Implementation of Battery Energy Storage System for the Electricity Grid in Singapore

By

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B.Eng. (Hons), Materials Science and Engineering (2009)

Nanyang Technological University

Submitted to the Department of Materials Science and Engineering
in Partial Fulfillment of the Requirements for the Degree of
Master of Engineering in Materials Science and Engineering

at the

Massachusetts Institute of Technology

September 2010

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ABSTRACT

The market of grid-level electricity storage is growing rapidly, with a predicted market value of 1.6 billion in 2012 and 8.3 billion in 2016. Electrochemical storages such as lead-acid, nickel-cadmium, sodium-sulfur and lithium-ion batteries are candidates with high potential for grid-level implementations. Among them, sodium-sulfur battery appears to be suitable for energy application while lithium-ion battery has the capability to meet power application requirement well. However, models based on the local electricity market in Singapore show that in order to be economically efficient, the cost of sodium-sulfur battery system and lithium-ion battery system need to fall by 30% and 50%, respectively.

Thesis Supervisor: Yet-Ming Chiang
Title: Kyocera Professor of Ceramics

Acknowledgments

My gratitude goes to my thesis supervisor, Professor Yet-Ming Chiang from the Department of Materials Science and Engineering, MIT. This work would not have been completed without his guidance and advises.

I would like to give my thanks to my fellow students from Singapore-MIT Alliance, who have provided me with support and company through the program. It is the time we spent together that makes the Master of Engineering Program an extraordinary experience of mine.

Last but not least, I would like to give my most sincere gratitude to my parents, who have always supported me, encouraged me and believed in me.

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Chapter 1 Introduction

1.1 Background

Energy is always a hot topic. However, in recently years it has been getting more and more attention from the public. Fossil fuels like coal and oil will be fully exploited in the near future; greenhouse gas emission may be the root cause of global warming; energy security of many imported-energy-dependent countries is largely affected by political conditions in the Middle East region. [1] As part of the strategy to increasing energy security and suppressing global warming, The United States and many other countries are investing heavily in renewable energy not only to reduce the dependence on oil but also to seek for a more reliable, self-sufficient energy source.

As the world is trying to utilize more renewable energy such as solar and wind, an inherent problem with renewable energy must be solved. The sun does not always shine, and the wind does not always blow. To enable a reliable supply of electrical power from renewable source, grid level storages are crucial. [2] Energy storage capacity is a decisive factor in the renewable energy system which ensures an output that is not vulnerable to natural condition changes.

However, this is just a bonus point of grid level storage. Even for fossil fuel power generation, grid level storage is a useful tool to manage the disparity of energy production and consumption.

Considering the continuous nature of fuel combustion, it's generally more efficient to have a constant electrical production output. Generators operating at a constant, near full capacity are critical for fuel economics. [3] In contrast, the consumption of electricity is fluctuating from time to time. The dynamics of consumption can be related to seasonal climate, for energy needs are higher in summer and winter rather then in the other two seasons. It can be also affected by consumer behavior. Electricity consumption is higher in the daytime than at night. If the output follows consumption pattern, certain amount of generating capacity must be reserved to cope with the fluctuation needs of electricity. In order to be able to run generators at a high capacity even at off-peak hours, energy storage is necessary, for they can store the extra energy for later use.

Energy commodities such as oil, natural gas and coal can be stored. The storage of electricity produced by them is much more complex. [4] Different tools are used by the electricity generators to cope with consumption fluctuation. Variation over a long time period, for example, day-by-day or hour-by-hour change in demand is usually managed by increasing or decreasing the set of resource being operated. Minute-by-minute or even second-by-second variation is managed by regulation service, which generators normally dispatch to regulation service providers. [5] In regulating storage, what matters is the prompt response rather then the time period the discharging lasts.

Many technical tools have been designed to meet not only the demand of storing the extra energy produced during peak-hour for later use, but also of regulating the power and frequency of electricity, thus the energy quality. Some of these tools apply mechanical principles, using the mutual conversion of potential and kinetic energy to store electricity. Pumped hydro, compressed air and flywheels are among them. Other than these, batteries form another category of storage technique.

In the United States, only 3% of the total power delivered by the national grid was supplied from grid-level storage by the year 2000. [6] Most of them facilitate pumped hydro. The future sites for pumped hydro system are very limited due to geometric limit and environmental concern. As for the two most commonly used batteries, lead-acid and Li-ion, the market potential is witnessed by both the limitation of mechanical storage and the increasing needs for grid-level storage. Annual consumption of the two types of batteries are 3.9 billions in the United States with very little potion used on grid level [6]. However, with more attention draw to battery development especially by hybrid cars, the future of economic, efficient grid-level batteries will have a much larger share in the battery market.

1.2 Objectives

The main purpose of this report is to have an overview of grid-level storage, especially battery storage system. The market needs and application opportunities are to be studied and compared. Based on the application requirements, the potential of current battery technologies to meet the application demand can be analyzed. For a prospective on storage system performance, one needs to understand the fundamental working principle as well as frontier development of the technologies. Furthermore, whether they will be suitable for certain grid-level implementation can be determined by considering the performance, cost and safety factors.

As there lacks mature methods to generalize the grid-level battery economy, implementation models need to be developed to analyze the cost-effectiveness of grid-level battery systems. Other than the direct economic revenue, some other benefits that are associated with grid-level battery implementation shall also be discussed.

A conclusion will be draw from the implementation models on whether grid-level battery systems are cheap and efficient enough to be accepted by market or how large is the implementation gap, if there is any.

Chapter 2 Application assessment of grid level storages

As the name implies, grid-level storage is the storage for electricity at the utility grid level. The first application in North America is the Rocky River storage plant, constructed in Housatonic River, Connecticut. [7]

Grid-level energy storage can help the generator to reduce reserve power generation capacity and ride through power outage, thus avoid unnecessary economic lost. For example, the direct economic loss brought by power outage is around thirty billion dollars in North America, with two thirds being outage less than five minutes. [8] If storage systems were installed to ride through some of these outages, billions of dollars can be saved.

Beside, with renewable energy being more and more widely utilized, implementation of grid-level storage is inevitable. Due to the non-continuity of renewable energy supply, bulk storage mechanism is needed for wider application of renewable energy. A study by Nano-markets predicts the market for grid level batteries can be US $1.5 billion in 2012 and U $8.3 billion in 2016. [9]

The application opportunities of grid level storage can be categorized into two families, power application and energy application, [10] while the boundary between them is not clear-cut. The requirements for storage technology differ when it comes to a specific application though.

2.1 Power applications

Power application refers to storage used to stabilize the frequency and voltage of electricity, known as grid regulator. [6] In relatively small power systems, a sudden increase of the load will cause the frequency and voltage to drop. In response, the motors will slow down at the generation site as well as end users' side, if there is any. The reverse happens when the load is suddenly lightened. The direct impact is that the motor demands greater current to maintain the same output. For end users, especially those with turbines, the variation of frequency and voltage means a degradation of electricity quality. [11] Grid level storage can discharge at time when load is heavy, thus acts as ancillary generation powers, they can charge when load is lightened, and act as extra load. The generators are sheltered from load fluctuation. Applications are widely adopted in countries like Japan and Germany. [8] The market for grid level regulators is quite competitive. Sodium sulfur, lithium ion, and some other batteries are commonly used for this application.

2.1.1 Transmission system stability

Many events in electricity generation will cause transmission instability. As random as customers switching loads, lightening strikes and generators going on or off the grid cause generator to fall out-of-sync with the rest of the system. If the difference between the phase angle of generator and load is too large, the whole generation system will collapse. [12] In this situation the generator must restart to synchronize with the system. Grid level storage helps to quickly damp off the unstable oscillations within a few cycles by charge (consume power) or discharge (provide power), thus maintain a high synchronization and stability in transmission.

For this application, the storage needs to have capacity of a few MW and the ability to discharge at full power for a few minutes to hours. [13]

2.1.2 Voltage regulation

When the consumer-end load is increased suddenly, the voltage may drop especially when the scale of the grid is small. Motors at the user end will then demand larger current to maintain the same power level, which exacerbate the voltage problem further. Electricity generators often rely on a dispatched voltage regulation service to maintain the stable voltage in the grid. [11] Generation resources generate reactive power to achieve the voltage regulation.

Reactive power is not well suited to long distance transmission and distribution. New storage technologies, especially distributed storage that locate at the user-end instead of the generator-end make alternatives to conventional reactive powers to solve voltage related problems.

Storage for voltage regulation must be able to response within a few seconds. The required discharge time is from a few minutes to up to an hour. [14] Storage equipment with other primary functions can be used for voltage support if they satisfy the stated requirement.

2.1.3 Power quality and reliability

Some electronic industry customers may be very sensitive to power loss or voltage fluctuation. Especially in electronics manufacturing, microprocessors may shut down and the effect may be costly; even a small voltage sag or spike will cause severe production loss. [15] In these industries, a storage system installed downstream can prevent power loss and voltage fluctuation from reaching the electronics. When the storage is installed parallel to the load, it disconnects the load from the grid and be a supply of power when the voltage in the main grid is abnormal. When the storage is installed in series with the load, it acts as another load or a generator, adjusting the voltage distributed on the electronics. [10]

The storage for power quality and reliability need to have the capacity of a few hundred KW and a discharge time of at least 10 minutes. [10]

2.2 Energy applications

Another catalog is commercial energy storage, in which bulk energy is stored for a relatively long time, and retrieved when needed. Under current situation, part of the inline generation capacity is usually reserved as inline spinning reserve to meet sudden surge of demand. [16] Other backup reserve is also needed to ride through peak demand or temporary breakdown of generators. Grid level storage can be charged during off-peak hours and be used as a supplementary supply source at peak hours. [17] This application is illustrated in figure 1. In this case total reserve capacity can be reduced and the main generators can run at full capacity, which relates to higher fuel efficiency.

For distributors and retailers, the grid level battery can also be used as an arbitrage tool. The detail will be explained in the business model later in this thesis.

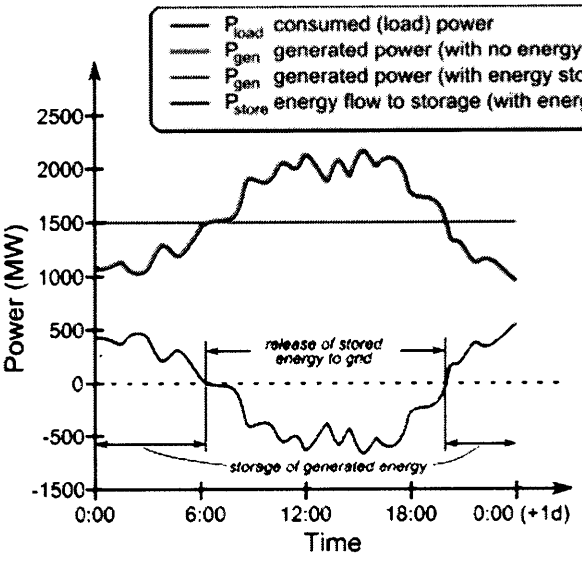


Figure 1: Principle of operation for energy applications

2.2.1 Spinning reserve

Avoiding interruptions of electricity supply requests that the reserve generation power must have an instantaneous response when the main electrical generation unit fails. This requirement posts a large cost to power producers. Cold thermal-power plants require hours, and fuel combustion turbines require at least half-hour response time to get generators ready to accept load. [18] For this reason reserve generators continuously run at a less-than-full capacity to keep them hot and spinning. Thus when reserved power is needed, they can response fast.

With grid level storage, reserved generation power that runs at less-than-full capacity can be reduced or eliminated. [6] When the failure happens on main generators, storage designed for rapid reserve can discharge and replace the failed generators, until it's repaired or until other back-up generators are ready.

Storages designed for rapid reserve must have power rating at the same range of the power plants they would temporarily replace, typically 10 to 100MW. Generation outage happens about once a week or two weeks, which means the storage technology must be able to address around 50 discharges in a year. [5]

2.2.2 Commodity storage

Commodity storage, or load leveling, is the first application of grid level storage realized by utilities. [5] By storing electricity produced during off-peak hours and sell them during peak-hours of demand, the profitability of utilities can be improved. The economic benefit depends on the difference of marginal cost to produce electricity during peak and off-peak hours.

Storage designed for commodity storage typically needs to have a capacity of at least 10MW, with a discharge time of a few hours (2 to 8 hours). [4] They may need to be operating at least during the weekdays, if not everyday. In regions where seasonal difference is clear, their operation may be clustered during seasonal peaking month, such as hot summer or cold winter.

2.2.3 Transmission and distribution (T&D) facility deferral

When electricity demand exceeds the capacity of transmission and distribution, utilities need new lines and transformers. Since the demand increases gradually, utility installs facilities that exceed the current demand level. This means for a period after the installation, the newly installed facilities will be under-utilized during the first few years in service. Moreover, T&D facility capacity is required to meet the peak electricity demand, which only happens rarely, maybe only a few days a year. At other times the facility is under-utilized. [5]

With energy storage installed downstream near the user end, they can be charged during off-peak hours and discharge when demand increases. In this way the peak-hour transmitted power in the main grid is maintained low while the increasing load will be satisfied at the same time. The expensive upgrade of transmission and distribution lines can be deferred with energy storage, until the demand increase can better justify the upgrade.

For T&D facility deferral, the energy storage system needs to operate during the seasonal peaks and be able to discharge for a few hours. A few MW of capacity is typical but it depends on the installation location, for an installation nearer to the end-user requires a lower capacity. [19]

2.2.4 Renewable energy management

Strictly speaking, renewable energy management covers both power application and energy application. The intermittent nature of renewable energy sources such as solar or wind determines that they alone are not able to be reliable and continuous energy source. Grid level storage helps variable energy source such as wind and solar to deliver constant and reliable electricity on demand. The viable delivering of high-quality energy adds to the economic value of renewable energy.

Meanwhile, storage systems can help to store renewable energy until the time they are mostly needed. By storing off-peak hour energy and deliver them at the time when grid level demand is high, the deliver peak can meet the demand peak. Since peak-hour electricity sells for a higher price, the overall economic gain is increased.

In the long term, a grid system that uses a large percentage of renewable energy sources may need storages capacity of days or weeks to cope with the rainy period or windless season. [5] However, talking about this application seems to be too early.

For renewable energy management, the storage capacity can be from 10kW to 10MW, depending on the renewable utility. [20] The discharge time varies from a few seconds (for transient instability ride through) to maybe ten hours for peak shifting. For peak-shifting purpose, the storage needs to discharge about 250 days a year. For power quality management, the discharge frequency depends on the renewable source.

2.2.5 Customer Energy management

Utilities usually charges industry a monthly fee based on the highest demand during the month. By shaving the peak with energy storage, which is connected to the grid, this peak demand fee can be significantly reduced. A storage system charges during off-peak hours and discharges to the user when the demand exceeds a predetermined value, thus shaves the demanding peak.

In this application, the required capacity and discharge time of the storage depends on the nature of the industry. Discharge frequency may vary from a few times a month to diurnal.

2.3 Comparison of storage systems for different applications

As shown from the table below, for different applications, parametric requirement for storage is different as well. For power application, the discharge is short but the requirement on the total energy capacity is usually not high. For energy application, the discharge time is longer and the required capacity is usually at least in megawatt range. [21]

Representative applications	**Discharge power range**	**Discharge time range**	**Stored energy range**
Commodity storage, spinning reserve	**10-1000 MW**	**1-8 hours**	**10-8000 MWh**
T&D deferral, customer energy management	**0.1-2 MW**	**0.5-4 hours**	**0.05-8 MWh**
Power quality and reliability	**0.1-2 MW**	**1-30 seconds**	**0.1-60 MJ (0.028-16.67 kWh)**

Table 1: Application category specifications

The application with renewable energy covered the whole range of power and energy capacity since both electricity quality assurance and bulk energy storage is needed in renewable energy management.

Chapter 3 Technologies for grid level electricity storage system

Various technologies can be employed to store large quantity of energy. Some of the technologies are based on the mechanical principles while others are based on electrochemical or electrical principles. Before focusing on battery storage, other technologies must also be introduced and compared.

