Innovations Deserving
Exploratory Analysis Programs

Transit IDEA Program

Advanced Wayside Energy Storage Systems for Rail Transit

Final Report for
Transit IDEA Project 66

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Final Report

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Prepared for:
Transit IDEA Program
Transportation Research Board
National Research Council

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EXECUTIVE SUMMARY

This project explored the use of wayside energy storage systems (WESS) in rail transit systems. The analysis monetized economic and technical benefits for transit agencies but also considered other stakeholders. Navigant Consulting modeled the costs and benefits of various applications through hypothetical simulations as well as case studies using real data from our participating transit agencies: Greater Cleveland Regional Transit Authority (GCRTA) and Denver Regional Transportation District (RTD). Representatives from the two case study transit agencies participated on an expert panel to direct this research, along with the American Public Transportation Association, Sacramento Regional Transit District, and New York City Transit.

The Analytica® modeling platform was used to build a customized economic and technical WESS simulation model. The project approach consisted of 7 steps:

1) Objectives – Identified objectives for transit agencies to utilize WESS.
2) Applications – Identified the specific use for WESS to achieve the application.
3) Technologies – Identified appropriate storage technologies to meet each application.
4) Benefits – Identified and monetized benefits associated with each application.
5) Cost – Estimated the capital and operating costs associated with each application.
6) Value – Calculated the 15 year Net Present Value (NPV) to estimate the direct financial value of each application.
7) Combined Applications – Optimized the NPV by combining applications.

As shown in TABLE ES-1, there are economic and technical reasons to invest in a WESS that can be grouped into four primary objectives. In addition to achieving their primary objectives, transit agencies may be able to realize additional revenue or other economic benefits by using the WESS for utility applications.

TABLE ES-1 Transit Agency Rationale, Objectives, and Applications for WESS

Rationale	Primary Objective	Transit Application
Economic	Electricity cost management	Time-Based Rate Management
		Demand Charge Management
	Energy efficiency & resource optimization	Regenerative Braking
		Renewable Energy Optimization
Technical	Power quality improvement	Voltage Control
		VAR Control
		Phase Balancing
	Reliability improvement	Backup Power
Rationale	**Secondary Objective**	**Utility Application**
Economic	Revenue optimization	Peak Demand Reduction
		Renewable Energy Integration
		Ancillary Services

Six different WESS technologies were modeled including: flywheels, ultracapacitors, and lead acid, sodium sulfur, lithium ion, and zinc bromide batteries. The cost, benefit, and net present value (NPV) were calculated for seven simulations for a hypothetical transit system and for two case studies. The simulations were individual applications or combinations of applications listed in Table ES-1 including:

1. Simulation #1: Time-based rates and demand charge management
2. Simulation #2: Regenerative braking
3. Simulation #3: Renewable Energy Optimization
4. Simulation #4: Voltage Control
5. Simulation #5: Backup Power
6. Simulation #6: Backup power with time-based rate management and demand charge management
7. Simulation #7: Voltage Support with regenerative braking

The results indicated that more positive NPVs occur when WESS applications are combined. For example, Simulation #6: Backup power with time-based rate management and demand charge management resulted in an NPV of about $80,000. However, the other simulations did not result in a positive NPV using the standard assumptions. Simulations #1 through #3 and #7 represent the applications with an economic rationale so the NPV for these applications is an important decision criterion. Technology capital cost or other parameters would have to change in order for these to be attractive applications.

However, Simulations #4 and #5 represent applications that would be implemented for technical reasons (i.e., the transit agency must invest in a technology to address a power quality or reliability issue). In this situation, the transit agency may consider implementation even if it required an economic investment in order to resolve the technical issue. The NPV of the WESS compared to an alternate technology is more important than whether the NPV is positive. In Simulations #4 and #5, the results of the model indicated that implementing a WESS was more attractive than implementing a traction power substation (TPSS).

The Denver RTD case study considered electricity cost management (time-based rate management and demand charge management) as well as regenerative braking. The GCRTA case study considered electricity cost management (demand charge management only) as well as regenerative braking. In both cases, electricity cost management was slightly more attractive than regenerative braking but neither provided a positive NPV.

