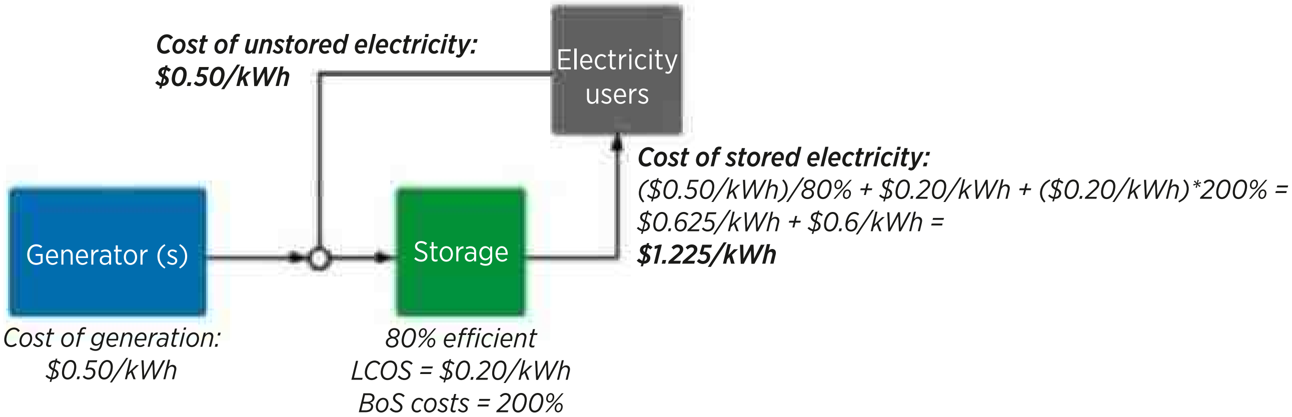

Figure B.3: Simplified diagram demonstrating the costs of storage, neglecting transmission and distribution costs

Appendix C: Websites for More Information About Storage

This section contains a number of useful references for exploring more storage and off-grid options.

Electricity Storage Association: ***www.electricitystorage.org/***

Battery Council International: ***www.batterycouncil.org/***

Power Engineer, Batteries: ***www.powerengineer.com/Reliable%20Battery%20Systems.htm***

Electropaedia: ***www.mpoweruk.com/***

EPRI Distributed Resources Web: ***http://disgen.epri.com/***

Secretariat of the Pacific Regional Environment Programme (SPREP): ***www.sprep.org/***

SPREP, Pacific Islands Greenhouse Gas Abatement through Renewable Energy Project (PIGGAREP): ***www.sprep.org/climate_change/piggarep/***

IEEE PES Stationary Battery Committee: ***www.ewh.ieee.org/cmte/PES-SBC/***

Investigations on Storage Technologies for Intermittent Renewable Energies (INVESTIRE): ***www.itpower.co.uk/investire/***

Leonardo ENERGY, The Global Community for Sustainable Energy Professionals: ***www.leonardo-energy.org/***

PowerStream Battery Chemistry FAQ: ***www.powerstream.com/BatteryFAQ.html***

Renewable Energy Systems Design Assistant for Storage (Resdas): ***www.ecn.nl/resdas/storage.aspx***

The Alliance for Rural Electrification (ARE): ***www.ruralelec.org/***

The Source for Renewable Energy: ***http://energy.sourceguides.com/***

The Renewable Energy and Energy Efficiency Partnership (REEP): ***www.reeep.org/***

Hybrid Optimization Model for Electric Renewables (HOMER): ***http://homerenergy.com/***

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