3.1 Electromechanical storage

Electromechanical storage stores electrical energy in the potential energy of massive objects. The earliest and most widely used grid-level storage is pumped hydro. It uses two water reservoirs with different altitudes. During off-peak hours water is pumped from the lower reservoir to the higher one. During peak hours, the water is released to generate hydroelectricity. The earliest application of pumped hydro can date back to the end of nineteenth century. Among current grid level storages in the world, majority is by pumped hydro. The overall storage capacity is over 110 GW. There are in total 19 humped hydro plants in the US. [2] The working principle of pumped hydro is illustrated below. [22]

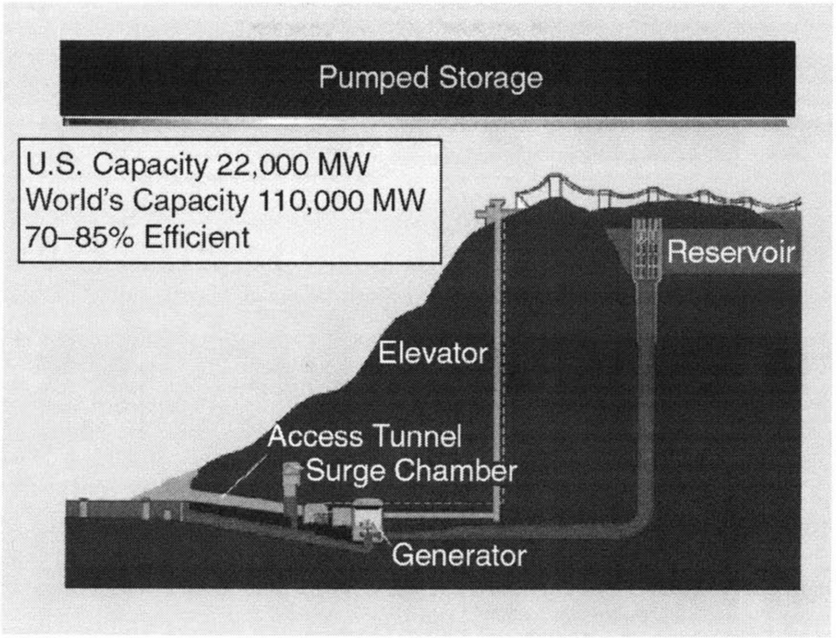


Figure 2: Pumped Hydro storage illustration

The main issue related to pumped hydro is its high capital cost and long building time. A large-scale reservoir takes years to build and the capital investment is huge. Furthermore, because of the required altitude difference, it's not applicable to regions with homogeneous geography feature.

Another similar technology is to store energy through compressed air. Compressed air energy storage (CAES) is a complicated system. Air is pre-compresses using low cost electricity from the power grid at off-peak times. Later the potential energy of compressed air is utilizes with some gas fuel to generate electricity through a turbine generator. [2] The compressed air is often stored in underground mines or caverns created inside salt rocks. It takes about 1.5 to 2 years to create such a cavern by dissolving salt. [23]

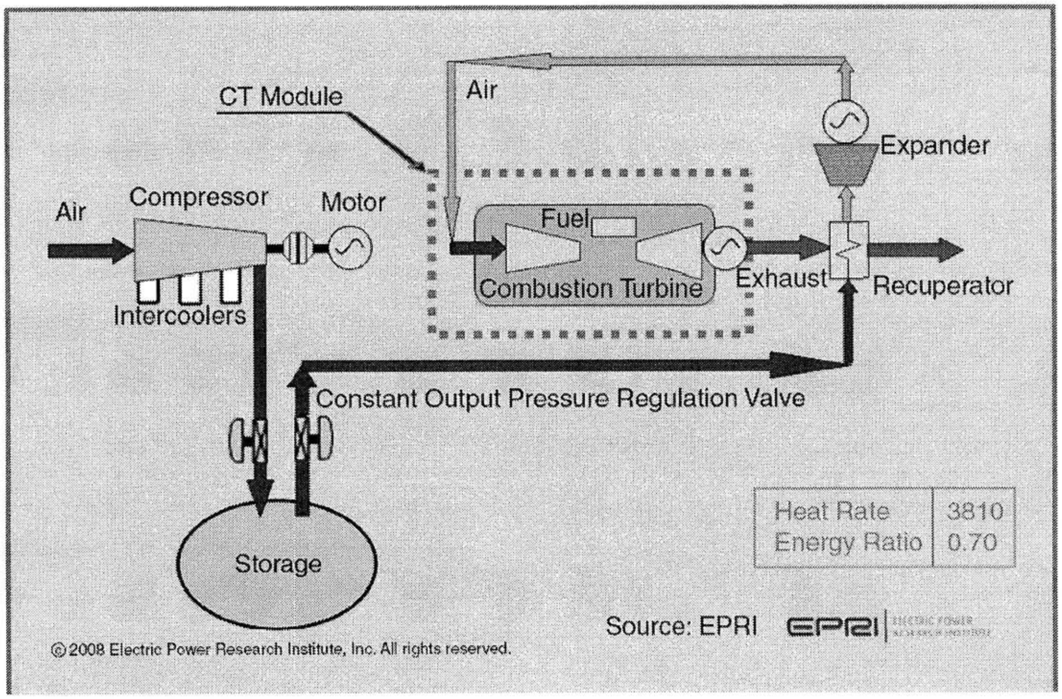


Figure 3: CAES system illustration

There are currently two CAES facilities in use. The first commercial CAES was a 290 MW unit built in Hundorf, Germany in 1978. The second commercial CAES was a 110 MW unit built in McIntosh, Alabama in 1991. The construction took 30 months and cost $65M (about $591/kW). Another 2700 MW system is under construction in Ohio, USA. [24]

The high capacity of compressed air storage is attractive. However, compressed air energy storage system bears the same issue as pumped hydro. Safety is another concern due to high pressure created underground.

Flywheel uses heavy plate linked to a shaft to transfer electric energy to rotational energy and store. Currently there is no large scale plant running. Flywheels with capacity in kilowatt range are applied in telecommunication system. [25] Larger scale flywheel system is still under research. The barrier for larger scale plant is on materials and the vacuum environment required for a low friction during operation.

Mechanical storages mentioned before share some common issues such as high capital cost, low energy density and long responding time. Geography is another crucial factor, especially for pumped hydro and compressed air. Their constructions not only have a strict requirement on the geographical condition, but also bring ecological damage to the sites. Due to the limit of land, countries like Singapore are not likely to adopt these storage schemes. This report will thus not focus on the electromechanical technologies, but on the more flexible battery technologies.

3.2 Battery storage

3.2.1 Lead-acid batteries

Lead-acid battery is one of the oldest battery technologies and is still active in the market for small portable devices. [26] Since the invention 150 years ago, it has been applied on small portable devices, automotive, uninterruptable power supply and telecommunication. It remains one of the most important energy storage technologies. The production and usage continue to grow because of the increased number of vehicles for which lead-acid batteries provide energy for engine starting, vehicle lighting and engine ignition. Lead-acid battery system is also used extensively in telephone system, power tools, communication devices, emergency lighting and the power source for mining equipment. Besides the conventional applications mentioned before, new designs for electric vehicle and energy storage are also being introduced.

Low price and the ease of manufacture account for the wide use of lead-acid battery. In addition, lead-acid batteries have energy efficiency of around 70%, which makes it attractive for energy storage usage. Traditional vertical-place batteries have an energy density of more than 40Wh/kg, and a horizontal-plate design can achieve a higher energy density. [27]

(a) Principle reactions

In a lead-acid battery, the positive electrode is made of lead dioxide and the negative electrode of metallic lead in a porous structure. Typically, a positive electrode composes both α-PbO_2 and β- PbO_2. α form has more compact crystal morphology and thus a lower surface-to-volume ratio, corresponding to a lower electrode activity. However, it promotes a longer cycle life than the β form. The positive active material is a major factor that determines the performance and life cycle of the lead-acid battery. The electrolyte is a sulfuric acid solution.

During the discharge process, both electrodes are converted to lead sulfate. The reactions of discharging are represented below.[27]

Negative electrode	$Pb \rightarrow Pb^{2+} + 2e$
	$Pb^{2+} + SO_4^{2-} \rightarrow PbSO_4$
Positive electrode	$PbO_2 + 4H^+ + 2e \rightarrow Pb^{2+} + 2H_2O$
	$Pb^{2+} + SO_4^{2-} \rightarrow PbSO_4$
Overall reaction	$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$

During charging, reverse of the reactions above happens. The charge-discharge reaction is referred as double-sulfate reaction. The electrolyte is an active material and in certain case can be the capacity limiting agent.

(b) Applicability on grid level storage

As the world's oldest rechargeable battery, lead-acid battery is available in large quantities and in a variety of seizes and designs. The discharge efficiency is fair for grid-level application, though cannot be competing with lithium-ion or sodium-sulfur batteries. The low energy density is a potential problem. However, the low cost of lead-acid battery still gives it an advantage of less capital per unit power. It's an option for some grid level applications such as power quality and reliability.

The world's largest lead-acid battery system was installed in Chino, California. This 1988 installation was a 40 MWh battery system with individual lead-acid cells in series and parallel connection to the grid. It delivered 10MW of power for four hours into the utility grid at 2000V and 8000A.

For energy application, the main limitation is the short cycle life. The typical cycle life of lead-acid battery is less than 500 cycles, [28] which makes it not suitable for applications that require frequent charge-discharge cycles.

A potential safety hazard is hydrogen evolution. Overcharge occurs in some design when battery is almost fully charged. The cell voltage is greater than the gassing voltage, resulting in the production of hydrogen and oxygen. [29]

Negative electrode $4H^+ + 4e \rightarrow 2H_2$

Positive electrode $2H_2O - 4e \rightarrow O_2 + 4H^+$

Overall reaction $2H_2O \rightarrow 2H_2 + O_2$

The resultant hydrogen and oxygen brings an explosion hazard.

Further than this, the large quality of lead used in lead-acid battery manufacture expose an environmental issue upon manufacturing and disposal.

3.2.2 Nickel-cadmium battery

Nickel-cadmium battery is a reliable, sturdy, long-life battery that operates over a wide temperature range and a high discharge rate. At the end of 19th century when it was invented, the only competitor was lead-acid battery. Compare to lead-acid battery, nickel-cadmium battery is more mechanically and chemically robust, being able to withstand both mechanical abuse and electrical maltreatment such as overcharging, reversal and short-circuiting. [30] With some modification, the energy density is significantly larger than lead-acid battery.

The earliest type of nickel-cadmium battery is the vented pocket-plate design. Later at 1940, the sintered plate type was invented. It has a higher energy density than the pocket-plate design, but more expensive and complex to manufacture. In 1947, completely sealed nickel-cadmium battery was available and became the predominant rechargeable battery until the invention of nickel-metal hybrid and lithium-ion batteries. [30]

(a) Principle reactions

Though there are variations of nickel-cadmium batteries, the principle chemistry is the same. The positive plate is made of NiOOH and the negative of porous Cd. The plates are immersed in the electrolyte KOH. During discharge, metallic cadmium is oxidized to form cadmium hydroxide. The following reaction happens.

$$2NiOOH + 2H_2O + Cd \rightarrow 2Ni(OH)_2 + Cd(OH)_2$$

The reverse reaction happens during charge. [26] In this reaction, water is the active material. The KOH electrolyte is not significantly changed with respect to composition or density. Lithium hydroxide is often added into electrolyte to improve the cycle life and high temperature operation by making the cell more resistant to electrical abuse.

(b) Applicability on grid level storage

New designs of nickel-cadmium battery have appeared in the last twenty years. Nickel-cadmium battery with plastic-bonded negative plates and sintered positive plates approaches 56Wh/kg of energy density, which is significantly higher than lead-acid and conventional pocket plate design. It also offers a longer cycle life of above 2000 cycles. [26] Because of the complex manufacture requirements, the cost for nickel-cadmium battery is higher than lead-acid batteries.

The largest nickel-cadmium battery installation was in Fairbanks, Alaska. It used four parallel strings of high-performance pocket plate cells and was able to provide 46 MW for 15 minutes. Since its first operation on November 11th, 2003, it served as a rapid reserve for the local grid to ride through the power cutoff before backup generation capacities are in place. It was triggered 56 times in the year of 2004 and saved 290,000 customers from getting disconnected. [31]

However, compare to its late competitors such as lithium-ion batteries, the energy density of nickel-cadmium battery is much lower. The Alaska installation measures

1300 tons and occupies a large area of 120 by 26 meters. [31] For future applications with larger capacity requirements (such as commodity storage), the energy density need to be improved. Furthermore, toxicity of cadmium exposes a safety hazard on cell production and recycling. These factors may impede the further applications of nickel-cadmium batteries for grid level storage, especially energy applications.

3.2.3 Sodium-sulfur batteries

Rechargeable high-temperature sodium-sulfur battery offers an attractive solution to large scale energy storage applications. Possible applications include load leveling, power reliability and quality. The sodium-sulfur technology was introduced in the 1970's and has been improved to variety of designs since then. The energy conversion efficiency is around 90%. [32] For sodium sulfur batteries, the principle reaction requires a high temperature of operation. The battery need to be maintained at a temperature between 270 and 350 degree C to keep the active electrode materials in a molten state and to ensure ionic conductivity in the electrolyte. The high operation temperature not only increases the cost of operation, but is also a safety hazard. The safety factor is mainly ensured by insulation, which adds to the cost of installation.

(a) Principle reactions

Sodium-sulfur battery consists of the positive electrode made of sulfur and negative electrode made of sodium. The sodium-ion conductive ceramic β"-alumina (β"-Al_2O_3) functions as the electrolyte, separating the two active electrodes. The electrodes are kept molten during operation while the electrolyte remains solid. [33]

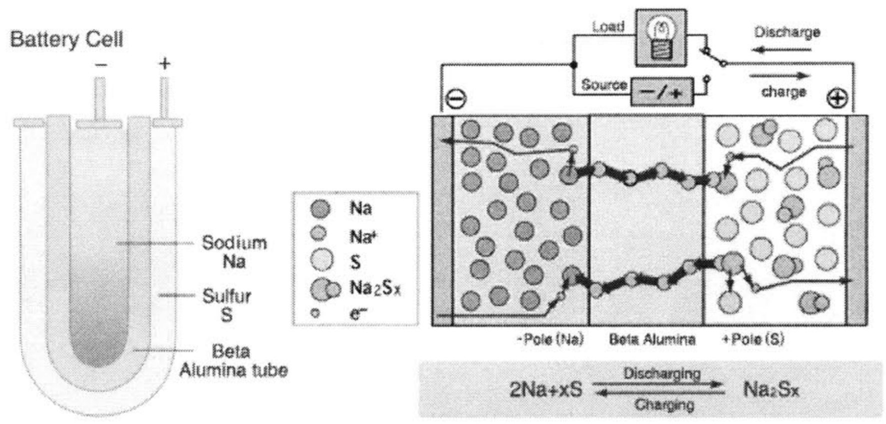


Figure 4: Structure and reaction mechanism of NaS battery

During discharge, the negative electrode is oxidized at the electrode/electrolyte interface, forming sodium ions (Na^+). The ions migrate to the positive sulfur electrode and combine with the sulfur to form sodium pentasulfide. (Na_2S_5). After all the free sulfur phase is consumed, the sodium pentasulfide is converted to polysulfide with higher sulfur content. The electrode and over all reactions can be shown as below.

Negative electrode (sodium)	$2Na \rightarrow 2Na^+ + 2e$
Positive electrode (sulfur)	$xS + 2e \rightarrow S_x^{-2}$ (x is between 3 and 5)
Overall reaction	$2Na + xS \rightarrow 2Na_2S_x$

The reverse reaction happens during charge. [34] The open circuit voltage is constant during the 60 to 75% depth of discharge when the mixture of sulfur and Na_2S_5 phase are presented. The voltage then decreases for further discharge and Na_2S_x forms. The corrosivity of Na_2S_x decreases as the value of x becomes smaller. Further discharge introduces the presence of Na_2S_2, which leads to a higher internal resistance and poorer rechargeability or even structural damage of the cell. For these two reasons, many developers choose to limit the depth-of-discharge below 100%. [35]

(b) Applicability on grid level storage

Only one company, NGK Insulators manufactures sodium-sulfur battery. Accroding to the data they provide, sodium-sulfur battery has an energy density that doubles that of lithium-ion battery, both on per weight and per volume base. The cycle life can be as long as 4500 cycles at 80% depth-of-discharge. [33] The long cycle life can be partly attributed to the liquid nature of electrodes, which prevent the classical morphology-based electrode degradation mode.