The annual benefits from regenerative braking are largely determined by the electricity rates. GCRTA's electric rates are 2 to 3 times higher than Denver RTD's electric rates, but Denver RTD faces significantly higher demand charges and has more regenerative braking opportunities than GCRTA. Therefore, the total annual regenerative braking benefits for Denver RTD are slightly more than those accrued by GCRTA.

The electricity cost management application provided more benefits for Denver RTD than for GCRTA. This is primarily due to the fact that GCRTA does not have time-based rates and cannot take advantage of those benefits. GCRTA's electricity cost management case study included only demand charge management. In addition, GCRTA pays demand charge rates that are only 10% to 20% of the rates faced by Denver RTD.

These case studies underscore the importance of transit system operational characteristics in any WESS analysis. The results vary widely based on the assumptions used, particularly from electricity load patterns.

In summary, the key findings were:

1) Combining applications provides benefits that result in the most attractive NPV. Simulations #6 modeled a combination of applications that resulted in a positive NPV.

2) Applications that solve a technical problem, such as to address a power quality or reliability issue, may be attractive to a transit agency even if the NPV is not positive. This was the case in Simulations #4 and #5. The important consideration is whether WESS is less expensive than the alternative technology.

3) The results for each of the applications could be improved with a reduction in WESS capital cost, which is expected for most technologies over the next few years as they become commercially available and are produced in larger quantities.

4) The financial value proposition for WESS would be improved by federal capital grants or other incentives. This project analyzed the value of WESS as an investment made solely by the transit agency without capital funds from other sources.

5) This analysis considered the business case for a transit agency and therefore monetized on the benefits that accrue to the transit agency. However, if a societal perspective had been modeled and other benefits were monetized, WESS would likely be much more attractive in these applications.

1.0 BACKGROUND

In the face of rising electricity costs and record-breaking ridership, many transit agencies are searching for innovative strategies to reduce expenses and increase operational efficiency. Between 2004 and 2009, electricity costs for transportation in the United States (US) grew by an average of 37%, while the total number of US urban rail rides grew by over 21%[1]. Beyond economic pressures, increased rail usage is complicating operational challenges for transit agencies, such as maintaining steady voltage within the rail system[2]. Transit agencies with electrified rail systems must effectively operate a small electricity distribution network serving intense and sudden loads from rapid train braking and acceleration. This leads to the generation of high demand charges, as well as common problems with voltage sag and resulting operational disruptions.

Many rail transit agencies are beginning to investigate energy storage technologies to confront rising costs and operational pressures. Energy storage technologies offer transit agencies the ability to rapidly store electricity, and then use it on command. The electric delivery sector and federal government have guided research in energy storage during recent years, and have confirmed the capability of grid energy storage to improve the reliability of electric transmission and distribution. Energy storage can be sited both onboard transit vehicles, and in stationary modules on the rail wayside, termed a wayside energy storage systems (WESS) to provide a variety of benefits.

A 2010 report, prepared by the American Public Transportation Association (APTA) and the Electric Power Research Institute (EPRI) and funded by the Transportation Research Board (TRB) identified four key applications for WESS for transit agencies[2] including:

1. WESS can provide voltage regulation, reducing challenges to train operations placed by rapid fluctuations in voltage.
2. WESS can reduce the level of peak demand, reducing the demand charges which many transit agencies face.
3. WESS can recapture braking energy, reducing overall electricity purchases and cost.
4. WESS can supplement traditional power substations capacity operated by the utility, resulting in deferral of investment in expanded substation capacity.

1.1 IDEA Product

In this project, Navigant Consulting, Inc. (Navigant) explored the use of WESS in transit systems, which focused on economic and technical benefits to the transit agency, and also considered other stakeholders as well. By considering the full range of stakeholders (such as electric utilities, merchant storage project owners, and society at large), the project identified a diverse set of benefits that can accrue through cost avoidance, reliability increases, sustainability improvements, and receipt of revenue or retail credits for energy and services sold to the grid. In addition, this project provides an overview of several WESS technologies. The result is a guide for transit agencies to use when considering a WESS installation.

