Stationary Applications of Energy Storage Technologies for Transit Systems

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Abstract **– Stationary energy storage technologies can improve the efficiency of transit systems. In this paper, three different demonstrations of energy storage technologies for transit systems were reviewed and discussed. The demonstrations reviewed were a sodium sulphide battery system in Long Island, a flywheel system for the London Underground, and a capacitor system for Madrid de Metro. Analysis was conducted from the point of view of a transit agency evaluating these demonstrations for practical lessons learned, effectiveness of the installation, and return on investment. Each installation showed that their technology was successful in their task and also provided valuable lessons on the challenges of implementing new technologies. Information from independent sources about longer demonstrations would be particularly valuable to help accelerate acceptance of energy storage technologies for transit systems.**

Index Terms – Energy Storage, Transit Systems

I. Conservation and Transit Systems

The current climate of high fuel prices, concerns about dwindling fossil fuel reserves and increased awareness of the harmful emissions of energy generation have peaked interest in energy conservation. A recent United Nations publication estimated that almost 200g of potentially climate changing carbon dioxide (CO_2) equivalents are produced per every kilowatt-hour (kWh) of electricity produced in Canada [1]. At the same time, increasing population density in urban areas and a desire to reduce automotive congestion are providing motivation for a renaissance in mass transit. The most visible elements of urban mass transit are heavy rail vehicles such as subway cars and light rail vehicles also known in some regions as streetcars. These rail vehicles are complemented by networks of buses and supported with large maintenance and control facilities. Although transit systems can divert hundreds of thousands of vehicles from the roads, these systems are energy and capital intensive. This paper will describe examples in which stationary energy storage technologies have increased the efficiency of transit systems.

II. Supporting Critical Loads With Lead-Acid Batteries

Electrical systems in North America operate under the assumption that the electricity being provided will be available at 120 volts, oscillating in a perfectly sinusoidal waveform at 60 Hz and will be available without any interruption, 24 hours a day, 365 days per year and have only limited tolerance for deviations from these expectations. Unfortunately, this quality of power is not always available. Poor power quality can be manifested as outages, voltage sags and swells, impulses and harmonics. A detailed description of these power quality events can be found in [2] and [3].

There are some particularly critical and sensitive systems in transit systems that cannot tolerate poor power quality events. Safety critical systems including security, control, lighting and ventilation cannot operate properly if there are interruptions or discrepancies to their electrical power source.

A. Lead-Acid Batteries in UPS Systems

A common safeguard against poor power quality events is to install an uninterruptible power supply (UPS). Lead-acid batteries are popular for this application. In fact, lead-acid based UPS systems are so popular they will be considered the baseline of comparison for all other energy storage technologies in this paper.

Lead-acid batteries operate on a simple reversible chemical reaction. In flooded lead-acid batteries, a dilute sulphuric acid electrolyte is immersed between a pure lead positive electrode and lead dioxide negative electrode. The chemical reaction is shown in (1).

$$Pb_{(s)} + PbO_{2(s)} + 2H_2SO_4 \leftrightarrow 2PbSO_{4(s)} + 2H_2O \quad (1)$$

Because lead-acid batteries are so well-developed, they have some distinct advantages. Their wide deployment lends itself to a very competitive price of about $580 per kW for a complete system [4]. Providing a benchmark for the entire industry, lead-acid batteries have a round-trip efficiency of about 75%. Even though the materials in these batteries are harmful, their many years of use have meant that tradespersons are very familiar with handling them. Along with familiarity with maintaining and handing these batteries, their widespread and long history mean that disposal and/or recycling is a well-established process. With their clear advantages, long history and wide deployment, lead-acid batteries have become the benchmark for energy storage technologies.