Sodium-sulfur battery utilizes inexpensive active materials and thus has a potential low manufacture cost. However, extra cost is associated to the high operation temperature. Effective enclosure of the cell is required to maintain energy efficiency and reduce heat loss. The sealed battery system requires little maintenance effort.

For its high energy density and energy efficiency, lack of maintenance requirement and long cycle life, sodium-sulfur battery provides a promising use for many applications at the grid level. Sodium sulfur batteries are used widely for grid level storage in Japan. The largest installation is a 34MW * 7hour site in Japan for wind power stabilization. Over 190 applications have been installed in Japan, with over 60% of them focused on customer peak-shaving. [34] Other applications include rapid reserve and power quality improvement. The main obstacle for a wider application and larger capacity is the high manufacture cost.

3.2.4 Lithium-ion batteries

Since its first commercial application by Sony in 1991, lithium-ion battery has rapidly become the standard power source in a broad array of markets. Meanwhile, the battery performance continues to improve as lithium-ion batteries being adapted to an increased diversity of applications. They include consumer electronics, such as cell phones, laptop computers and personal data assistants, as well as military electronics such as radios, thermal weapon sights and mine detectors. A newly merged market is the electric/hybrid car battery, where extensive capital and research effort have been devoted.

The positive electrode of lithium-ion battery is usually a metal oxide with a layered structure or a tunneled structure. The negative electrode is typically a graphitic carbon on a copper current collector. [36] The major advantage of lithium-ion battery is its high energy density and long cycle life compare to other battery technologies. These features make it attractive for weight, volume and life-time sensitive applications.

(a) Principle reactions

The two electrodes in a lithium-ion battery are made of a lithium metal oxide (positive electrode) and lithiated carbon (negative electrode). The first batteries on the market utilized $LiCoO_2$ as the active material for positive electrode. More recently, other cathode materials such as $LiMn_2O_4$ or $LiNi_{x-1}LiCo_xO_2$ have been introduced to improve the performance. These active materials are adhered to a metal foil current collector with a binder and a conductive diluent, typically a high surface-area ratio carbon black or graphite. The positive and negative electrodes are separated with a porous polymer separator that hosts a liquid electrolyte. In recent designs, the electrolyte can be replaced by conductive polymer,

Lithium-ion battery operates by reversibly incorporate lithium ion in an intercalation process, where lithium ions are reversibly insert or removed from a host material without significant structure change to the host. The metal oxide, graphite and other materials act as host to incorporate lithium ions. When a lithium-ion battery is being charged, lithium ions are released from the positive electrode and intercalated into the negative electrode. The process can be represented by the following chemical reactions, where M is the metal in the metal oxide. [37]

Positive electrode $LiMO_2 \rightarrow Li_{1-x}MO_2 + xLi^+ + xe$

Negative electrode $C + xLi^+ + xe \rightarrow Li_xC$

Overall reaction $LiMO_2 + C \rightarrow Li_{1-x}MO_2 + Li_xC$

An illustration is also given to show the charging and discharging process. [38]

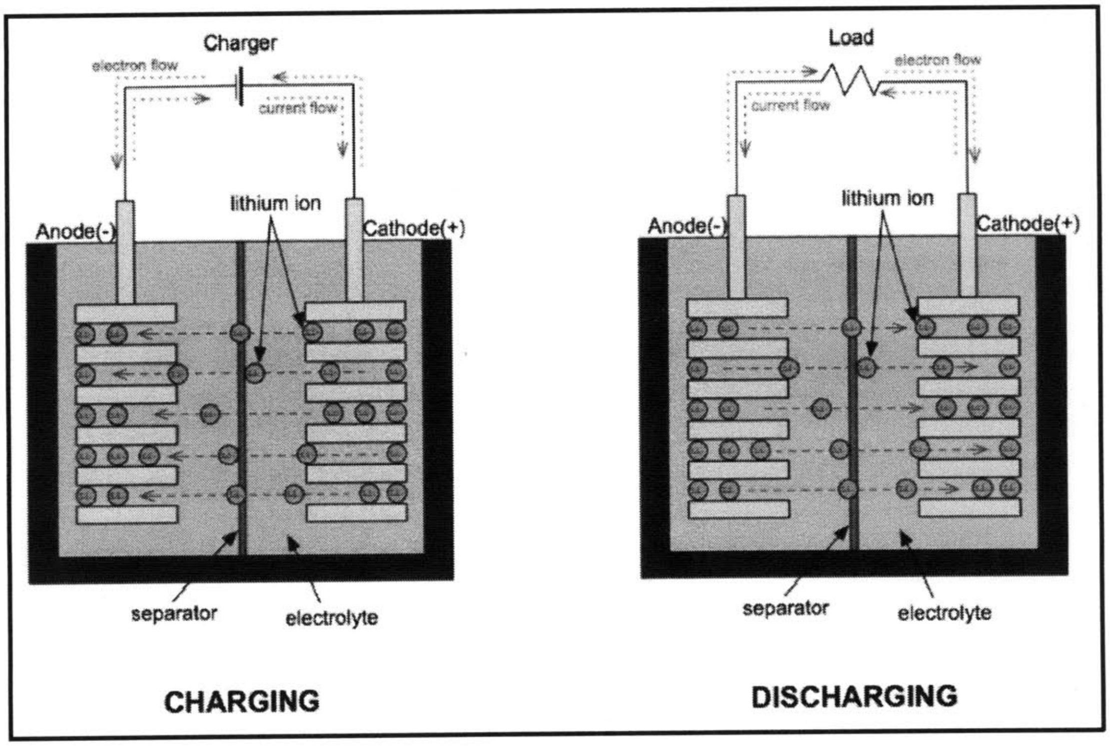


Figure 5: Lithium-ion battery charging mechanism

(b) Applicability on grid level storage

In conventional secondary batteries, the structures of electrodes change during charge and discharge process. The chemical reactions happen to the electrodes introduce deterioration to the battery. Since the charge and discharge processes only happen though the movement of lithium ions, lithium-ion battery has a lower chemically activity, thus a slower deterioration rate than the conventional secondary batteries. Lithium-ion battery also has a high energy density of around 150Wh/kg, which exceeds most of other batteries. The lifetime of lithium ion batteries can be 3500 cycles at 80% depth of discharge when manganese system is used as positive electrode material. [39]

Some drawbacks of lithium-ion batteries include the high manufacture cost, especially for high-voltage applications where safety is a critical issue. A protective circuit is necessary to prevent overcharging, which adds to the cost. Despite this, some researchers consider lithium-ion batteries one of the most promising candidates for high-voltage, high-capacity grid level applications.

Lithium-ion batteries are used at a number of sites in Japan as frequency regulators or renewable energy support; US battery producer A123 installed a 12MW battery system in Chile, providing frequency regulation and spinning reserve to the electricity grid. Before that, another 2 similar projects were carried on in the US, with power capacity of 1MW and 2MW. [40] Cost and safety are probably the main issues to prevent applications with a larger capacity.

Other than the battery technologies described before, flow batteries, including polysulfide/bromide redox battery, zinc/bromine battery and vanadium redox battery are also promising candidates for grid storage application. Mr. Yaliang Chen completed a detailed study on flow batteries in the year of 2009. Thus flow batteries are not studied in this report.

3.3 Battery technology comparison

The advantages and limitations four types of batteries discussed before are listed in the following table.

Battery type	Advantages	Limitations
Lead-acid	Low cost Available in a wide range of sizes and designs Cell components are easily recycled	Relatively low cycle life (50-500 cycles) Limited energy density (~40Wh/kg) Relatively low efficiency (70% turnaround efficiency) Hydrogen evolution can be an explosion hazard
Nickel-cadmium	Long cycle life (>2000 cycles @ 80% depth of discharge) Withstand electrical and mechanical abuse	Relatively low energy density (~ 56Wh/kg) Higher cost Toxicity of cadmium

	Low maintenance	
Sodium-sulfur	Long cycle life (~4500 @80% depth of discharge) High energy density Little maintenance required	High operating temperature (270 – 350 degree C) High cost
Lithium-ion	Long cycle life (~3500 @80% depth of discharge) Higher energy density (150Wh/kg) Rapid charge capability No memory effect	High cost Protective circuit needed

Table 2: Battery advantages and limitations comparison

Lead-acid battery has the lowest cost among all. This is the main reason why it dominants the battery market for a long time. However, its cycle life is apparently a shortcoming. Service life is a crucial factor for grid level applications, especially for applications like power quality and reliability, voltage regulation or commodity storage, in which frequent charge and discharge cycles are required. Lithium-ion and sodium-sulfur batteries have superior cycle life performances. For instance, NGK website sites the service life for lithium-ion and sodium-sulfur batteries to be 10 years and 15 years. [33]

Other than a limited cycle life, the low energy density and conversion efficiency limit the further application of lead-acid batteries. Nickel-cadmium battery suffers from the same problems with lead-acid as well.

The following figure gives the power density and energy density of different technologies. [41] The sloped lines give the discharge duration at rated power. Lithium-ion batteries give the highest power and energy density except for fuel cells while fuel cell suffers from the problem of unrechargability. Thus from the prospective of minimizing battery size and weight, lithium-ion battery has advantage over other battery technologies. Not being shown in this figure, sodium-sulfur battery has longer discharge duration than lithium-ion battery at rated power.

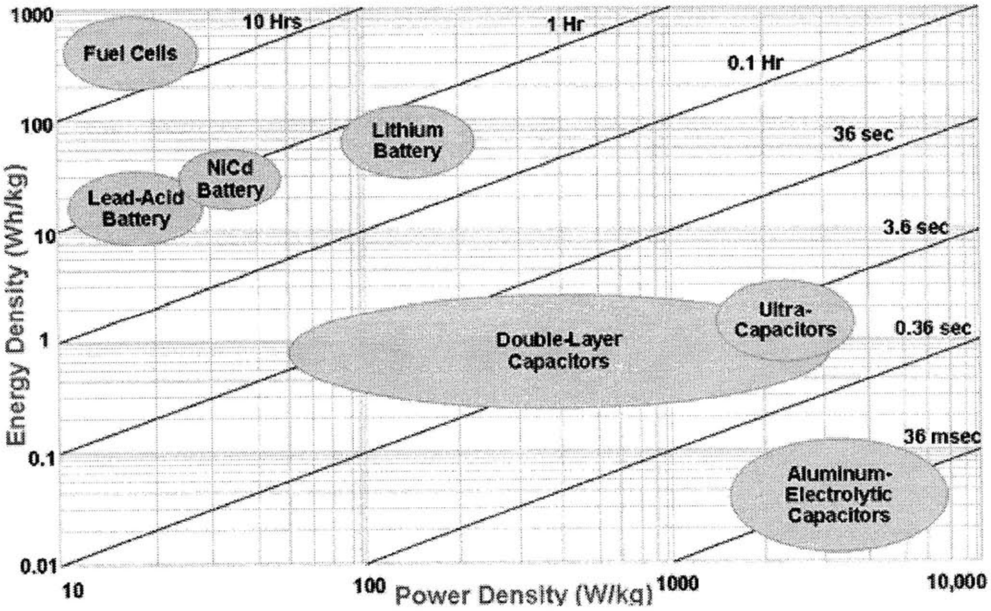


Figure 6: Energy density and discharge rate

Another important factor that need to be carefully considered is the cost. The following figure gives the approximate cost per power rate for some technologies. [42] Sodium-sulfur battery has the highest cost among the all. However, since the service life can be significantly longer than other battery technologies, even lithium-ion battery, the cost per cycle may be able to compete with other technologies.

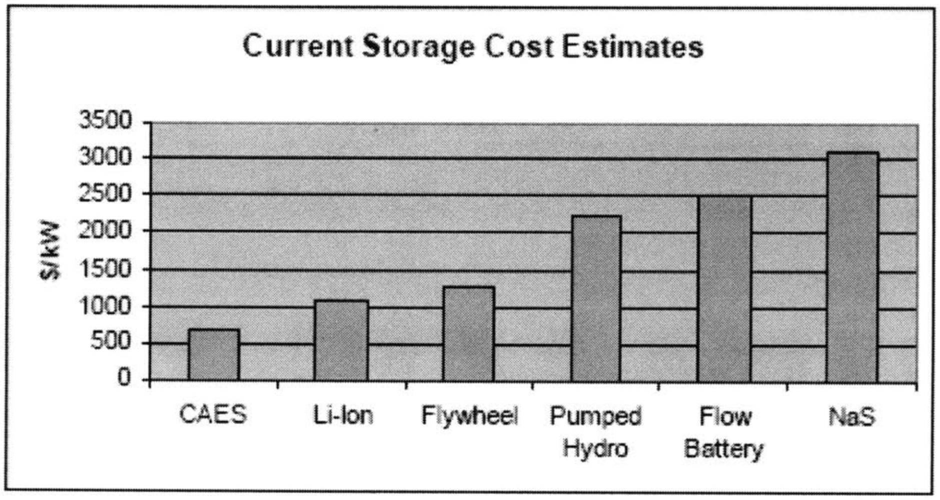


Figure 7: Storage technologies – cost estimation

For lead-acid and nickel-cadmium batteries, the toxicity of materials lead and cadmium may bring contamination problem. At the end of the service life, the battery must be well disposed and recycled to control the toxic contents from polluting the environment. Any leakage during operation will also bring severe environmental issue.

For lithium-ion batteries, the high cost and potential overcharging problem limit the scale of applications. Presently lithium-ion batteries are mainly used for applications in which low power rating and small energy capacity are required.

From the comparison above, lithium-ion battery and sodium-sulfur battery seem to be more competitive than the other two technologies. Due to the longer discharge duration, sodium-sulfur batteries are more suitable for applications in which long time discharge is needed, e.g. commodity storage. While lithium-ion batteries are more likely to be applied to short time discharge applications such as frequency regulation. Nonetheless, to choose the best suited technology for a specific application, factors like required power rate, energy capacity, service life, discharge frequency, cost of ownership, maintenance cost and so on need to considered collectively.

The utilization of different technologies for grid level storage is shown in the following figure. [42] The number of pumped hydro sites sees a steady increase over the past few decades. Since 2000, the number of sodium-sulfur battery systems increased rapidly, with most of them in Japan. The implementation of sodium-sulfur battery may continue to grow since in the year of 2008, NGK Insulators, the manufacturer of sodium-sulfur battery made an announcement to increase their annual production volume from 90MW to 150 MW. [33]

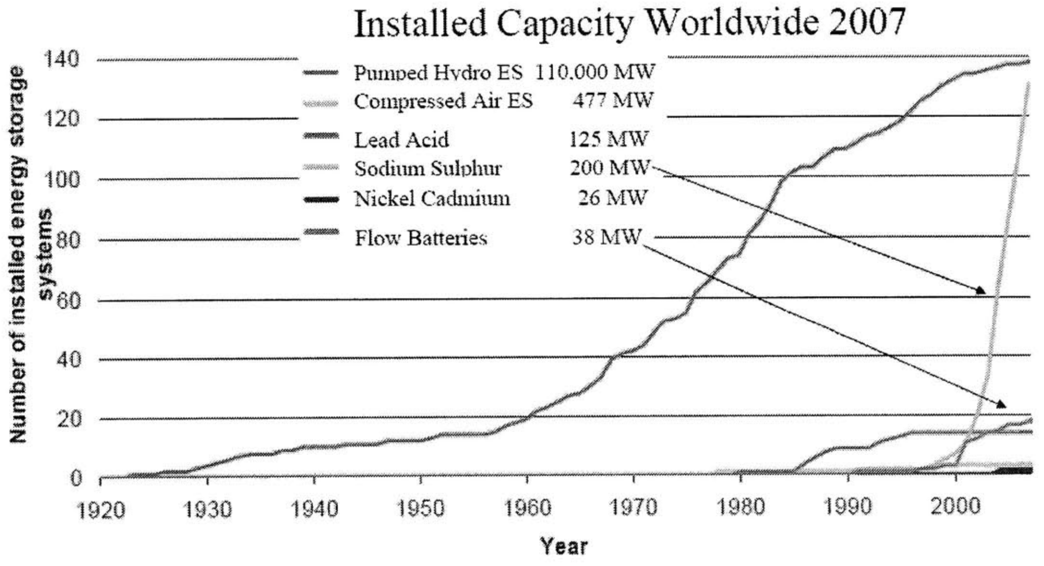


Figure 8: Worldwide installed capacity until 2007

3.5 Power Conversion system

The power conversion system is an essential part of grid energy storage. It serves as an interface of storage equipments and the AC grid. The PCS can be further break down to four components, the power stage, the controller, DC interface and AC interface. [43] Transformers, filter inductors, DC-link inductors, resonant-link inductors and resonant-pole inductors are the main magnetic components in the PCS. The PCS connects storage device and load in the way illustrated in the figure below. [43]

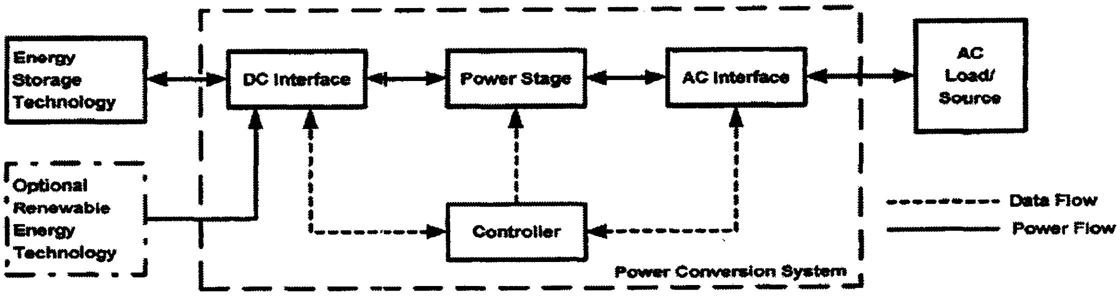


Figure 9: Power conversion system for grid level storage

The PCS generally converts DC from storage or renewable source to AC at a specific frequency so it can be used at the load. PCS takes power from a DC source and form a sinusoid from it, using high power switching devices. The PCS switches rapidly from positive and negative DC voltage supply, creating a sinusoidal output. [44]

The technical designs will not be discussed in detail in this report. However, the cost of PCS affects the cost of storage battery system to a large extent. The cost of PCS can be 20% to 60% of the total cost for grid level battery system. [43] The cost for PCS is closely related to power rating, thus varies for different applications.