1.2 Concept and Innovation

This project explored the key innovation of using an advanced WESS in transit systems to reduce electricity costs and accrue other benefits to the transit system and to key external stakeholders. Through a value analysis model, simulation, and case studies, Navigant explored the full range of value propositions associated with WESS. We modeled the costs and benefits of various applications using simulations as well as

case studies using real data from our transit agency partners, Greater Cleveland Regional Transit Authority (GCRTA) and Denver Regional Transportation District (RTD). These two agencies are leaders in sustainability and are located in states with Renewable Portfolio Standards.

1.3 Investigation

The approach for conducting this project consisted of several steps:

1. Establish the basis – In order to establish the basis for this project, we conducted a literature review and a survey of WESS technology demonstrations for transit applications. The status and results of these studies and demonstrations are summarized in Section 2 of this report.

2. Develop the value analysis model – We developed an analysis framework which considers the transit agency objective and WESS application, technology, benefits, costs, net value, and combinations to increase the value. This framework is described in Section 3. We then built a computer model using Analytica® to implement the framework and conduct the value analysis.

3. Run the model with simulated inputs – We then ran the model to estimate the value for various applications. The assumptions used in each simulation and results are provided in Section 4.

4. Run the model with case study input data - In addition, we ran the model with data supplied by Denver RTD and GCRTA to estimate the value of various applications in the Denver RTD and GCRTA case studies. Wherever possible, we used historic load data. For parameters that must be estimated, we conferred with Denver RTD and GCRTA to determine the most appropriate value for their system. The final parameters input to the model and the results are presented in Section 5.

5. Summarize conclusions – Section 6 presents the overall findings, lessons learned, and recommendations from this project.

1.4 Plans for Implementation

We implemented the value analysis by running the model with various hypothetical simulations and with two case studies using data from our transit agency partners: GCRTA and Denver RTD. The results and conclusions drawn from these simulations and case studies are presented in Sections 4 and 5 of this report. Based on the results from this project, GCRTA and Denver RTD may choose to continue the analysis and implement WESS in their systems.

2.0 LITERATURE REVIEW

2.1 Existing Research on Transit WESS

In the past four years, academic and industry researchers in the US have released two key studies seeking to model the optimal operations and benefits of WESS for municipal rail systems.

In 2007, the Bay Area Rapid Transit District commissioned a study of various energy savings options for the agency's heavy rail system, including analyses of both wayside and onboard energy storage options. The study modeled energy storage for energy recapture, and identified storage as the retrofit option with the highest absolute savings potential. The evaluation estimated annual savings of $8.7 million and a 10 year payback period for WESS. This report also compared the costs and benefits of wayside versus onboard energy storage, and recommended WESS if the planned retrofit is near-term, and the replacement of the train fleet is planned for the distant future[2].

In 2010, TRB funded a WESS study under the Quick Response Research program of the Transit Cooperative Research Program. American Public Transportation Association (APTA) and Electric Power Research Institute (EPRI) formed the Energy Storage Research Consortium (ESRC) to perform this study entitled "Guiding the Selection & Application of Wayside Energy Storage Technologies for Rail Transit and Electric Utilities"[3]. The project (TCRP J06/Task 75) reviewed storage projects currently in development, and outlined the data needed for WESS feasibility studies by transit agencies. The report presents a model built by ESRC for the simulation of WESS operations, costs, and benefits. This model shows WESS benefits for voltage regulation, demand charge reduction, and deferred substation investment. WESS benefits and cost-effectiveness are highly dependent on specific system parameters such as train headway, train schedule synchronization, and power system voltage limits. The study provides guidance for transit agencies to evaluate WESS technical benefits for their particular rail system.

A search of the National Transportation Library identified only two other studies, one article, and one white paper published in the past 20 years that explored advanced WESS devices for rail transit systems generally. The first study, published in 2005 and called "Return on Investment from Rail Transit Use of Wayside Energy Storage Systems" discusses energy and power savings and capital costs of flywheels, capacitors, and batteries[4]. The second study, published in 2007 and called "Wayside and On-Board Storage Can Capture More Regenerated Energy," focuses only on benefits from increased braking energy capture and reuse possible with batteries or ultracapacitors[5]. The article, published in Passenger Transport Magazine in 2008 and called "Smart grids and wayside energy storage: opportunities for transit" outlines WESS technologies and potential benefits to transit agencies[6]. The article is closely related to a 2008 APTA white paper on the "Energy, Environment and Transit Research Program." [7] This paper calls for research to assess available technologies in five key areas, including renewable energy and energy storage technologies.