A disadvantage of lead-acid batteries is that they may produce hydrogen gas and oxygen rather than water during discharge. Because they are 'gassing,' the water level in the flooded or vented style of these batteries needs to be topped up occasionally. Also, since lead-acid batteries may evolve highly flammable hydrogen gas, very stringent building and ventilation codes govern their installation and operation. The

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sealed or valve regulated lead-acid (VRLA) battery is a variant to lead-acid batteries that addresses some of these issues but has a shorter life.

There are other disadvantages to lead-acid batteries. During each discharge, lead sulphate may accumulate on the electrodes, reducing the efficiency and capacity of the battery. Also, lead-acid batteries are capable of only a finite number of discharges. These batteries are best suited for applications where they can supply a fixed amount of power for a long time. They are not well suited for rapid charging and discharging. Depending on the depth of discharge, their life may be shortened even more. They are also very susceptible to temperature variations. Lead-acid batteries are also very heavy due to the high volume of water in each battery.

Although the use of lead-acid batteries is well-established in UPS applications, new energy storage technologies are being developed for other applications and are nearing commercialization. The following sections evaluate three new energy storage technologies in transit system applications.

III. Peak Shaving with Sodium Sulphide Batteries in Long Island

Peak shaving (also known as load levelling, load following or peak shifting) is a practice in which electrical energy is collected from the utility grid at off-peak times and then used at a later time.

Peak shaving may be performed by users to save money in domains where there are varying time-based prices. Demand-based pricing models vary the cost of energy depending on the time of day to encourage users to shift energy-intensive activities to times when there is less demand. Users may be able to avoid some or all of the peak energy premiums using this technique. The Long Island sodium sulphide system that will be explored later in this paper is an example where this technique is used.

A. Sodium Sulphide Batteries

Sodium Sulphide batteries, sometimes called NaS batteries, operate similarly to conventional chemical batteries like lead-acid batteries. They have a much greater energy density than traditional batteries, but have additional complications such as their high temperature and use of dangerous materials.

Each NaS cell has a positive electrode of liquid sulphur and a negative electrode of liquid sodium. The two elements are separated by a beta alumina ceramic electrolyte. During discharge, the positive sodium ions are able to pass through the electrolyte as electrons pass through the external circuit [5]. The process is reversible where the sodium ions return to their elemental state. To maintain the sodium and sulphur elements in their molten state they must be kept at about 300ºC. This is usually accomplished by heaters. Since these cells have a chemical efficiency of only 89%, heat is generated by their reactions when they are being used. This can maintain the temperature of the cells. In fact, energy storage systems using sodium sulphide batteries may even include cooling units to prevent the temperature from rising too much.

The cost of a typical NaS battery is estimated at $810 per kW [4]. The most expensive component of this system is the batteries. Additionally, battery replacement, maintenance, heating, and complying with safety requirements should also be considered as ongoing operating costs.

There are noteworthy disadvantages to using this emerging technology. As a relatively new technology, it does not have as much accumulated field experience as traditional technologies. Also, as a new technology, neither the end of life disposal nor the environmental impacts have been explored yet. There are obvious safety concerns with such large quantities of a volatile material like molten sodium. Pure sodium is highly reactive with water and as such the material in the cells must be completely insulated from moisture. The consequences of a catastrophic failure are very serious, such as the potential for a dangerous chemical fire or explosion.

B. MTA Long Island NaS System

The material in this section is derived from references [6] – [10] and personal correspondence with Charles Hermann, Research & Technology Development Engineer with the New York Power Authority (NYPA).

The Metropolitan Transportation Authority (MTA) of New York operates a fleet of 220 compressed natural gas (CNG) buses. These buses are serviced and fuelled at the Long Island Garage in Garden City, New York using three 600 horsepower compressors. This is a very energy intensive activity. This region uses time-of-day pricing, meaning price varies with expected demand. This garage had a night shift to take advantage of the reduced energy cost. The MTA wanted to eliminate the night shift to reduce labour costs and simplify the facility's operation. To achieve this goal, they chose to use a 1.0MW, 7.2MWh NaS energy storage system for peak shaving.