Chapter 4 Development in battery technologies

4.1 Recent development of lithium-ion battery

4.1.1 Cathode materials

a. Lithium nickel cobalt oxides cathode with aluminum and magnesium doping

The solid solution of lithium nickel cobalt oxides, $Li(Ni1-yCoy)O_2$ appears to be very promising cathode active materials for high energy and high power lithium-ion batteries. Between the two popular lithium cathode materials, $LiCoO_2$ battery has a good thermal stability and cycle life property, while $LiNiO_2$ provide a high energy density and opportunity for cost reduction. [45] $Li(Ni1-yCoy)O_2$ offers a compromise between them [46]. The most advantageous compositions range is from y=0.2 to 0.3. However, safety and cycle life concerns remain. Safety problems arise from the instability of the delithiated "NiO_2" phase releasing oxygen at elevated temperatures. The thermal stability in charged state can be enhanced by aluminum or magnesium doping.

Albrecht et al. synthesize $Li(Ni_{1-y}Co_y)O_2$ with aluminum and magnesium as dopants. The maximum cobalt content was set to 20 mol% due to economic reasons. The minimum cobalt content adjusted was 10 mol% and the maximum aluminum and magnesium contents were set to 5 mol%. The resultant $Li(Ni1-y-zCoyMz)O_2$ (M=Al, Mg) was examined by XRD and SEM. It observed that both aluminum and magnesium stabilize the layered crystal structure arrangement of the mixed oxide materials. The impact of aluminum is more pronounced than the impact of magnesium. [46]

By adding aluminum and magnesium as dopants, the extent of delithiation in cathode is suppressed. Since the decomposition temperature of charged electrodes without electrolyte is a function of the delithiation, aluminum and magnesium enhance the cathode thermal stability of the delithiated phase mainly by an intrinsic limitation of the delithiation. Fire and explosion risk is thus lower. Furthermore, the specific capacity after 150 charge-discharge cycles is improved from 125mAh/g to around 135mAh/g compared to $Li(Ni_{1-y}Co_y)O_2$ without doping. [47]

b. Lithium iron phosphate

For the long run, a significant development could be the adoption of lithium iron phosphate to replace lithium cobalt oxide as the cathode material. [48] This material has the advantage of lower cost and improved safety than lithium cobalt cathode, and thus of high commercial interest. However, a major technical disadvantage is the low conductivity. Conductivity can be increased by partial substitution of iron by other atoms (doping) or coating with carbon or Fe_2P. For high rate applications, nanocomposite $LiFePO_4$ has also been tested.

Regarding safety concerns, lithium iron phosphate may be safer due to the lower voltage of oxidation reaction at 3.4V. The oxidation product of lithium iron phosphate is ferric phosphate, which is a stable material.

$$LiFePO_4 + 6C \rightarrow LiC_6 + FePO_4$$

Besides the advantages mentioned, lithium iron phosphate could also be a cheaper material for cathode. By replace the expensive cobalt by iron and phosphate, it's estimated that the cathode cost can be reduced from 50% to 10% of total battery cost.

4.1.2 Anode materials

a. Nanowire anode material

Searching of an anode material which can absorb lithium ion reversibly with a higher capacity than carbon has been attracting attention recently. However, cracking caused by anode volume change has always been a problem. This is reduced by using nano-size particles as anode active material. [49]

Silicon-based anode for lithium-ion batteries has attracted great attention due to the high theoretical specific capacity of 4200 mAh/g. However, the large volume change (>300%) of silicon during charge and discharge leads to electrical disconnection, which will further lead to rapid fade of cell's capacity. By decreasing the size of silicon particle to nano-size or using elemental thin film of silicon, the cycle stability of capacity can be improved. [50]

The silicon nano-wire anode has many advantages. Nano-wire with a small diameter better accommodates the large volume change during the lithium-ion intercalation and de-intercalation processes. Secondly, Si–Al alloy layers at the back of silicon substrate improve electronic contact and conduction. Thirdly, as the silicon nano-wires are formed on a wafer, the electrode does not need conducting additives or binders, thus a weight reduction can be realized. Furthermore, the SiNW films can be easily prepared by using metal catalytic etching method, presenting opportunity of industrial production. Huang's group [50] used a silicon film with a silicon-aluminum array at backside to produce silicon nano-wire with a near unity transformation rate. The diameters of nano-wires range from 20 to 300nm. The thickness of the film is about 90μm. The silicon nano-wire array showed much larger anode capacity than silicon nano-crystals, thus a better cycle performance. At a current rate of 150mA/g, the first-cycle charge-discharge capacity of the nano-wire anode reached 3653 and 2409 mAh/g. After 30 cycles, a stable capacity of 1000mAh/g was achieved.

b. Spinel lithium titanate

$LiCoO_2$/graphite is the most commonly used electrode couple in commercial lithium-ion batteries because of their high energy density and light weight. However, the LiC_6 present at charged state is highly reactive and thus raises safety concern. [51] In order to resolve the safety limitation, the spinel $Li_4Ti_5O_{12}$ has been studied as an alternative anode active material. It has a stable voltage plateau of approximately 1.5 V versus Li/Li^+. Though it is higher than that of carbon material, it can be coupled with high-voltage cathode materials such as $LiMn_2O_4$, $LiCo_{0.4}Fe_{0.4}Mn_{3.2}O_8$ or $Li_2CoMn_3O_8$ for an approximately 2.5 V lithium-ion battery with high safety and reversibility. [52]

One important feature of $Li_4Ti_5O_{12}$ to be anode material is that there is very little volume change during insertion and extraction of lithium ions. Three lithium ions can be accommodated in every formula unit of $Li_4Ti_5O_{12}$, which means a theoretical capacity of 175 mAh/g. [52] The framework of $Li_4Ti_5O_{12}$ lattice is very robust. Therefore, insertion and extraction of lithium are extremely reversible. [53]

The spinel $Li_4Ti_5O_{12}$ was usually synthesized by a solid-state reaction of stoichiometric amounts of TiO_2 and Li_2CO_3 or $LiOH \cdot H_2O$, with heating at 800–1000 °C for 12–24 hours. Li's group [53] implemented a novel microwave synthesis of $Li_4Ti_5O_{12}$ in which the required temperature, thus energy consumption s much lower than conventional solid-state processes. The tested discharge capacity reached 162mAh/g at 0.1mA/cm^2 and 144mAh/g at 0.4mA/cm^2, suggesting $Li_4Ti_5O_{12}$ to be a high-potential anode material. [51]

4.1.3 Electrolyte

a. Polymer electrolyte

Polymer electrolyte is defined as a membrane with comparable transport properties as ionic solutions in lithium-ion batteries. Over the last few years polymer electrolyte for lithium-ion battery has draw much research attention because of several advantages it has over liquid electrolyte, such as no leakage problem, no combustible reaction products and no internal shorting. [54]

To be efficient electrolyte for lithium-ion battery, the polymer needs to have high ionic-conductivity, good mechanical strength and chemical stability. Since it's first introduced in 1973, polymer electrolyte has gone through three stages, namely, solid, gel and composite polymer electrolyte. [55]

Dry solid polymer electrolyte, e.g. poly(ethylene oxide) (PEO), has low ionic conductivity. The cycle performance of dry solid electrolytes is not satisfying with lithium metal electrode, usually as low as 200 to 300 cycles. [54, 56]

In comparison, gel-state polymer electrolyte possesses both the mechanical strength of solid and transport property of liquid. Several polymer hosts have been developed which include poly(ethylene oxide) (PEO), poly(propylene oxide) (PPO), poly(acrylonitrile) (PAN), poly(methyl methacrylate) (PMMA), poly(vinyl chloride) (PVC), poly(vinylidene fluoride) (PVdF), poly(vinylidene fluoride-hexafluoro propylene) (PVdF-HFP), etc. [54]

Electrochemically inert filler can be incorporated into polymer matrices to make composite electrolyte. The fillers are generally of high surface area such as ZrO_2, TiO_2, Al_2O_3 and hydrophobic fumed silica. By adding the fillers to polymer matrices, the ionic conductivity can be enhanced, and the stability at the interface can be stabilized at the mean time. [56]

Energy densities of 200-230Wh/kg have been reported for lithium-ion batteries with polymer electrolyte, with the value being close to estimated limit for lithium-ion batteries. [51]

b. Room temperature ionic liquid electrolyte

Room temperature ionic liquid (RTIL) was firstly reported by Wilkes and Zaworotko in their 1992 report. [57] A number of RTIL, or molten salts comprising cations and anions, have gained attention as potential substitute electrolyte materials for conventional carbonate based solvent to conducting lithium-ion.

Ionic liquids have negligible vapor pressure, non-flammable nature and high thermal stability in general. In addition the RTILs have intrinsic ionic conductivity at room temperature and a wide electrochemical window, exhibiting good electrochemical stability in the range of 4.0–5.7 V, which is necessary for lithium-ion batteries with high energy cathode. [58]

The most common type of room temperature ionic liquids is quaternary ammonium salts. While the RTILs based on quaternary ammonium cations cannot be directly applied in batteries, it is possible to dissolve a lithium salt $[Li^+][X^-]$ in ionic liquids $[A^+][X^-]$, with the formation of a new ionic liquid $[Li^+]_m[A^+]_n[X^-]_{m+n}$, consisting of two cations. Over 60 combinations of electrodes/ionic electrolyte have been tested. [59]

Ionic liquids that are used as lithium-ion battery electrolyte include quaternary ammonium salts, such as tetraalkylammonium $[R4N^+]$, or cyclic amines, both aromatic (pyridinium, imidazolium) and saturated (piperidinium, pyrrolidinium). Most RTILs also consist of inorganic anions, such as $[BF4^-]$, $[PF6^-]$, $[AsF6^-]$ and organic, such as triflate $[CF_3SO_3^-]$ or imide $[N(CF_3SO_2)2^-]$, $[N(F_2SO_2)2^-]$. [60]

Presently, ionic liquid electrolyte is still under investigation. The energy density of Li/electrolyte/$LiCoO_2$ battery at 20 °C was 108.9mAh/g while at a temperature increased to 35 °C the specific capacity was 128.2mAh/g. This increase is possibly due to the viscosity reduction of electrolyte. [58] Another major problem is that the cycle life. 10 to 100 cycles are usually reported in the case of RTIL electrolyte. The capacity loss over cycles is also higher.

4.2 Recent development in sodium-sulfur battery

Compared to other well established battery technologies, the development of sodium-sulfur batteries is at a very initial stage. Development is mainly on optimization of battery design and production techniques. There is, however, some novel advancement in the field which may change the dynamic of sodium-sulfur battery application in future.

4.2.1 All-solid, low temperature sodium-sulfur battery

At the high operating temperature, sodium (melting point = 97.8 °C) and sulfur (melting point = 110 °C) melted into liquid states that were more reactive and corrosive than the solid states. Further, liquid sodium and sulfur could induce explosions and corrosion, and power was consumed in maintaining the operating temperature. [32] Sealed design of sodium-sulfur battery is necessary out of safety concern, but also adds on the cost of battery production. [61]

For these reasons all-solid battery that operates at a low temperature attracts much interest from researchers. By using polymer electrolyte, compact, flexible and all-solid state battery is possible. Some polymers, such as Poly (ethylene oxide) (PEO) and 'glymes' ($CH_3O(CH_2CH_2O)_nCH_3$), are found to be ion-conductive and compatible with sulfur electrode, and are thus potential candidates for solid-state NaS battery. [62]

Park's group [62] studied the electrochemical properties of an NaS battery with PEO electrolyte that operated at 90 °C. They prepared the PEO polymer electrolyte by dissolving PEO and $NaCF_3SO_3$ in acetonitrile at a weight ratio of 9:1. The solution was mixed for 2 h and then cast on to a glass dish. The PEO electrolyte film was placed in a vacuum oven and heated at 50 °C for 12 h. All preparations of the polymer electrolyte were carried out in glove box-filled with argon. A sulfur electrode was prepared from a suspension of 70 wt% sulfur powder, 20 wt% carbon and 10 wt% PEO in acetonitrile and the sodium electrode from cutting a sodium ingot.

During the first discharge cycle, high energy density of 505mAh/g and potential plateaus at 2.28 and 1.73 V were obtained, which is similar to reported value of high temperature NaS battery. However, after a few cycles, the capacity declined sharply to around 160mAh/g in ten cycles. Based on the cycling performance, there is a long way to go before any practical applications.

Utah based company Ceramatec is currently developing solid electrolyte NaS batteries using ceramic membrane separators. The company estimates that the battery will cram 20 to 40 kilowatt hours of energy into a package about the size of a refrigerator, and operate below 90 degrees C. [63] Through the current development is focused on primary cells, this may be the initial step of further research on low temperature, high density NaS battery with good safety aspect.

Chapter 5 Implementation of grid-level battery system in Singapore

5.1 Methodology of analysis

To analyze the economic feasibility of grid level storage system, one needs to compare the cost and benefit of installation. Cost models have been done on small battery packs such as electric vehicles battery packs. [64, 65] However, grid level battery system is not achieved by simply multiply the number of battery cells. The cost of grid level storage system can be break down to the following components. [10]

- Storage medium
- Interface to AC load and source
- Power conversion system
- Monitors and controls for all subsystems
- Building/shelter, transportation of the system including permits
- Engineering service or training to start-up and operate
- Operation and maintenance cost

These factors vary from project to project. The levels of technology maturity are not the same for different technologies either. The following table gives the relative maturity of technologies and the certainty of cost estimation. [21]

Technology	Commercial Maturity	Cost Certainty
Lead-Acid Batteries	◆	◆
Ni/Cd Batteries	▲	■
Na/S Batteries	■	■
Li-ion Batteries	■	●
Zn/Br Batteries	■	▲
Vanadium-redox Batteries	■	■
Flywheel (high-speed)	■	■
Pumped Hydro	◆	◆
Compressed Air Energy Storage (CAES)	■	▲

Legend

Symbol	Commercial Maturity	Cost Certainty
◆	Mature products, many sold	Price list available
▲	Commercial products, multiple units in the field	Price quotes available
■	Prototype units ordered, under construction, or in the field	Costs determined for each project
●	Designs available, nothing built	Costs estimated

Table 3: Commercial maturity and cost certainty of grid level storage systems

Thus an application scenario must be assumed before the cost can be estimated. In this report, two application cases will be discussed, with different power rating and energy capacity. Based on the assumption in each case, the investment on the battery system will be estimated.