2.2 Existing U.S. Transit WESS Projects

Since 2001, transit agencies including New York Metropolitan Transportation Authority (MTA) and Sacramento Regional Transit District have been demonstrating and testing WESS at electrical substations to perform peak shaving and regenerative braking storage. These efforts have focused on flywheels, ultracapacitors, and batteries which can store enough energy to shave demand peaks, ensure consistent voltage, and increase the yield of regenerative braking. TABLE 1 provides an overview of these WESS projects for transit applications.

TABLE 1 Existing U.S. WESS Demonstrations for Transit Applications

Transit Agency	Project Status	Rail Type	Technology	Applications	Notes	Citation
Sacramento Regional Transit District	Operational	Light Rail	Battery	Voltage support		[3]
Sacramento Regional Transit District	Operational	Light Rail	Ultracapacitors	Regenerative braking	$400,000 grant from the California Energy Commission in 2007 to install Sitras SES by Siemens Transportation Systems, Inc. along an 8-mile stretch of the Folsom line.	[8]
New York City Transit/ Metropolitan Transportation Authority	Complete	Heavy Rail	Flywheel	Voltage support	2.4MW 30 second flywheel design funded by NY Power Authority (NYPA), New York State Energy Research and Development Authority (NYSERDA) and US Department of Energy (DOE) for the Long Island Railroad.	[9], [10]
New York City Transit/ Metropolitan Transportation Authority	Operational	Heavy Rail	Battery	Regenerative braking	NiMH batteries are currently being tested.	[2]
Los Angeles County Metropolitan Transportation Authority	In process	Heavy Rail	Flywheel	Demand charge, regenerative braking, substation replacement	Awarded $4,466,000 FTA grant in March 2010.	[7]
Washington Metropolitan Area Transit Authority	In process	Heavy Rail	Battery	Regenerative braking	Awarded $300,000 FTA grant for administration in June 2010; seeking contractor to build and own battery at zero cost.	[11], [12]
Southeastern Pennsylvania Transportation Authority (SEPTA)	In process	Heavy Rail	Battery	Regenerative braking	Awarded $900,000 from Pennsylvania Energy Development Authority (PEDA); Viridity will use Saft's Intensium Max20 lithium-ion batteries.	[13], [14]

3.0 VALUE ANALYSIS MODEL

The framework developed to model the overall value of implementing WESS in a transit system consisted of seven steps:

1. Objectives – Identify objectives for transit agencies to utilize WESS.
2. Applications – Identify the specific use for WESS to achieve the application.
3. Technologies – Identify appropriate storage technologies to meet an application.
4. Benefits – Identify and monetize benefits associated with an application.
5. Cost – Estimate the capital and operating costs associated with an application.
6. Value – Calculate the 15 year Net Present Value (NPV) to find the overall value of an application.
7. Combined Applications – Optimize the NPV by combining applications.

3.1 Objectives

From a transit agency's perspective, there are economic and technical reasons to invest in a WESS. These can be grouped into four primary objectives:

- Electricity cost management
- Energy efficiency and resource optimization
- Power quality improvement
- Reliability improvement

In addition to achieving their primary objectives, transit agencies may be able to realize additional revenue or other economic benefits by using the WESS for utility applications.

3.2 Applications

As presented in TABLE 2, these primary and secondary objectives can be achieved by implementing WESS in various applications. Each of these applications is described in more detail below.