There were several challenges with installation. Transporting the system to site was difficult because the units were so tall that they could not fit under certain bridges. The batteries were considered hazardous materials, so specialized transportation techniques needed to be used. There were safety concerns about the presence of 5000 kg of molten sodium. It was considered a serious fire and explosion hazard by the local health department. The local fire department needed specialized training and the customer arranged for permits and annual inspections.

The size of the installation caused connection issues and lead to a serious delay. For systems this large, the local utility has specific connectivity and control requirements. Satisfying these requirements took several months. NGK, the manufacturer of the batteries, specified that these batteries would need to be cycled at least once within 30 days of delivery. Because of the delay, several cells failed before they were ever used.

The system was finally commissioned in April 2008, more than a year after its initially expected commissioning of January 2007. Including unexpected transportation expenses, safety certification and training, connection costs and replacement batteries, the final cost to commissioning was over 4.5 million dollars, about $650,000 more than originally expected.

The NYPA estimates that the system will annually save about $220,000 in labour costs and about $26,500 in electricity. However, these estimated savings of $246,500 a year means that this project has a payback period of over 17 years. This is especially discouraging since the system is only expected to have a 15 year life.

Only limited data about the project is currently available, but data collection is continuing. It still needs to be seen what, if any, operating issues will surface during the system's expected life. Similarly, it needs to be seen what end-of-life and disposal issues will be encountered when this system is decommissioned. Updated project information is being released on the following website as it becomes available: http://www.storagemonitoring.com/nyserda-doe/battery.shtml.

IV. Regenerative Braking Support Using Flywheels in the London Underground

In electrical braking, the motors usually used to propel trains forward act as generators and absorb the vehicle's kinetic energy. The absorbed energy can also be stored and reused. In some transit systems, the energy recovered through regenerative braking is returned to the distribution system for neighbouring trains. According to London Underground, it is only possible to transfer about 14% of regenerative energy between trains [12]. However, Baxter [4] reports that up to 66% of energy generated by regenerative braking can be used by the system. Depending on the system arrangement, too much energy can returned to the system which can cause dangerous voltage surges. This energy can be captured by wayside energy storage systems until it is needed. Although there is limited field data, some estimate that a wayside energy storage system could achieve energy savings of up to 30% in a subway system [13].

A. Flywheel Energy Storage Systems

The material in this section is derived from references [14] – [17].

In flywheel energy storage systems, energy is stored in the form of kinetic energy of a rotating mass. A common motor drives the mass and acts as the generator to capture this kinetic energy. This motor/generator is coupled to a power conversion module that collects and supplies energy as necessary.

To reduce noise and bearing wear, the spinning mass in modern flywheels is levitated using electromagnets. Air resistance is addressed by placing the spinning mass in a near vacuum. Several models on the market use a permanently sealed vacuum to make noisy and complicated pneumatic equipment unnecessary. To maximize energy storage capacity in a flywheel system, it is desirable to spin the mass as quickly as possible. Unfortunately, with very high tip speeds there is increased risk of a potentially disastrous sheer failure. To address this, the spinning masses in modern flywheels are made of very high tensile strength materials such as carbon fibre. The resulting products have round-trip efficiencies between 70% and 90%. They are also capable of very rapid power transfer, require little or no maintenance, have a small footprint, are theoretically capable of unlimited deep discharges, can be scaled simply by adding more units in parallel or in series, and can be recycled or safely disposed of in a typical landfill at the end of their life.

Unfortunately, flywheel energy storage systems also have some disadvantages. They are capable of delivering and receiving great amounts of power, but not much energy. The risk of catastrophic failure for flywheels is also very daunting. The damage that could be caused by a mass rotating at 100,000 RPM is extensive.

B. London Underground Flywheel Trials

The material in this section is derived from references [12] and [18] – [20].