The next step is to estimate the benefit of installation. As mentioned before in chapter 2, the installation of grid level battery has multiple benefit, with different audiences, for example, electricity generators, distributors, public, etc. In this study, the main benefit of the installation will be reflected in money term. The present value of all the revenue generated over the service life of battery system and the battery cost are used to calculate the net present value for the investment. The investment is justifies only when the net present value is positive.

In this study, the local utility market of Singapore is chosen to be studied. There are a few reasons for Singapore to be a suitable case study of grid-level battery implementation. First of all, the scale of the energy market is small compare to other countries, and is appropriate to analyze in a report of this type. Secondly, market data is open to public. Data for half-hourly consumption volume, retail and whole sale price can be found in database of Energy Market Authority, Singapore. The transparency of data eases the modeling to a large extent. Moreover, government's support in developing Singapore as the regional solar hub brings larger chance for subsidy in energy related areas such as the grid level battery installation.

5.2 Overview of Singapore

5.2.1 Social and economic indicators

The Republic of Singapore is an island country located off the southern end of Malay peninsular. The total area of the country is 710.3 square kilometers, a little smaller than New York City. As a state country, Singapore is the world's forth leading financial center, and a cosmopolitan world city. [16]

By the end of year 2009, the total population of Singapore is 4.99 million, with 75% of them local residence. [66] Indicated by data from the World Bank, Singapore's gross domestic product (GDP) was 181.95 billion US dollars. Singapore is also the forth wealthiest country in the world in terms of GDP per capita. The Economist Intelligence

Unit ranked Singapore in its "Quality-of-life Index" as the best place to live in Asia and the ninth in the world. [67]

5.2.2 Climate

Singapore has a tropical rainforest climate without distinct seasons. The country has uniform temperature, abundant rain and near unity humidity all through the year. Maximum and minimum average temperature in 2009 was 31.7 and 25 degree C. May and June are the hottest month and November and December are the monsoon seasons. Although the precipitation normally increases during monsoon seasons, the average temperature varies less than 2 degrees over the whole year. [66] Because of the stable temperature in Singapore, seasonal fluctuation of electricity consumption is not significant.

5.2.3. Energy market in Singapore

a. Electricity market structure

Singapore electricity market had been traditionally owned and operated by government. Tremendous change has been made since 1995 to liberalize the electricity industry for greater efficiency and innovation. The Energy Market Authority (EMA) was formed in 2001 to promote competition and ensure reliability in the electricity and gas industries.

The National Electricity Market of Singapore (NEMS), which is essentially a real-time electricity trading pool, started to operate in Jan 1st, 2003. [66] The generation companies bid to sell electricity every half hour on NEM. Electricity retailers buy electricity on NEMS and offer packages to contestable consumers. A total number of about 10,000 contestable consumers are able to exercise their choices of electricity purchase, whose consumption comprise 75% of total electricity sales. Those non-contestable consumers – more than 1 million in number- represent 25% of total electricity sales in Singapore. Currently they continue to purchase their electricity from SP Service Ltd. at the regular tariff. [68] The Full Retail Contestability, which will involve small businesses and households, is under review.

The EMA oversees the operation of NEMS. Half-hourly electricity transaction price and quantity data is recorded and open to public. The data is available from EMA website and will be utilized later in the model.

b. Electricity generation and sales data

Annual electricity generation and sales data is provided in the following table. [66] The generation of electricity constantly has a 10% surplus than the total sales.

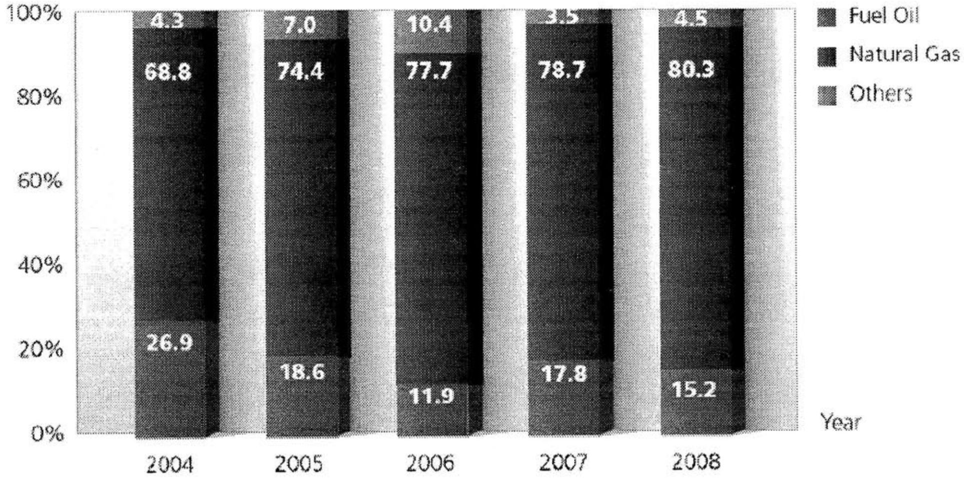
Gigawatt Hours

	1998	2003	2004	2005	2006	2007	2008
Generation	28,374.8	35,281.5	36,809.6	38,212.7	39,442.1	41,137.7	41,716.8
Sales	26,081.2	31,985.7	33,171.2	34,761.3	35,921.8	37,420.3	37,940.3
Domestic	5,328.4	6,507.1	6,524.8	6,750.3	6,764.3	6,820.8	6,748.5
Manufacturing	11,121.8	13,706.7	14,446.2	15,005.0	15,041.5	15,621.6	15,482.6
Other Industries	9,631.0	11,771.9	12,200.2	13,005.8	14,116.0	14,977.9	15,709.2

Table 4: Annual electricity generation and sales data

c. Fuel mix

Majority of the electricity generation capacity in Singapore use natural gas as fuel. Other fuels include oil, synthetic gas and biomass, etc. The fuel mix for electricity generation is provided in the figure below. [69]



Note: Others consist of orimulsion fuel (no more available since Oct 2006), synthetic gas, diesel and refuse incineration.

Figure 10: Fuel mix for electric generation

d. Electricity price

The price of utilities saw a relatively significant increase in the past few years. Especially, electricity tariff kept climbing up for the last five years, with an average annual increase of 10%. [70] The figure below gives the price indices for main utility goods including electricity, gas and liquefied petroleum gas. Prices in 2004 are taken as the base point.

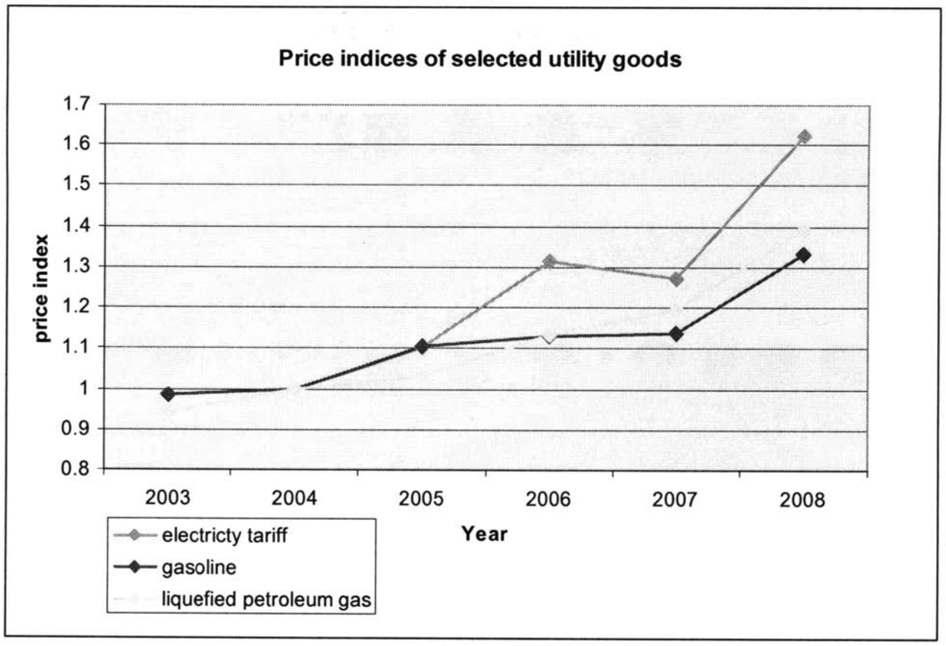


Figure 11: Price index for utility goods

Although the tariff only applies to non-contestable consumers, it is an indicator on price change for both contestable and non-contestable markets.

e. Market players

Currently there are eight generation licensees in the electricity market with five of them competing in the NEMS, namely, Senoko Power Ltd, Power Seraya Ltd, Tuas Power Ltd, Keppel Merlimau Cogen Pte Ltd and Sembcorp Pte Ltd. [69] The first three companies together represent 90% of total generation capacity in Singapore. National Environment Agency (NEA) operates the incineration plants and sells electricity generated from these plants. The remaining two licensees have not started operation. [69]

As of December 2008, the total licensed generation capacity was 12.17 GW. The peak power demand in 2008 was 6.073 GW. [66]

There are six licensed electricity retailers, with five of them, namely Keppel Electric Pte Ltd, Sembcorp Power Pte Ltd, Senoko Energy Supply Pte Ltd and Tuas Power Supply Pte Ltd. The sixth company has not started operation. [66]

f. Renewable energy

Although a small country and alternative energy disadvantaged, Singapore has a responsibility to environmental sustainability. Furthermore Singapore's interests in clean and sustainable energy solutions are also driven by the need for energy security, i.e., less dependence on imported fossil fuel sources.

Singapore's geographical location, with 50% more solar radiation than temperate countries, makes solar photovoltaic (PV) technology a promising option as a source of renewable energy. The Housing and Development Board (HDB) has test-bedded solar PV systems at two existing public housing precincts at Serangoon and Wellington, generating 220kWh of electricity per day for each precinct in the process. As of June 2009, there are 31 grid-connected commercial solar PV installations with a total capacity of 422.1 kW in Singapore. And there are also 9 households with solar PV installations connected to the grid, making up 56.6 kW of capacity. [71]

The country's average wind speeds are too low for the economical use of large wind turbines. Although the technology for micro-wind turbines is improving quickly to help to harness lower wind speeds, wind energy options remain weak.

Overall, renewable energy generation only covers an insignificant portion of total generation capacity presently. However, intensive interests have been focused on solar PV sector. To give further impetus to the efforts in this area and facilitate better connections, Energy Market Authority (EMA)'s $5 million Market Development Fund will fund the market charges to test-bed new generation technologies for all approved projects. Solar power producers selling to the National Electricity Market can apply to the EMA for refund of their market charges.

In addition, EDB has launched the Solar Capability Scheme (SCS) for the private sector to offset capital cost in installing solar technologies in the new energy-efficient buildings. This aims to build up capabilities of companies in the solar ecosystem through increased adoption by lead users in Singapore. EDB also launched the $17 million Clean Energy Research and Test-bedding (CERT) platform which targets the public sector and complements the SCS. [68]

g. Electricity grid reliability

Singapore's electricity supply is among the most reliable in the world. In November 2003 and June 2004, Singapore experienced power outages that were the result of natural gas supply disruptions. After the June 2004 incident, the government set up the Energy System Review Committee (ESRC) to study the root causes of the gas disruptions and propose measures to strengthen the energy system's reliability.

System Average Interruption Duration Index (SAIDI) is commonly used to evaluate the power system reliability. It's the sum of total customer interruption durations divided by the total number of customers. The following figure gives the SAIDI trend from the year 1998 to 2009. [70] The peak in year 04/05 corresponds to the outage mention in the previous paragraph. As a comparison, in the year of 2004, the US average SAIDI was 381 minutes. [72] A benchmark study in 2007 spinning 26 countries shows that Singapore has the fewest and shortest electricity outages of cities worldwide. [70]

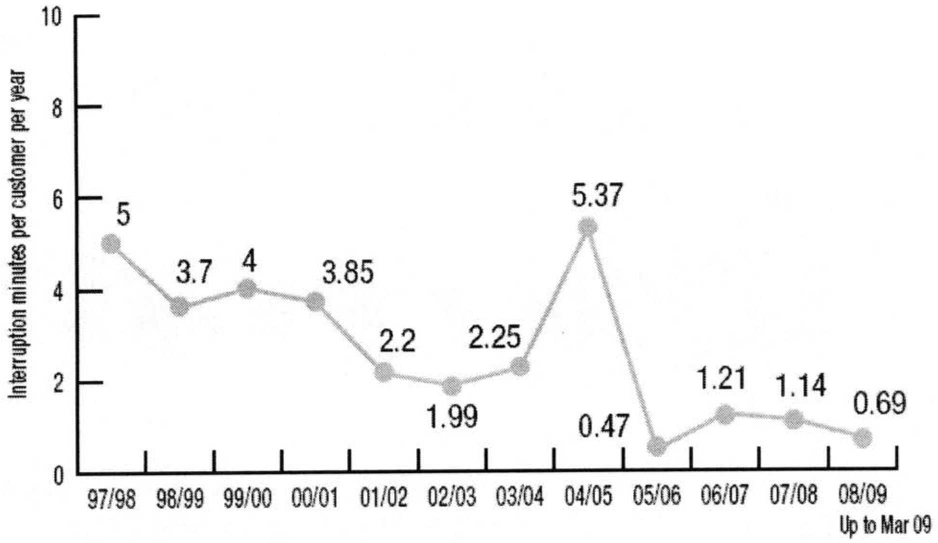


Figure 12: System Average Interruption Duration Index

In Singapore, power quality is even more important than in other cities due to the large number of high technology industries with highly sensitive equipment. At cutting-edge semiconductor wafer fabrication, pharmaceutical and petrochemical plants, a slight dip in supply voltage for a fraction of a second can cause severe production losses. [8] Singapore has the fewest and shortest power outages among global cities. The outstanding electricity grid is a reason many multinational companies choose the city to base their operations.

5.3 Retailer arbitrage model

5.3.1 Assumptions

In summer 2005, American Electric Power (AEP) chose to install a 1 MW (peak 1.2MW), NaS battery storage system in the AEP system at Chemical Station in Charleston, WV. The station is a combination of transmission (138kV) and distribution station (12kV). The main purpose for the installation is peak shaving and power quality control. [44]

Since the technology for NaS battery is not mature, the cost of battery system can only be decided case by case. A bottom-up cost model is difficult because of the confidentially and complexity of battery technologies, and also because of the cost of installation varies between projects. However, the cost of previous projects carried on by NGK is available. By assuming the installation of a similar system, the cost can be roughly estimated.