TABLE 2 Transit Agency Rationale, Objectives, and Applications for WESS

Rationale	Primary Objective	Application
Economic	Electricity cost management	Time-based Rate Management
		Demand Charge Management
	Energy efficiency & resource optimization	Regenerative Braking
		Renewable Energy Optimization
Technical	Power quality improvement	Voltage Control
		VAR Control
		Phase Balancing
	Reliability improvement	Backup Power
Rationale	**Secondary Objective**	**Application**
Economic	Revenue optimization	Peak Demand Reduction
		Renewable Energy Integration
		Ancillary Services

3.2.1 Time-Based Rate Management

A transit agency could use WESS to reduce their monthly electricity bill if they have a rate structure that varies through the course of the day, week, month or year. For this project, we are using the term "time-based rates" in the most general sense where a rate structure has at least a low priced off-peak electricity rate and higher priced on-peak electricity rate for each day. The intent of these rates is to encourage customers to shift their electricity usage to off-peak hours, reducing the cost of electricity for the customer and reducing the peak demand for the utility. These rates also more closely reflect the true cost of electricity. A transit agency could use WESS to charge with off-peak rates during the night and early morning and then discharge during periods of peak demand and rates. This concept is illustrated in FIGURE 1. Using WESS to take advantage of time-based rates is cost-effective only if the on-peak to off-peak price differential compensates for energy losses in the WESS. For example, use of a WESS with 75% roundtrip efficiency requires that the electricity rate for peak hours be at least 25% greater than off-peak prices to realize an operational savings. The lifetime savings would also need to be great enough to cover the capital and O&M costs of the WESS.