On the London Underground's Piccadilly line, the distance between the Northfields and Acton Town stations is so great that there is significant voltage variation on the line. In this stretch of track, the voltage would vary from as low 450 direct current volts (VDC) to over 880VDC. Part of this voltage instability was created by the regenerative braking ability of subway trains in this system.

A flywheel energy storage system was chosen to be demonstrated in this location for one week in October 2000. This trackside energy management system (TESS) consisted of three 100 kW units in parallel and an electronic power control module installed in the Northfields substation. This system is easily scalable to accommodate additional power or energy requirements by simply adding more units in parallel or series.

The particular models of flywheel used for this demonstration could rotate as quickly as 37,800 RPM, meaning each could store up to 11 MJ or about 3 kWh of re-usable energy. Each unit has a footprint of only 600mm × 600 mm (3.9 square feet) and is 1500 mm high. The manufacturer boasts that their conversion efficiency between electrical and kinetic energy is 95%, meaning the system would have a round-trip efficiency of approximately 90%. The manufacturer also reports that these flywheels have zero maintenance and a life of approximately 20-25 years.

The nominal voltage in this location was 630VDC. The system used in Northfields substation was designed to supply energy when the track voltage dropped below 620 VDC, and to absorb energy when the track voltage exceeded 650 VDC. With a large load, the unregulated voltage may drop as much as 180VDC to 450VDC. With the same load, the FESS was able to reduce the voltage drop to only 100 volts, or a final voltage of 530VDC.

The system was also shown to be actively absorbing energy while the test train was using regenerative braking. However, the total energy produced by the braking train exceeded the 300 kW capacity of the system meaning some energy still needed to be dissipated as heat using resistors. Based on the amount of excess energy available, the manufacturer estimated a 1MW flywheel installation would be appropriate.

The London Underground had estimated that it was only possible to transfer 14% of regenerative braking energy between trains. With this addition of this energy storage system, it was shown that the energy transfer could be increased to up to 30%.

In 2000, a typical London Underground substation consumed £195,000 of electricity annually. With a 1MW energy storage system, the manufacturer estimated the energy consumption could be reduced by up to 26% or £50,000. A 1MW unit would cost £210,000 and have an annual operating and maintenance cost of £2,500. By this calculation and energy prices at that time, the payback period for this system would be about five years. This is a reasonable length of time and does not account for the benefit of reducing demand on the local electricity grid during peak periods.

IV. Regenerative Braking Support Using Capacitors with the Madrid de Metro

A. *Capacitor Energy Storage Systems*

The material in this section is derived from references [13] and [21].

Capacitors have the ability to store electricity directly as charge without a chemical change or mechanical medium. Typical capacitors can be thought of as a pair of parallel plates separated by a non-conducting medium. Opposite direct current charge is accumulated on the plates and an electrical field develops in the medium. The energy can be easily extracted as direct current electricity.

Electrochemical double layer capacitors (EDLC's) colloquially called ultracapacitors operate similarly to parallel plate capacitors but use an electrolyte solution to create a much greater surface area. Within these pop-can shaped cells, an organic electrolytic solution becomes polarized to store charge. The electrolytic solution accumulates on the surface of a porous carbon electrolyte, creating a significant surface area over which to accumulate charge. Not surprisingly, the charge capacity as measured in Farads is several orders of magnitude greater than parallel plate, ceramic or other electrolytic capacitors.

This technology has a number of advantages over its competitors such as batteries and flywheels. Since there is no chemical reaction, the process is highly reversible and theoretically capable of millions of cycles. Another advantage of no chemical reaction is that the capacitor is capable of deep cycling or complete discharge with very limited degradation. As discussed before, storing electrical energy without another transformation into another form of energy is highly efficient and less prone to parasitic losses. Despite these advantages, capacitors also have some downsides.