The assumptions of this model are as follow:

- The battery system is installed at a 22kV distribution station in Singapore
- The power electronics resembles the one used in Chemical station mentioned before
- The battery system is composed of twenty 50kW NaS battery modules, with a discharge duration of 6 hours at rated power
- Electricity distributor installs the battery system primarily for the purpose of price arbitrage
- Only the revenue generateed by price arbitrage is counted although other benefits such as voltage stabilization, T&D deferral may occur
- The cost for the battery includes preassembled enclosure and installation fee
- Operational cost and maintenance costs are omitted
- The service life for the battery system is 10 years

- The battery system complete charge-discharge cycles 250 times a year (workdays)
- The battery system has a conversion efficiency of 90%
- A 7% tax is opposed on the electricity distributor who purchase the system
- A discount rate of 5%

5.3.2 NaS battery system components

a. Battery modules

A 50 kW NaS module consists of around 300 cells. Each cell has the structure as shown in the left illustration below. The central sodium design is adopted in this cell, in which the sodium electrode in contained in beta-alumina electrolyte. Besides this tubular design, central sulfur design and planar design is also possible. In tubular design, beta-alumina acts as separator and electrolyte at the same time. [73]

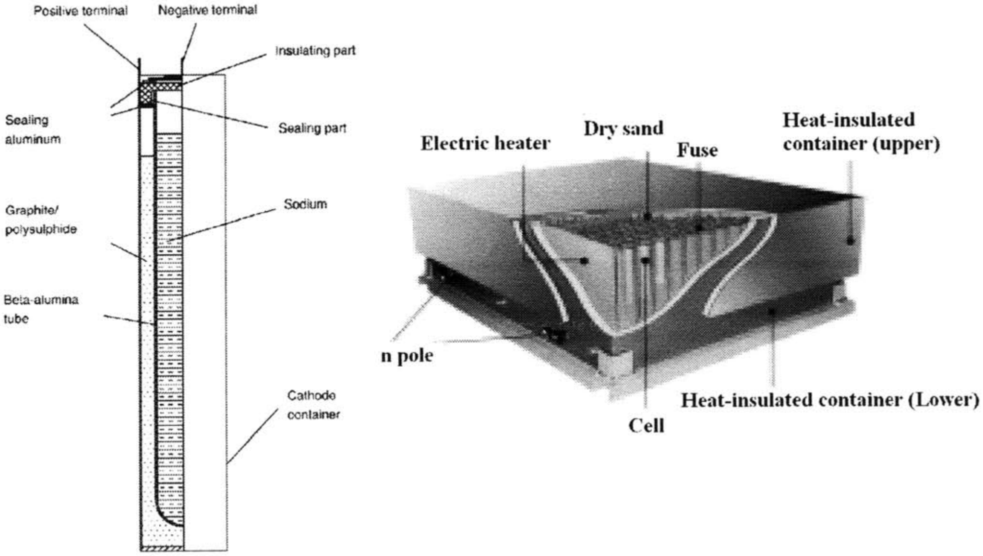


Figure 13: left: NaS cell structure; right: module structure

β"-alumina (β"-Al_2O_3) is synthesized by conventional solid state reaction. The preparation of β"- Al_2O_3 via a solid-state reaction is typically carried out with the starting materials of α- Al_2O_3 and small amount of Na_2CO_3 and Li_2CO_3. Na_2CO_3 and Li_2CO_3 provide bridging oxygen ions in the spinel block. The introduction of bridging oxygen ions imparts an overall negative charge into the Al_2O_3 structure and permits the diffusion of lithium ions into the defected spinel blocks. The lithium ions act as pins to stabilize the close-packed spinel block. Since sodium ions are too large to enter the spinel block, they remain in the conduction plane. The manufacturing process of β"-Al_2O_3 is illustrated in the flowchart. [74]

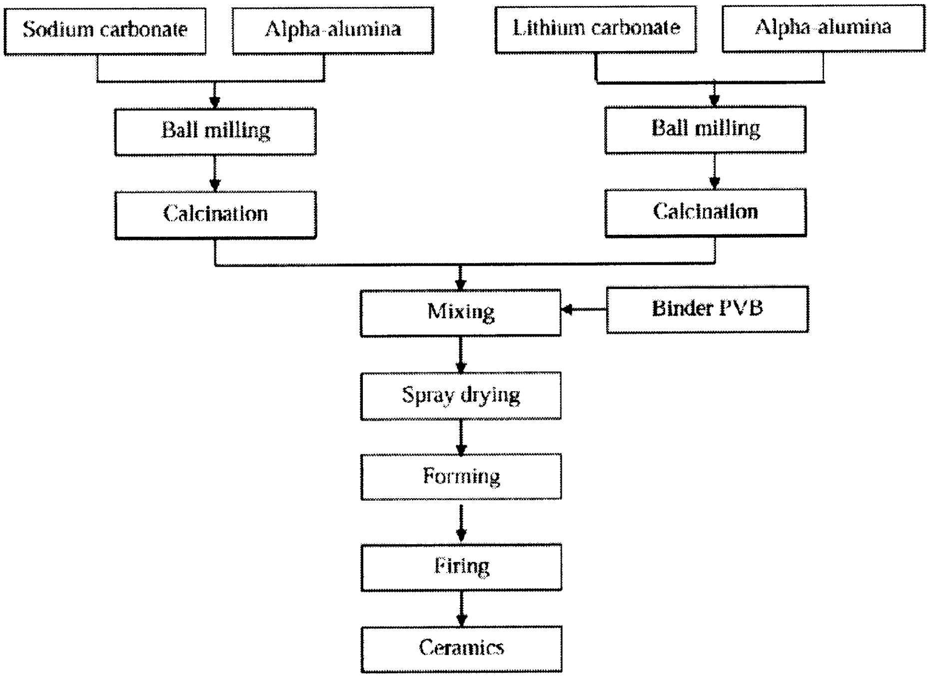


Figure 14: Schematic illustration of β"-alumina production process

b. Battery enclosure

The NaS batteries and their controllers need to be contained within a waterproof enclosure and mounted outdoors on a concrete pad. The enclosures are designed with a natural draft ventilating system to provide a proper environment for the battery modules. The design also facilitates relocation, as the battery system may need to move several times during their useful life. Five battery modules are located inside a 15-meter tall steel enclosure that supports a total of almost 18 tons. Four such enclosures accommodate the 20 battery modules of this installation. [44]

The enclosure can also be provided and installed by the battery provider. An illustration of the enclosure and battery arrangement inside is given below. [33]

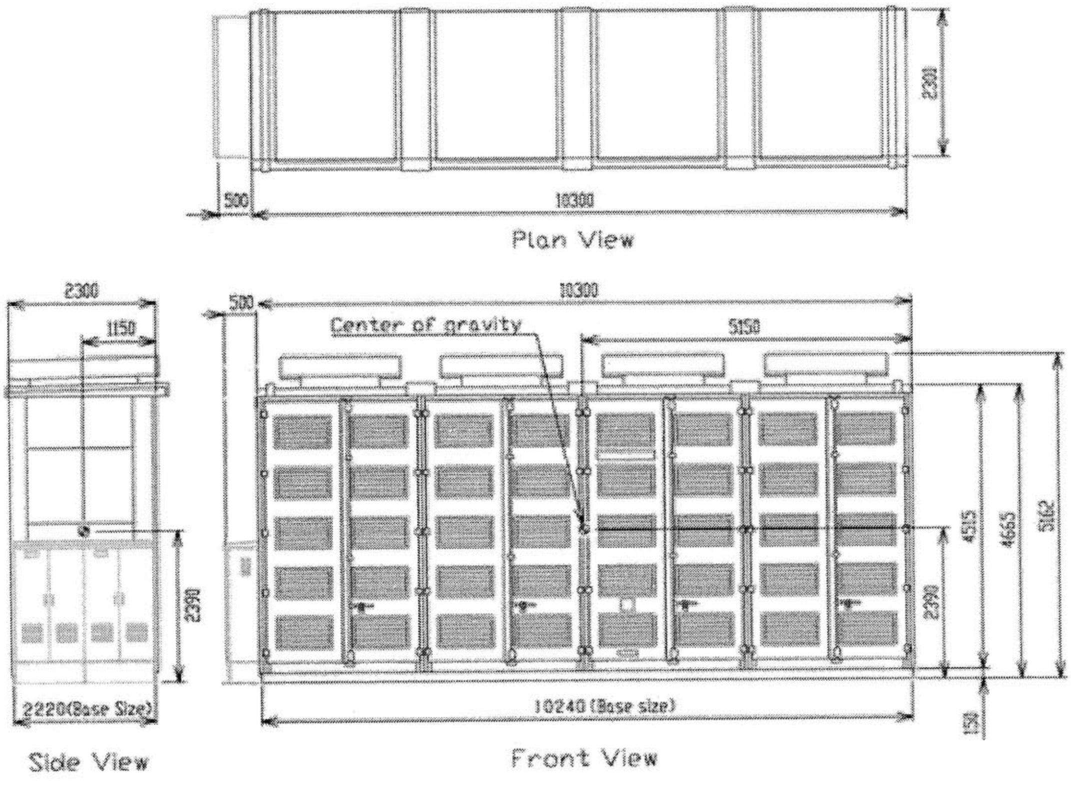


Figure 15: Battery enclosure

c. Power conversion system

The power conversion system was purchased from a separate vendor. It arrived at the site as one pre-assembled unit, which was installed between the battery and transformer. The 220V/12kV transformer connected the battery system to a 12kV feeder through fused, cut-off switches on a power pole. Data and energy flows go through the utility system, PCS and the battery controller. [44]

5.3.3 NaS system cost

The two main components of the overall cost are the battery cost and PCS cost. However, in total, there are many other costs to be considered. The following pie chart gives the relative cost of the system installed at Chemical Station project. [44]

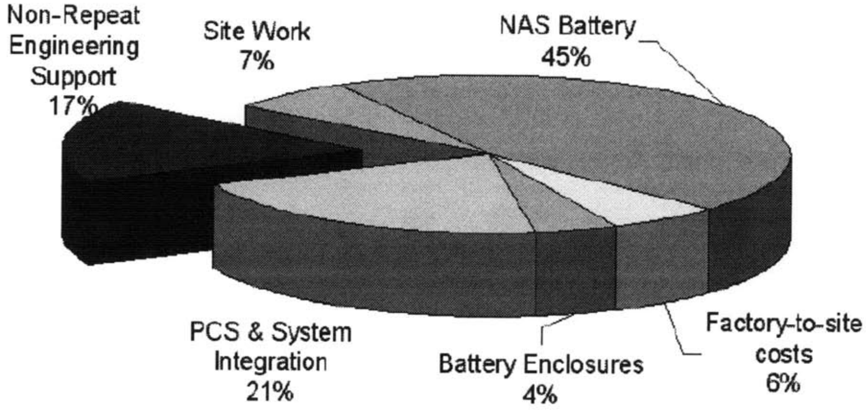


Figure 16: Cost breakdown of 1MW*4 hours NaS battery system

The non-repeat engineering support cost includes design, engineering and test of the battery system, and was subsidized by the US Department of Energy in Chemical Plant project. Though the cost, especially the non-repeating engineering support cost is unique for the Chemical Station project, the relative cost of each component can be used as a reference for similar project.

The overall installed cost for Chemical Station project is finalized to be U$2500/kWh, with 45% of the cost related to the NaS battery manufacturing. This price for the NaS grid battery system will be used as reference in the model being discussed here.

5.3.4 Daily electricity wholesale trend

The target customer in this model is electricity retailer in Singapore, who buys electricity at a wholesale price from the generators. The consumption and wholesale price data from a random working day (March 26th, 2010) is plotted in the following figure. From the wholesale price we can clearly see that the price varies in a large interval daily. The highest price of around S$600/MWh happens between 12pm to 6pm. The price valley is 2am to 8am.

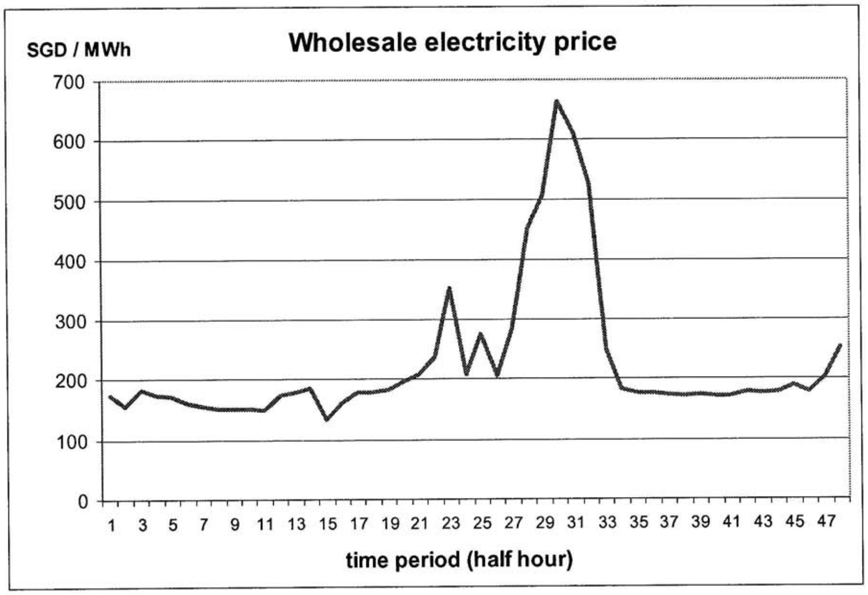


Figure 17: Singapore electricity wholesale price, half-hourly

For transaction volume, the next figure shows the total quantity purchased by electricity retailers every half-hour. If there is no storage equipments installed at the distribution stations of retailers, the purchase volume then reflects the demand from end users. The peak and valley time are mainly determined by the industrial working hours. The peak and valley of price and consumption coincide with each other. The raw data for half-hourly electricity wholesale price and volume is given in appendix 2. [68]

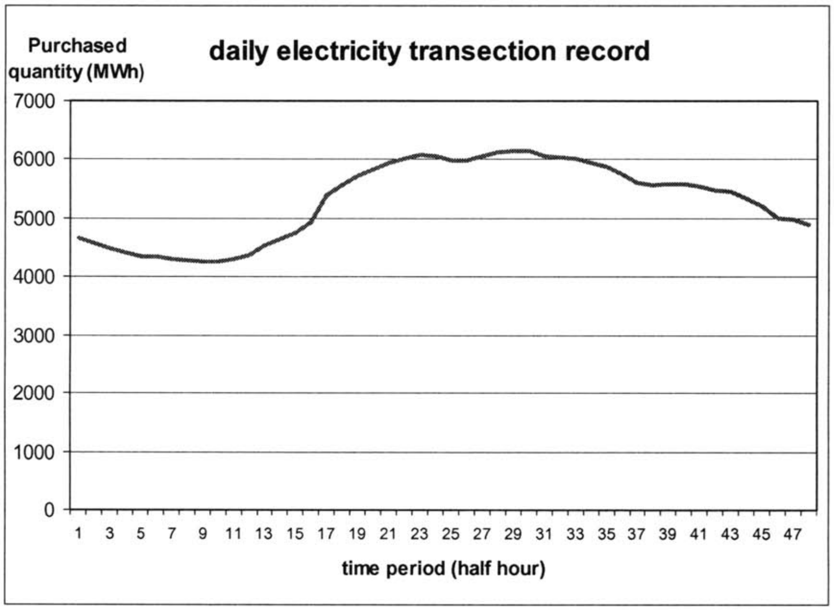


Figure 18: Wholesale electricity transaction volume

5.3.5 Profit mechanism

The electricity retailer installs the 1MW*6 hour NaS battery system at a 22kW distribution station. The battery system charges between 12am to 8am, when electricity wholesale price is the lowest. The battery charges continuously for 6 hours, with a 0.9MWh/hour rate (90% efficiency). This means the electricity flows into the battery is 0.45MWh in each half hours during the charging period.

The battery system discharges during the time when demand is high and wholesale price is at the peak, namely, from 12pm to 6pm. The electricity is discharged to the grid and sell to industry user to meet their usually demand. The battery system operates daily during workdays, which adds up to 250 days a year.

By installation of the battery, the electricity retailer's capability to provide electricity power package to contestable users is not affected. The only change is part of its purchase from wholesale market is shifted from price-peak period to price-valley period.

Based on the assumption made, the investment (I_{NAS}) on the battery system is

I_{NAS} = (Unit price of NaS System per power output) * (Power rating) * (1+ tax rate)

= U\$ 2500 /kW × 1MW × (1+7%)

= U\$ 2.675 million

As for the revenue r that the battery system creates by each charge-discharge cycle,

r = Σ (peak price in a half-hour period × electricity stored in that half-hour) –

Σ(valley price in a half-hour period × electricity discharged in that half-hour)

= S\$ 1,365.1/cycle

Revenue through the year r_y

r_y = r × operating frequency × operating days

= S\$ 1,365.1/cycle × 1 cycle/day × 250 days/year

= S\$ 341,275.5/year

The NaS battery system has a service life of ten years and constantly delivers the same performance during its service life. The present value of the total revenue generated in the ten year can be calculated by treating the revenue as a ten-year annuity. The present value of annuity is

$$\text{PV (Annuity)} = \frac{A}{1+r} + \frac{A}{(1+r)^2} + \cdots + \frac{A}{1+r)^T}$$
$$= A \times \frac{1}{r}\left[1 - \frac{1}{(1+r)^T}\right].$$

Thus the present value of NaS system (PV_{NaS}) is

$$PV_{NaS} = S\$\,379{,}195 \times \frac{1}{0.05} \times \left[1 - \frac{1}{(1+0.05)^{10}}\right]$$

= S$ 2,635,238.7

= U$ 1.89 million (based on an exchange rate of 1U$ = 1.4 S$)

The net present value (NPV) of the investment is

$NPV = PV_{NaS} - I_{NAS}$

= U$ 1.89 million - U$ 2.675 million

= - U$ 0.785 million

The negative NPV indicates that investment on the NaS system does not justify itself as economically efficient. For the investment and revenue to break even, the total cost of NaS battery system need to be

Break-even cost = PV_{NaS} / (1+tax rate)

= U$ 1.89 million /(1.07)

= U$ 1.766 million

This corresponds to a unit price of U$1766/kW, which is 29.3% lower than the current estimated price.