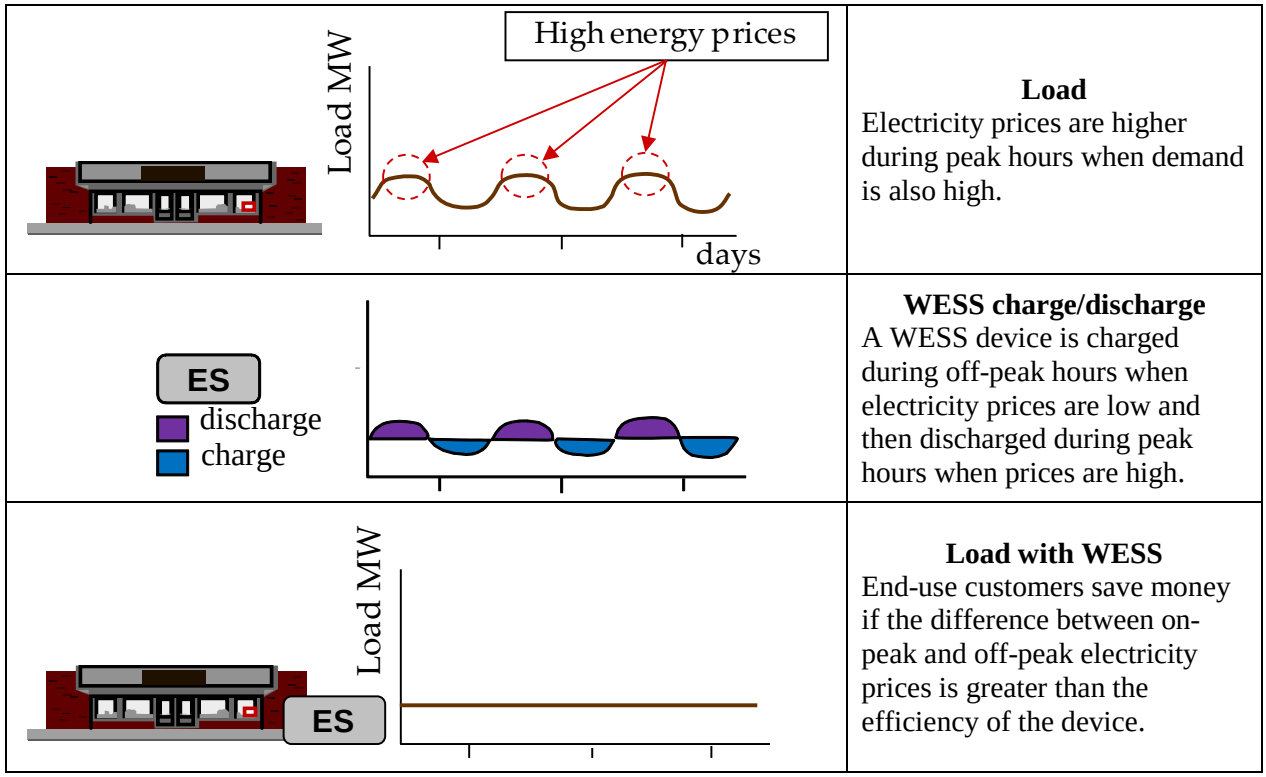


FIGURE 1 Use of WESS for Time-Based Rate Management

3.2.2 Demand Charge Management

Demand charge management is similar to time-based rate management. A transit agency could use WESS to reduce their monthly electricity bill if they have a rate structure that includes a monthly demand charge. Some rate structures charge a fee for the maximum electricity use during a specified interval (e.g., 15 minutes or 30 minutes) during the month. The intent is to encourage customers to reduce their peak electricity usage which would reduce the cost of electricity for the customer and reduce the peak demand for the utility. A transit agency could install WESS to reduce the peak amount of electricity used by supplying their peak energy demand with power stored during lower use periods. This concept is illustrated in FIGURE 2. In this example, the highest continuous level (477 kW) over 30 minutes, which occurs on day 10, is multiplied by the demand charge ($2.405/kW) to find the total monthly demand charge of $1,147.18.

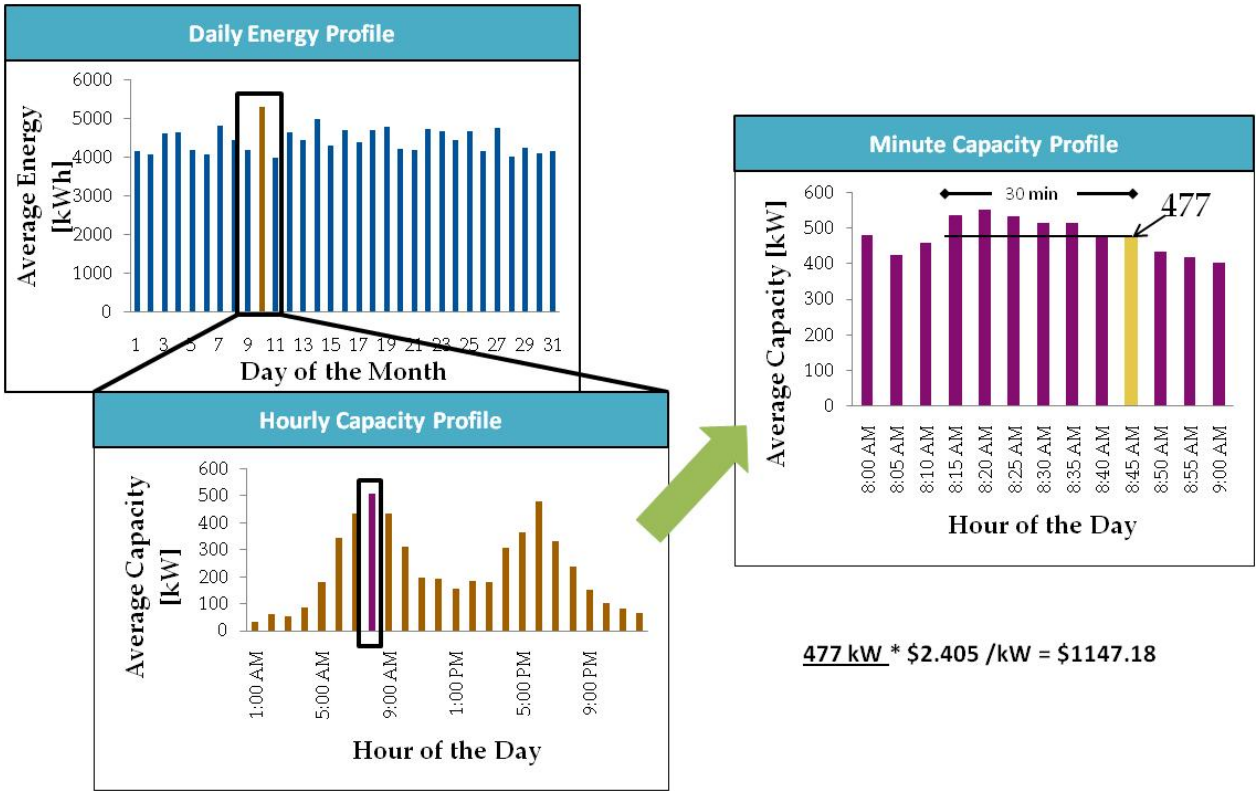


FIGURE 2 Use of WESS for Demand Charge Management

Using WESS for Demand Charge Management is cost-effective only if the reduction in demand charges compensates for energy losses in the WESS and the capital and O&M costs of the storage device. As shown in FIGURE 3, WESS would be most economical in situations where the user's peak demand is significantly higher than the normal demand for a short amount of time.