Ultracapacitors suffer some disadvantages because of their limited use in the market (and high unit cost) and because of the materials they use. These capacitors are designed to hold significant charge, but are susceptible to voltage surges. If the voltage within any cell exceeds its rated voltage of about 3 volts, the cell will break down. The voltage is largely controlled by the power electronics, but exceeding the maximum rated voltage is still a concern for long-term sustainability. The electrolyte in ultracapacitors may contain sulphuric acid, caustic potash and/or an organic electrolyte. These may be considered hazardous substances and as such safety precautions may be needed to store, transport or use these products. Similarly, because of the limited market exposure of ultracapacitors, their end of life disposal and recyclability has yet to be fully explored.

B. *Madrid Ultracapacitor System*

The material in this section is derived from references [13], [22] and [23].

In an effort to reduce ecological and economic burdens, the Madrid de Metro invested an energy storage system to support their light-rail system. The hope was to use this system to maximize the benefits of the regenerative braking, stabilize voltage and reduce overall power consumption. The nominal voltage for Madrid de Metro is 600VDC, but at times at certain locations the voltage sagged to as low as 470VDC.

A Siemens Sitras SES energy storage system was commissioned in Madrid in March 2002 near its Ventas stop. This system consists of 42 pop-can sized ultracapacitors, each with a volume of 500 mL and a capacitance of 2400 farads. This system is designed to store up to 2.3 kWh of energy and provides approximately 1 MW of power. The capacitor bank is reported to have an efficiency of 95%; however the round-trip efficiency of the entire system is closer to 85%.

Field tests of this system showed average power requirement per train was reduced by 50kW, or about 30%. The system also demonstrated that it was able to provide voltage stabilization, eliminating voltage drops below 470VDC and greatly reducing the occurrences of voltages below 530VDC.

Siemens' documentation claims that their system can reduce energy consumption by about 65 kWh per hour, or about 320 MWh per year. Calculations by Maher [13] estimate each unit could lead to an annual electricity savings of $32,000.

Unfortunately, there is no reliable 3rd party data estimating the initial purchase, installation and maintenance costs of these systems available. As such, it is not possible to have an appropriate calculation for payback period.

V. Discussion

In all three case studies, published literature suggests that each of the three energy storage systems demonstrated was successful in their intended duties for their respective transit systems. However, simply demonstrating that the technology works is not the same as proving that it is effective.

A. *Valuable Lessons Learned*

The Long Island bus demonstration was particularly valuable for demonstrating non-technical challenges of incorporating new technologies into transit systems. In that demonstration, a technical shortcoming of NaS batteries was revealed. This shortcoming was that these batteries must be discharged within a certain amount of time after manufacturing. Without a real-world mistake, the importance of this may never have been known. Similarly, this case study demonstrated the challenges that local safety and power authorities may pose to energy storage demonstrations. Although not anticipated, these real-world experiences may be the most valuable results from this demonstration.

B. Unreliabile Data

It is also somewhat discouraging that there is a lack of independent, third-party data on demonstrations of energy storage technologies in transit systems. Manufacturers are naturally very keen to talk about the benefits of their systems, but may be reluctant to highlight shortcomings. In particular, most of the literature available on the Siemens SES demonstrations is either from Siemens itself, or Maxwell, the supplier of the capacitors. Similarly, most of the data from the London Underground tests was from Urenco Power Technologies, the manufacturer of the flywheel used. Independent comment on the data would be valuable to point out potential shortcomings and give a more complete view of the demonstrations. However, since there are likely many demonstrations of energy storage technologies where any data accumulated has not been published to maintain confidentiality, the transit community is likely thankful for information that is available.

These energy storage systems need to operate many years to recover their investment, but the publications on these case studies were based on very short amounts of time. The London Underground flywheel system was only demonstrated for a week. The reports on the Long Island NaS were based on less than one year of operating experience. There are many valuable insights that may be drawn from long-term data such as failure rates, real maintenance costs and illustrations of the performance of the system with respect to time.