5.3.6. Limitation of implementation model

- The cost of the battery module is not obtained by a strict bottom-up approach. Such cost model is only possible if more information regarding the manufacturing process is revealed by NGK, the battery system manufacturer. The cost in Chemical Plant project only gives estimation to the possible cost that may incur to installation in Singapore. Real investment may vary from the estimated number.

- The analysis was based on a daily data of electricity purchase quantity and price. A larger data pool needs to be used to get the average though the year to reduce the inaccuracy. Fortunately since Singapore doesn't have a clear seasonal weather, the season to season variance of electricity consumption is minimal. Thus the daily date used in this model provides a good estimation of the situation over the year.

- Only the benefit from electricity arbitrage is evaluated in this model. In fact, installation of grid-level battery system usually has more than one benefit. In this case, the battery may also help the electricity retailer in increase revenue through T&D upgrade deferral, power reliability, transmission stability and frequency regulation. To include these factors in this evaluation, the economic gap may be much smaller or even disappears.

- Operational cost and maintenance cost are omitted.

5.4 Customer energy management model

5.1.1 Assumptions

In addition to being an arbitrage tool to electricity retailers, grid level battery system can also be implemented near the customer end. However, in Singapore, where households meet a constant utility tariff regardless of time and industrial users buy electricity from retailer as a package, the chance for direct arbitrage using battery is slim for community and industry. Other profit mechanisms must be exploited, such as integration of backup generators and battery system. This scenario will be discussed in this section.

Backup power supplies such as small-scale generators are commonly installed in locations where electricity consumption is large and economic loss due to power outage is huge. However, in a country like Singapore where the chance of power blackout is low, the level of backup generator utilization is low. Some facilities use backup generator to support part of the load when the overall electricity consumption is high. This production and consumption of electricity happens simultaneously. During hours when not much electricity is required at the facility, the backup generators are idle.

With the installation of battery system, there is opportunity for a higher level of utilization of backup generators. They can continue to perform at emergency power source as well as part of the primary power source at peak hours. During off-peak hours, the operation of generators can be continued, charging the battery system for later use. In this case, the cost for this part of electricity is only the operational cost of generators. Providing the investment on battery system is cost-effective, if helps to better justify the investment on the backup generation capacities. Furthermore, when the generator is down, the battery system can also be charged from the grid, and be a backup power source itself.

Singapore Turf Club is the only racecourse operator in Singapore. Majority of the energy consumption goes to the floodlights that illuminate the racecourse during night races. There are approximately 2500 floodlight bulbs installed on the roof of the grandstand, camera towers and on the high mast around the track. They have a total backup generation capacity of 2000kW by standby generators. On top of the electricity utility tariff, an additional monthly fee of contracted capacity, which is S$7.4/kW and is proportional to the maximum output power occurred during the month. [75] The Turf Club will be used as an example of installation site in this model.

The assumptions are as follow.

- The battery system is composed of forty 50kW lithium cobalt battery modules, with a discharge duration of 2 hours at rated power (4000kWh energy capacity)
- The battery system charges daily during night and discharges during days
- The service life for the battery system is 10 years (~3500 cycles)
- The backup power generators have a constant operation cost per unit power generated regardless of the total utilization level
- Operational cost and maintenance cost of the battery system are omitted
- The battery system has a conversion efficiency of 90%
- A 7% tax is opposed on the electricity distributor who purchase the system
- A discount rate of 5%

5.4.2 Li-ion battery system cost estimation

The main cost of grid level lithium-ion battery system can be divided into two parts: the cost for the battery pack and the power conversion system (PCS). The cost for battery back is directly related to the total energy capacity of the battery ($/kWh), while the price of the PCS is related to the power output of the system ($/kW)

a. Battery pack cost

Since the production processes for large scale or small-scale lithium-ion battery pack are similar, the cost estimation can be done on a 50kW battery pack. Li-ion cell production starts with the manufacturing the cathode and anode. The process is very similar for both. For cathode, the active material is combined with a binder and other additives in a solvent to make a paste. The paste is then deposited onto the current collector, usually aluminum foil, in a coating process. For anode, typically a graphite paste is used and deposited onto copper foil in a similar process as the cathode production. The coated electrode foils are then dried and calendaring so the thickness of the deposited material on the foil is uniform through. The foils are trimmed and cut to the proper size, and wound up with the separator material. Electrical connections are also welded to the cathode and anode. The wound electrodes and separator are inserted into the canister with electrolyte and ancillary components such as vents and safety devices. The cell canister is sealed by crimping or welding a cover to it. Modules are made by packaging individual cells together, and are further integrated with other systems into a complete battery pack. [64] The figure below summarizes the Li-ion battery manufacturing process. [38]

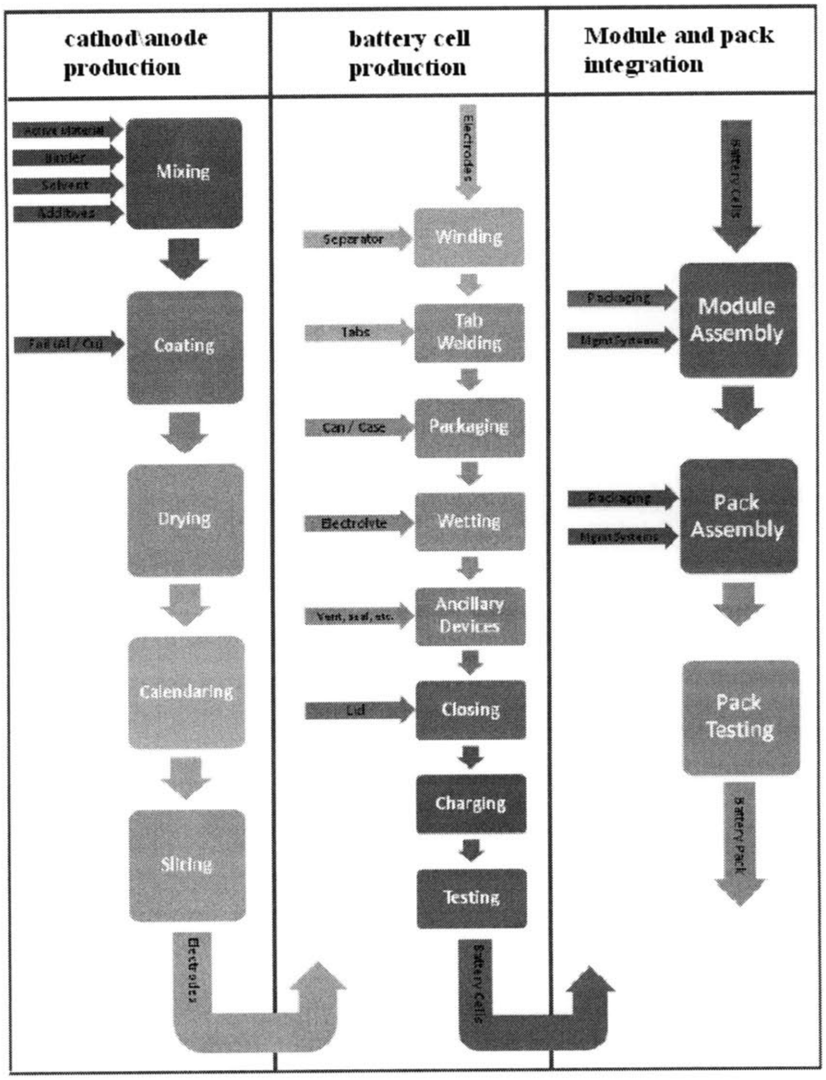


Figure 19: Manufacturing process of lithium-ion battery packs

For lithium-ion battery used at grid level, the quality control is typically much stricter than those used in consumer electronics. Additional testing and quality control result in a lower yield, thus a higher cost.

Once the battery manufacturing process is broken down, the cost model can be developed in excel spreadsheet format. Three cost categories were considered: materials, manufacturing, and other (including corporate overhead, depreciation, general, sales and administration and R&D cost). Cell-level materials were further broken down into raw materials for the cathode, anode, separator, and electrolyte. The cost for cell level materials is taken from Fu's thesis. [76] The model is based on the production of 50kW battery packs on a 100,000packs/year production volume.

The cost components are shown in the following figure. [64] The model gives a cost of U$26320 per battery pack. Based on the 100kWh capacity, the specific cost is U$263.2/kWh.

In the master thesis completed by Fu [76], the author estimated the cost for electric vehicle lithium-ion battery pack to be U$293/kWh. This model is close but more optimistic than his.

Battery cost reductions may occur through two main mechanisms: economies of scale associated with increased production volume, and technological breakthroughs. In this case where material cost takes over 60% of the total cost, the higher cost reduction opportunity may be in later category, regarding alternative active materials.

The cathode active material may be subject to both effects as well: per-unit cost for cathode materials is highly sensitive to quantity purchased, and traditionally expensive cathode materials such as cobalt and nickel based oxides are replaced with less expensive material, such as iron.

Research and development costs are currently high, and may remain so until the cost of lithium-ion battery falls to a publicly acceptable range.

Based on the model, the battery cost in the battery system with capacity of 4000kWh is U$1,052,800.

b. Power conversion system cost

The most significant difference between high-power and low-power PCS operation is the need for thermal control. This drives the cost up for high-power, long-term operation. Schoenung et al. in their report [21] gave an estimation of grid level power conversion system cost based on different length of operation. For long-term grid level operation, the cost is estimated to be U$500/kW. As being reflected in the 2000kW system, the cost on power conversion system will be as high as U$1,000,000.

Thus the overall cost for the battery system is the sum of battery modules and PCS. The investment for the system is calculated to be

$$
\begin{aligned}
I_{\text{Li-ion}} &= [\text{U\$}263.2/\text{kWh} \times 4000\text{kWh} + \text{U\$}500/\text{kW} \times 2000\text{kW}] \times 1.07 \\
&= \text{U\$}2{,}196{,}496 \text{ or U\$}549.1/\text{kWh}.
\end{aligned}
$$

The Electricity Storage Association website cited the cost of lithium-ion battery grid storage to be over U$600/kWh. [20] This cost predicted by this model may under estimate the cost of battery packs. Protective circuit and installation cost for large scale storage system may also bring up the actual cost for the battery system. These parts of cost are omitted in this model.

5.4.3 Profit mechanism

The primary purpose of the backup generators is to deal with power discontinuity. However, since the power supply of Singapore is very reliable, it was largely under-utilized.

Currently Turf Club is using the backup electricity generator as a supplement power supply during race night, when power need is high. At race nights, 30% of the total load is supported by the backup generator and the rest by the utility grid. By doing this, the maximum lead power is reduced, thus the fee for contracted power. However, the generators are not operating during other non-peak hours.

By installing the battery system with the backup generators, the battery system can be charged at late night, and discharge during race nights. It serves as part of the power source along with the generators.

During charging, the generators produce electricity at a price of S$0.2/kWh. When the electricity is fully charged, the total energy capacity is

Stored energy $= 40 packs \times 50 kW / pack \times 2 hours \times 0.9 = 3600\text{kWh}$

The cost of operating the generators is S$0.2/kWh. While the cost for electricity tariff from utility is S$0.243/kWh. [77]

By discharging the battery during race days or race nights, the savings compare to purchase electricity from the grid in each cycle is

Energy bill saving $= 3600 kWh \times S\$0.243 / kWh - 3600 kWh \times S\$0.2 / kWh = \text{S\$154.8/cycle}$

This corresponds to S$56,502 each year, based on a daily charge-discharge model.

In addition, the power output of the battery is

Power output $= 40 packs \times 50 kW / pack \times 0.9 = 1800 kW$

By discharging during race night, when maximum load happens, the peak power can be bring down by 1800kW. This reduces the fee for contacted power.

Contracted power fee saving $= 1800 kW \times S\$7.4 / kWh.month = S\$13{,}320$ /month

This is S$159,840 of saving per year.

Thus with the lithium-ion battery system installed, the annual saving on electricity bill and contracted capacity fee is:

Total annual saving = S$56,502 + S$159,840 = S$216,342

Use the same annuity function as in last model

$$\begin{aligned}\text{PV (Annuity)} &= \frac{A}{1+r} + \frac{A}{(1+r)^2} + \cdots + \frac{A}{1+r)^T} \\ &= A \times \frac{1}{r}\left[1 - \frac{1}{(1+r)^T}\right].\end{aligned}$$

Thus the present value of lithium-ion battery system in this case is

$$PV_{\text{Li-ion}} = \text{S\$ } 216{,}342 \times \frac{1}{0.05} \times \left[1 - \frac{1}{(1+0.05)^{10}}\right]$$

= S$ 1,670,535

= U$ 1.19 million (based on an exchange rate of 1U$ = 1.4 S$)

The net present value of lithium-ion battery system investment is

NPV = $PV_{\text{Li-ion}} - I_{\text{Li-ion}}$

= U$ 1.19 million - U$ 2.20 million

= - U$ 1.01 million

As indicated buy the negative net present value, there exists a huge gap between investment and return. For the investment and revenue to break even, the total cost of lithium-ion battery system for this application need to be

Break-even cost = $PV_{\text{li-ion}}$ / (1+tax rate)

= U$ 1.19 million /(1.07)

= U$ 1.112 million

This corresponds to a unit price of U$278/kW, which is approximately half the price estimated by the cost model.

In a report by Boston Consulting Company regarding batteries for electric cars, they commented that the battery price needs to fall below U$250/kWh before it can be accepted by the public car owners. [65] It appears that on the grid level, the price of battery system need to fall around the same region before it becomes economical to small industry or households users.

5.4.4 Limitation of implementation model

- The cost model for lithium-ion battery is based on basic battery production processes. For grid-level battery with a large capacity and power rate, more steps and components may be needed to ensure the efficiency and safety. Thus cost estimation based on small-scale (e.g. electric vehicle scale) lithium-ion battery may be too optimistic for grid-level battery.

- Singapore Turf Club is possibly a contestable customer who can buy electricity at a bundle price. The bundle price may be less expensive then the electricity tariff for non-contestable customers.

- Additional benefit for the battery system installation includes maintaining a continuous power supply during blackouts. This benefit is not counted in the cost model. In Singapore where utility grid is stable, this benefit would be minor, though.

- Operational and maintenance costs of the battery are omitted

5.5 Long-term benefits of grid-battery implementations in Singapore

The two models here are merely means to evaluate the direct economy of grid-level battery systems. However, in the long term, there will be other benefits brought from grid-level battery system that cannot easily be put into money term right now.

5.5.1 Long-term economic benefits

The benefit for grid-level battery system is seldom single-folded. In the previous models, the battery system is assumed to serve only one function. This is almost never true in real cases. For example, batteries installed at substations serve to avoid power outage, stabilize voltage and frequency. Though the value of a more stable, high-quality electricity supply is difficult to estimate, it is the common goal of electricity systems across the world. Furthermore, the installation of the battery reduce the peak-hour load in the transmission system, thus can delay the upgrading plan of transmission and distribution lines and substation. Revenue is generated here by the time value of capital.

If the cost for grid-battery system can drop to an affordable level, it can replace the inline reserve capacity at the generators'. This means no more "running the generators under full capacity" necessary. A high utilization of generator not only means better return of investment, but also less emission due to incomplete combustion.

More economic benefits of grid level battery may realize when renewable energy is used more widely. For commercial generators using renewable source, battery system adds to the reliability and quality of their energy output. For household or small industries, solar penal on the roof with battery system in the basement makes is possible to make them self-sufficient energy “islands”. In either way, battery systems add to the value of renewable energy.

5.5.2 Social benefits

Since the seventies of last century, semiconductor and oil refining sectors have become the two focuses of Singapore's industrial growth. Today Singapore still hosts the largest oil refinery and produce 10% of the world’s wafer output. [15] Though Singapore is trying to develop its future towards service and information sectors, the two industries will remain to provide large income to the country. Energy stability and quality is crucial for both semiconductor fabrication and oil refinery. To attract a stable investment in into these two sectors, Singapore must commit to a stable and reliable energy system. For other industries such as information service and telecommunications, power stability is also a main factor to consider for investors. Grid-level battery system helps the utility grid to main high efficiency and reliability, hence provides Singapore a competitive edge to attract investment.