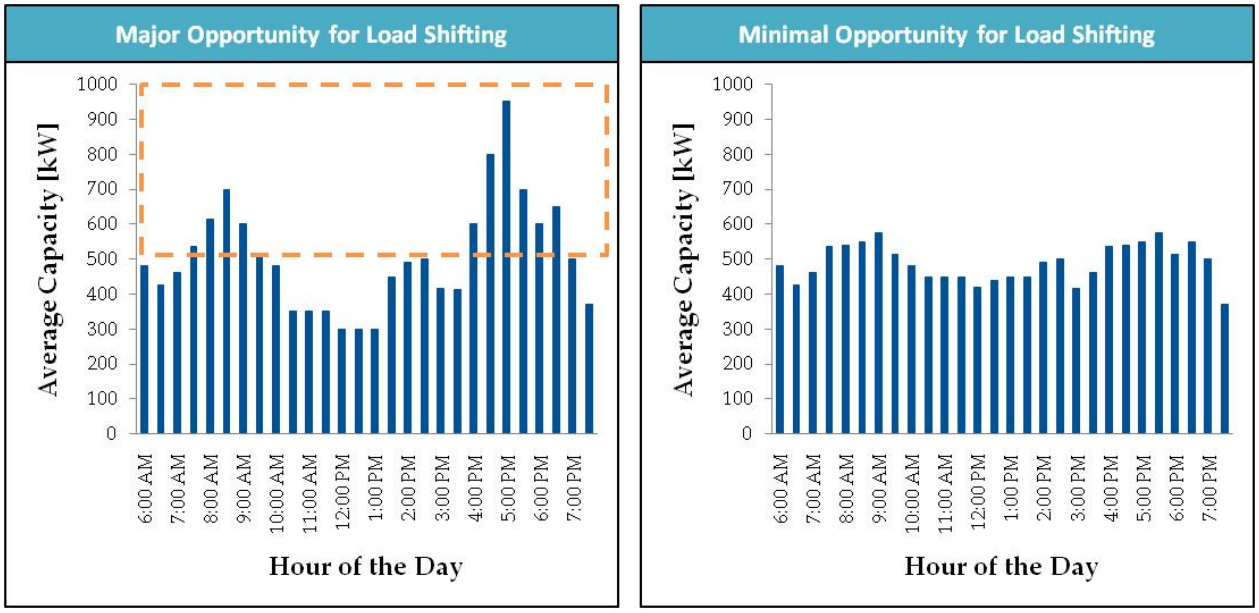


FIGURE 3 Opportunities for Demand Charge Management

In order to achieve an effective electricity cost management strategy, it is difficult to optimize for time-based rates or demand charges alone. This is due to several factors including: the typical transit system load profile (i.e. a double peak, one during morning commute and one in the evening), utility rate schedule (a combination of both demand charges and energy charges) and WESS inefficiency. For example, if one attempts to reduce costs associated with time-based rate charges without considering demand charges, the optimal solution is to charge heavily at night and discharge the WESS during the day at peak rate periods. However, the storage WESS inefficiency and nightly charge schedule can lead to higher peak loads during the late evening and early morning than what previously existed without storage. This new peak can result in increased demand charges that negate any time-based rate management benefits. The inverse can also be true if one attempts to optimize for demand charges rather than the energy rates. While the optimal solution will vary based primarily by utility rate schedule and the existing load profile, we found that the best approach for addressing this issue was to level the overall load. A comparison of substation load profiles with and without WESS is shown in Section 4 of this report.