The lack of unbiased, independent data about energy storage systems may be one of the biggest hurdles for implementing this technology. The widespread acceptance of energy storage technologies may be hampered by this lack of information since customers, particularly transit systems, want information about previous installations before they commit. This creates an obstacle for growing this technology: customers are reluctant to use a technology until it has been demonstrated, but are unwilling to demonstrate the technology until someone else has used it. Manufacturers and proponents of energy storage technologies will need to be proactive in securing and advertising successful installations to improve acceptance of their products.

C. Incomplete Economic Data

Regrettably, the round-trip efficiency data for each demonstration likely excludes the cost of some auxiliaries. For example, the Siemens SES system claims to be able to save up to 320 MWh per year. However, that system also requires an advanced ventilation system that will continuously require power. It is unclear if the energy savings calculation considers the energy required for the ventilation. Similarly, the heating and air conditioning for the Long Island NaS system may not have been included in their energy and cost-saving analysis. In all three case studies, it is not specified if the power required to operate the control systems is included in the round-trip efficiency data. Because it is unclear if auxiliaries have been included in the cost and energy saving calculations, the claims of energy and cost savings should be taken as preliminary.

In each of these demonstrations, the end cost-effectiveness was never completely proven. In particular with the Long Island NaS system, the payback period seems to be longer than the life of the system. Similarly, the payback of the London Underground flywheel is only based on estimates. Although the technology was proven to be viable, the cost effectiveness from a customer point of view has not yet been demonstrated.

D. Impact on Utilities

The financial analysis for these case studies looked at the impact of energy storage on the customer but did not examine the impact on the local electrical distributing utilities and power generation facilities. At first glance, it may seem that reduced demand may be a disadvantage for utilities because they may make less money. However, the impact of energy storage systems is more complicated than that. If utilities are able to properly accommodate energy storage systems their profits may actually increase.

Meeting peak demand is a major cost for local power authorities because it requires construction and maintenance of generation and distribution resources. To meet peak demand, which may only last one hour each day, the utility must have that amount of power available all the time. To have this power available, the utility may have a fossil fuel plant on standby for 23 hours a day which is very inefficient. A more uniform energy demand means the utility can supply a more uniform level of power while making better use of their existing infrastructure and possibly even selling more energy.

All three applications discussed in the case studies have the value of reducing peak power demand. When the Long Island NaS system uses peak shaving, it uses power that may not otherwise be required at night. The local power authority must plan and accommodate this demand, which may even require increasing power output in the middle of the night. Similarly, by making use of existing energy in the system, the regenerative braking energy storage systems for the London Underground and Siemens SES reduce peak demand. In all three case studies, reducing energy consumption reduces the peak power demand on the local power grids. Surprisingly, from an economic point of view this is of great benefit to local power authorities.

Upon further analysis, it is clear that reducing peak demand is a major benefit to power authorities. Since energy storage systems are not 100% efficient, the utilities may have to produce more energy meaning they can sell more product. The energy storage systems explored in this document reduce peak power demand. This is a major advantage for utilities because they can reduce the amount of standby power they need, and reduce the need for new installations, upgrades and maintenance. Such benefits change the economic case with which energy storage systems should be evaluated.

Economic analysis of energy storage technologies should reflect benefits to both customer and power utility. As discussed earlier, reducing peak demand and the costs associated with meeting peak demand can cause significant financial savings. As a case in point, the Long Island NaS system is not economically viable if you only look at it from the customer's point of view. Because it had benefits for the local power authority, this installation received financial support from its local power authority. This model of looking at all the benefits of an energy storage system will be important in justifying future installations.