In Singapore, environmental awareness has been growing steadily over the last decade, led by the government's efforts to maintain Singapore as a "clean and green city". These efforts include a comprehensive climate change mitigation policy, extensive re-using of water, increasing of recycling rates and continuous support of clean energy development. As an essential part of renewable energy system, grid-level battery storage is included in the developing map. By a wider application of grid-level batteries with conventional or renewable power source, a message can be sent both locally and internationally, that the government’s commitment to a clean, efficient energy future is steady and specific. This would not only encourage more research and development in the clean energy industry in Singapore, but further improve the global image of Singapore.

5.6 Remarks on grid-level battery applications

Though the models provided here use rough estimations on the cost and benefit, they give some idea on how far we are from broad application of grid-level battery systems. The first model shows that in order to be accepted by electricity retailers as arbitrage tool, the price for grid-level NaS battery need to be 30% lower than now. The second case gives a possible application model to install grid-level battery for small industries or even households. However, the economic gap appears to be large.

To gradually close the economic gap, the cost of battery needs to fall by a large extent. The cost reduction can be through replacing the components with cheaper materials, or innovation of the manufacturing processes. Other than these, increasing the efficiency and service life are also priorities.

Customers will only accept grid level storage when it's cost-effective. In order to present the value of grid-level storage, its benefit must be reflected in money term. It's mentioned that the benefit is usually multi-folded. Models need to be built to estimate the overall benefit of battery implementation and present them in the term of cash flow. For implementation in Singapore, the model must consider the actual situation of Singapore utility grid, its current status and future upgrading plans. In order to get first-hand information, cooperation with the Energy Market Authority or Energy Market Company can bring advantage of information collection.

For near future implementation, obtaining subsidy from Singapore government is of high possibility. Singapore Energy Market Authority provides fund to both energy research and market development. The Energy Market Authority (EMA) has set up a $25 million Energy Research Development Fund (ERDF) to provide financial support for the implementation of new and innovative energy solutions to address the following goals:

- Diversify Singapore's energy sources and improve our energy security;
- Help achieve Singapore's energy intensity reduction targets; and
- Develop Singapore's energy industry. [68]

Grid-level battery system meets the criteria above, thus has a high chance of getting government support.

Currently, it's not likely that the customers in Singapore will accept grid-level battery systems unless strong government support is in place. Future application will only be possible with a reduced cost of battery system and a better-defined overall profit margin for each implementation.

Chapter 6 Intellectual Property

From the comparison of different technologies, sodium-sulfur and lithium-ion battery stand out to be high-potential candidates for grid level storage. Intellectual properties regarding these two batteries are reviewed in this section.

There are numerous of patents related to the two types of batteries. First of all, patents that are directly on grid-level battery installations were searched. The number of this type of patent is not large though. Secondly, those related to the recent development of lithium-ion batteries and sodium-sulfur batteries, which were covered in Chapter 4, are discussed. Other than this, patents addressing the challenges facing the two types of batteries, such as corrosion problem for sodium-sulfur battery, and electrode volume expansion for lithium-ion battery are reviewed.

The review will give a rough idea on what patent might be infringed or filed if a particular advancement is to be employed by grid-level battery system. When it comes to specific installation project, more patents of the particular type of battery installed and the power conversion system need to be reviewed. If there is no similar patent existing, it is possible to file the whole implementation project as a new patent in the same form of the first one below.

6.1 Sodium-sulfur battery patents

US Patent No. 6747370 [78] claims a higher-temperature sodium-sulfur battery system was used for the purpose of energy storage and power compensation. The system consists of 10 units of 500kW PCS and a sodium-sulfur battery is electrically connected to the power supply system through a high-speed switch. Under normal conditions, the electric storage system charges at night when the demand for electricity is low. During daytime, when the electricity demand is high, the system discharges 1MW power thereby providing load leveling. When there is voltage sag or service interruption, the high-speed switch automatically disconnect the power supply system, and the battery system spontaneously discharges a power of 5WM within 30 seconds. Thereby it ensured the continuous supply of power service.

US Patent No. 6329099 [79] claims that a cell container for positive electrode of sodium-sulfur battery can be implied to avoid deterioration by corrosion. The cell container is assembled by integrating plural members made of a high corrosion resistant alloy consists of Cr, Co, Ni, W and Mo, within carbide containing precipitated from at least one of W, Cr or Mo. A readily deformable portion is provided to the positive electrode as well. This design claims a better corrosion resistance comparing to conventional Al container design. Using the claimed material recipe and process in the patent, the thickness reduction in 10 years under 400°C is 24 μm, while for conventional design, the reduction is 400 μm.

US Pat. No. 4649022 [80] discloses a method to make a current collector for a sodium/sulfur battery, which is electronically conductive and resistant to corrosive attack by sulfur/polysulfide melts. The current conductor is formed of composite material, containing aluminum and conductive fibers. The conductive fibers consist essentially graphite fibers having a diameter of 10 microns and silicon carbide fibers having a diameter between 500 to 1000 angstroms. After the collector is formed, it's treated so as to remove a small layer of aluminum from surface thus the fibers can extend outwards to form contact with the sulfur/polysulfide melt. The fiber provides electrical contact while passivated aluminum sulfide layer formed on the surface of fibers provides good corrosion resistance against attack from sulfur/polysulfide melt.

US Pat. No. 6245455 [81] claims another method of producing current collector for sodium-sulfur batteries. Within the a cathode electric collector in the cathode chamber, wherein the cathode electric collector comprises tangled conductive fiber balls made of conductive fibers of an electrically conductive material, and having a porosity of at least 80% and an elasticity.

6.2 Lithium-ion battery patents

US Pat. No. 7150940 [82] claims the cathode of lithium-cobalt battery consists of cathode active materials, conductive agent and binder. The cathode active material comprises a lithium-containing composite oxide represented by the formula $Li_a(Co_{1-x-y}Mg_xM_y)_bO_c$, where M is at least one from Ni and Al. The amount of conductive agent is no more than 3wt% and the amount of binder is preferred to be 1wt% to 4wt% of the cathode active material weight. When the values of a, b, c x and y take the range $0<a<1.05$, $0.85<b<1.1$, $1.8<c<1.2$, $0.03<x<0.15$, $0<y<0.25$, the deterioration of cycle characteristics is suppressed and the safety aspect is improved, too. By partially replace the cobalt by elements like magnesium or aluminum, the crystal structure of cathode active material is stabilized.

US Pat. No. 5888670 [83] discloses lithium-ion battery with anode which contains porous carbonaceous materials. The pores in the anode material are oriented. The method of making the carbonaceous material with oriented pores is presented, too. A liquid crystal, p-methoxybenzylidene-p'butylaniline, is added to an Ndimethylformamide solution of polyvinyl alcohol and mixed. The resultant mixture is dropped into ethanol to prepare precipitates. The obtained precipitates are dried under reduced pressure, gradually heated to 800° C. and burned at this temperature in a stream of argon gas, and then ground to prepare a carbonaceous powder. Observation of the carbonaceous powder under an electron microscope shows oriented pores having a diameter of 5 microns or less. The porosity takes up 15% of the carbonaceous powder volume.

After 5 wt % of polyvinylidene fluoride is mixed with the carbonaceous powder, N-methylpyrrolidone is added to the resultant mixture to prepare paste. The paste is then coated on a copper foil and dried at 150° C to form the anode.

Battery with a non-porous carbonaceous anode is used as a comparative sample. From battery performance evaluation, the oriented-porous feature improves the cycle lifetime by a factor of 1.3 and energy density by a factor of 1.1.

US Pat. No. 7235332 [84] discloses a lithium-ion battery with a polymer electrolyte substrate. The substrate comprises a fluoropolymer with vinylidene fluoride as a main unit and having a density of 0.55-1.30 g/cm^3. The porous electrolyte along with a salt and a compatible solvent, are disposed between the positive electrode and the negative electrode. The salt can be at least one of the compound selected from $LiClO_4$, $LiBF_4$, $LiPF_6$, $LiAsF_6$, $LiCF_3SO_3$, $LiAlCl_4$ and $Li(CF3SO_2)_2$. The solid electrolyte substrate is impregnated with the salt dissolved in a compatible solvent, which gels to show ion conductivity itself.

The lack of liquid electrolyte affords a huge advantage of avoiding leakage in the battery. Using polymer electrolyte also provides a potential weight reduction, which may leads to a high energy density per weight. However, the lithium-ion battery with solid electrolyte generally shows an interior low temperature characteristic, cycle life performance and high rate discharge performance. The improvement therefore is a major goal.

US Pat. Appl. No. 09/974283 [85] claims the application of single-wall carbon nanotubes (SWCNT) as an additive to the electrodes of lithium-ion batteries. By substitute carbon black, a commonly used conductivity enhancer in lithium-ion battery, with a small amount of SWCNT results in a higher electrode capacity. It's also shown by experiment that by adding 0.5wt% of SWCNT to the carbon black conductivity enhancer, there are considerable increase of the reversible capacity of carbon fiber anode and lithium-cobalt oxide cathode. Since the amount of SWCNT used is very small, the cost of lithium-ion battery with the application of this invention will not be largely affected.

Chapter 7 Conclusion

In this thesis, grid-level energy storage system and the potential applications were studied. Although grid-level energy storage systems are not widely installed at the electricity grid level, the benefits are recognized. The application of energy storage at grid level can be categorized into two main areas: power application and energy application.

For power applications, energy storage systems can help to stabilize transmission synchronization and voltage by discharging at time when there is a fluctuation in the transmission system. Furthermore, power quality and reliability can also be assured by using energy storage. With a proper capacity and discharge time, voltage fluctuation and power cutoff can be avoid, thus ensure the power security for high-sensitivity industries such as microelectronic fabrication facility.

For energy applications, grid-level storage system can replace the inline reserve capacity to be the spinning reserve. With even larger storage capacity, commodity storage of electricity is also possible. By storing bulk energy and discharge when necessary, arbitrage opportunities can be created. Transmission and distribution capacity upgrade need not to follow the maximum load and thus the investment can be deferred. Other than this, energy storage is an essential part for large-scale renewable energy generation system to cope with the discontinuity and volatility of renewable source. For both conventional fuel and renewable energy source, grid-level storage can be applied on either generator side or customer side as a peak-shaving tool.

discharge at rated power for 1 to 8 hours. For T&D upgrade deferral, the rated power need to be 0.1 to 2 MW and discharge time 0.5 to 4 hours. For power quality and reliability, the rated power need not to be large and the discharge time is generally less than a minute.

Various technologies can be employed to store large quantity of energy. Some of the technologies are based on the mechanical principles while others are based on electrochemical or electrical principles. Although this report focused on battery storage system, other electromechanical systems were also reviewed, for example, pumped hydro, flywheel and compressed air energy storage.

For batteries systems, lead-acid, nickel-cadmium, sodium-sulfur and lithium-ion batteries were discussed in the report. Their working principles and potential as grid-level storage were studied. From their respective characteristics such as cycle life, energy capacity, safety concern and cost, sodium-sulfur and lithium-ion batteries turn out to be competitive candidates for grid-level applications. Sodium-sulfur batteries are more suitable for applications in which long time discharge is needed, e.g. commodity storage. While lithium-ion batteries are more likely to be applied to short time discharge applications such as frequency regulation. Cost is the main limitation for these two battery types.

Since sodium-sulfur and lithium-ion battery technologies are not mature enough to support general cost estimation of products, implementation models were built using Singapore as an example. The development and regulation of energy market in Singapore was reviewed as background information for the models. The reliability of electricity grid in Singapore is among the best worldwide. Daily peak of electricity assumption happens while seasonal variation is little.

For the first model, sodium-sulfur battery system was assumed to be installed for electricity retailer as an arbitrage tool. Under the assumption of ten-year service life, the investment is estimated to be U$ 2.675 million while the present value of 10-year revenue is only U$1.89 million. In order to be economically competitive, a 30% reduction of battery system cost is essential.

The second model analyzed the feasibility of install lithium-ion battery system at customer site as a supplement energy source. The cost is around UW$2.2 million while the present value of revenue is only U$1.19 million. The economic gap for installation is large. From this model, in order to be economically benign, the cost for grid-level lithium-ion battery system needs to fall by half. That is in the same situation for electric vehicle battery.

Through the two models over-simplified the installation situation, they gave rough ideas on how far we are from broad use of grid-level battery systems. Currently battery systems are not likely to be installed at grid-level without any government subsidy. However, they may have a chance when the benefits of grid-level batteries can be better defined in money term, and when technology breakthrough brings significant cost reduction.

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Appendix 1: Lithium-ion battery cost model

1. Investment costs

Investment costs	**Description**	**Calculation**
Plant space	Land cost plus building cost	5000m^2 space assumed
Equipment	Equipment cost of ownership	Estimate the cost for machinery in each manufacturing step
Launch cost	Plant start-up, recruitment, training cost	5% of annual material cost
Working cost	Payroll, inventory, etc.	30% of annual variable cost

2. Annual fixed costs

Fixed costs	**Description**	**Calculation**
General, sales and administration	Sales, office expense, tax, etc.	25% of direct labor cost and 35% of depreciation
R&D	On-going research to ensure competitiveness	50% of depreciation
Depreciation	Cost of equipment replacement	12.5% equipment cost

3. Variable costs

Fixed costs	**Description**	**Calculation**
Materials and purchased parts	All the materials and purchased part in products (including yield loss)	Based on price of materials
Direct labor	Labor cost for operators, researchers and administration staffs	Based on average salary in electronic industry
Overhead	Utilities, maintenance cost, etc.	60% of labor cost

Appendix 2: Daily electricity wholesale price and volume

PRICE TYPE	DATE	PERIOD	WEP (S$)	VOLUME (MWh)	REAL TIME
WEP	26-Mar-10	1	172.24	4669	0.5
WEP	26-Mar-10	2	155.73	4559	1
WEP	26-Mar-10	3	183.18	4479	1.5
WEP	26-Mar-10	4	173.84	4405	2
WEP	26-Mar-10	5	171.26	4348	2.5
WEP	26-Mar-10	6	160.73	4335	3
WEP	26-Mar-10	7	156.08	4288	3.5
WEP	26-Mar-10	8	150.62	4273	4
WEP	26-Mar-10	9	150.23	4252	4.5
WEP	26-Mar-10	10	150.61	4258	5
WEP	26-Mar-10	11	149.26	4292	5.5
WEP	26-Mar-10	12	173.28	4375	6
WEP	26-Mar-10	13	178.85	4532	6.5
WEP	26-Mar-10	14	184.33	4629	7
WEP	26-Mar-10	15	132.15	4741	7.5

WEP	26-Mar-10	16	160.24	4940	8
WEP	26-Mar-10	17	178.83	5383	8.5
WEP	26-Mar-10	18	177.17	5550	9
WEP	26-Mar-10	19	183.18	5714	9.5
WEP	26-Mar-10	20	195.92	5822	10
WEP	26-Mar-10	21	208.03	5933	10.5
WEP	26-Mar-10	22	236.24	6007	11
WEP	26-Mar-10	23	354.01	6072	11.5
WEP	26-Mar-10	24	207.22	6048	12
WEP	26-Mar-10	25	274.16	5995	12.5
WEP	26-Mar-10	26	203.71	5977	13
WEP	26-Mar-10	27	283.88	6052	13.5
WEP	26-Mar-10	28	452.74	6130	14
WEP	26-Mar-10	29	505.92	6149	14.5
WEP	26-Mar-10	30	663.41	6145	15
WEP	26-Mar-10	31	611.07	6058	15.5
WEP	26-Mar-10	32	526.71	6029	16
WEP	26-Mar-10	33	248.54	6002	16.5

WEP	26-Mar-10	34	182.9	5943	17
WEP	26-Mar-10	35	174.59	5879	17.5
WEP	26-Mar-10	36	175.59	5749	18
WEP	26-Mar-10	37	173.81	5607	18.5
WEP	26-Mar-10	38	171.71	5567	19
WEP	26-Mar-10	39	173.1	5592	19.5
WEP	26-Mar-10	40	171.12	5586	20
WEP	26-Mar-10	41	171.9	5538	20.5
WEP	26-Mar-10	42	177.96	5474	21
WEP	26-Mar-10	43	175.8	5441	21.5
WEP	26-Mar-10	44	178.87	5332	22
WEP	26-Mar-10	45	188.59	5196	22.5
WEP	26-Mar-10	46	178.21	5008	23
WEP	26-Mar-10	47	201.75	4973	23.5
WEP	26-Mar-10	48	253.03	4880	24