E. Comparing Flywheels and Capacitors for Regenerative Braking

There are some interesting contrasts and comparisons between the London Underground flywheel and Madrid capacitor systems, both of which supported regenerative braking. Both systems were demonstrated to be able to capture regenerative braking energy and return it to the systems to stabilize voltage. Both had similar energy capacities and behave the same way when idle. A notable difference is the difference in their power capacity. Some advantages of the flywheel system are that it has a notably smaller footprint and does not require the extensive HVAC of the capacitor system. The importance of proper system sizing was demonstrated during the London Underground flywheel trials. During that demonstration, the flywheel system did not have enough capacity to capture all of the regenerative braking energy. This could be easily remedied by adding more modules. This problem of not being able to capture all the available energy could have easily also occurred with a capacitor system but comparable data is not available for the Siemens SES system. Also, the flywheel system was supporting heavy rail subway cars rather than light rail streetcar vehicles. From the demonstration data, it is unclear which technology of energy storage for regenerative braking is better.

Despite similar technical characteristics, it is interesting that capacitors are emerging as the prevalent technology for the application of capturing regenerative braking energy. Flywheel systems have the advantages of being easy to dispose of, a simple design, and use no hazardous substances. However, there seems to be more interest in capacitor systems because they do not have any moving parts. A catastrophic failure of a capacitor system could lead to chemical fires or acid spray. But customers may be more afraid of a catastrophic failure by a flywheel because they can understand and foresee the damage caused by a rapidly spinning mass. In this case, the simplicity of the flywheel system may be a disadvantage because its failure risk may deter potential customers.

F. The Future for Energy Storage Technologies

These demonstrations showed that each technology worked for their intended tasks, but additional information and steps are required before there is widespread acceptance. Although there are many other technologies available, they will remain in laboratories and brochures until manufacturers demonstrate their systems in the real world. If demonstrations like these continue, they will be more effective if third-party analysis is allowed because it will present an unbiased opinion of the technology and show a different point of view than the manufacturer or customer. It will be very valuable to release data after many years of service because it will demonstrate if a technology is robust and reliable. Lack of quality information and real experience are a major hurdle to the acceptance of energy storage technologies.

Despite the hurdles, the increased deployment of energy storage systems in transit systems and other applications is very necessary. Reducing peak power demand and improving energy efficiency are very important in an era where energy conservation and reducing fossil fuel consumption are on the top of everyone's mind. In any era, reducing cost is certainly beneficial. As these technologies mature and are demonstrated more widely, they will become very popular and almost commonplace. It is only a matter of time before today's advanced technologies such as sodium sulphide batteries become as common as lead-acid batteries.

VII. Conclusion

Energy storage systems show great promise for transit systems and other applications. This paper reviewed three demonstrations which showed that these technologies are capable of improving the efficiency of energy use. Table 1 summarizes the characteristics of the three systems. The Long Island sodium sulphide battery system was successful in peak shaving which caused labour cost reductions. The London Underground flywheel and Madrid capacitor demonstrations were both shown to be able to reduce energy consumption by supporting regenerative braking. By building on these and other demonstrations, manufacturers will be able to deploy additional systems and continue to improve energy storage systems throughout the world.

TABLE I
Summary of Characteristics of Reviewed Systems

	Long Island NaS	London Flywheel	Madrid Ultracap
Power (kW)	1000	300	1000
Energy (kWh)	7200	3	2.3
Cost ($/kW)	$4,500	$488	?
Life expectancy (years)	15	20-25	10
Life expectancy (cycles)	4500	100,000	millions*
Footprint (square feet)	510	4	45
Round-trip efficiency (%)	75%	90%	85-95%

*Life for this ultracapacitor system is unknown but expected to be millions of cycles

Before energy storage systems become completely mainstream, there are certain hurdles that need to be accommodated. Additional demonstrations will improve acceptance of energy storage. Not only do there need to be more demonstrations, but these demonstrations will need to have data from many years of operation. Independent review, analysis and comment of these demonstrations will be helpful in removing the manufacturer's bias. Since the energy storage system may not save enough energy for the customer to justify its installation, customers such as transit systems should partner with their local power distributing authorities. Financial incentives from local power authorities will speed the acceptance of energy storage by improving the economic case for their installation. With better information and relationships between power authorities and customers, and improved information, energy storage systems can become a dominant technology for improving energy efficiency.

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