3.2.3 Regenerative Braking

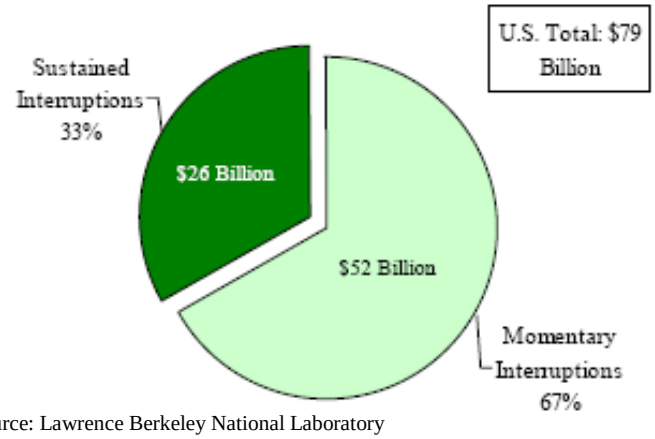
A transit agency could use their purchased electricity more efficiently by using WESS to capture energy that is normally converted to heat during train braking. By retaining some of this energy, the overall system electricity consumption can be reduced.

3.2.4 Renewable Energy Optimization

If a transit agency has intermittent renewable energy resources such as solar or wind, WESS may be used to optimize the use of that renewable resource. If time-based rates or demand charges apply, the transit agency could charge the WESS with the renewable energy resource and discharge the WESS during times when peak rates are charged by the utility or to reduce the monthly demand peak load.

3.2.5 Voltage Control

A study conducted by the Lawrence Berkeley National Laboratory (LBNL) indicates that 98 percent of power interruptions last for less than 15 seconds[15]. Momentary interruptions cost the U.S. industry $52 billion, or 67% of the total power interruption cost in the U.S. [11] (See FIGURE 4.) Additionally, annual power quality vulnerability has been estimated to be in the range of U.S. $10 to $100 billion[16].



Source: Lawrence Berkeley National Laboratory

FIGURE 4 U.S. Cost of Momentary Interruptions

If a transit agency is experiencing power quality problems due to poor voltage control, WESS can be used to stabilize voltage in the event of short term fluctuations in grid supplied power or local system demand.

While voltage sags can cause short term problems, repeated voltage excursions can lead to shorter equipment life. By reducing voltage swings, operational reliability (short term interruptions) can be reduced while also reducing equipment replacement costs. In addition, it could also provide an economic savings if the WESS eliminates or defers the investment in a substation upgrade.

3.2.6 VAR Control

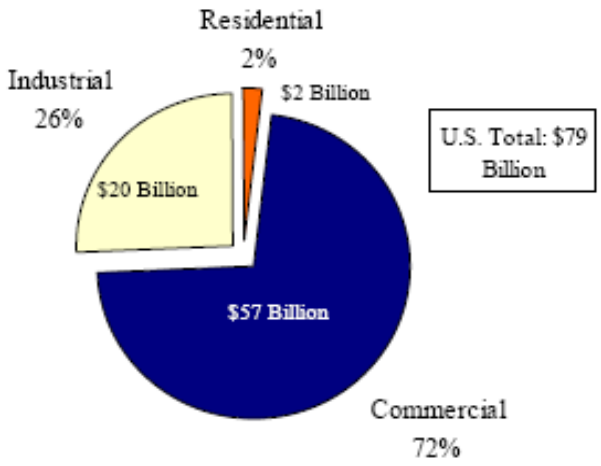
If a transit agency is experiencing power quality problems due to Voltage-ampere-reactive (VAR) control, the inverter from a WESS can function as a reactive power resource. The inverter could supply or absorb reactive power controlled by remote commands via the utility through the asset's communication system or the inverter could be programmed to sense when reactive power is required and automatically act. This would provide an operational benefit however, it may also provide an economic savings if the transit agency is charged for the VARs in its utility rate schedule. For WESS to provide VAR support, inverters must be able to adjust power factor either in response to changing voltages in response to communication signals from smart devices such as a substation or master controller. Alternatively, the inverter must be able to adjust power factor based on local bus voltages. For the latter, the inverter would automatically respond to low or high voltages. However, since the vast majority of light rail systems currently operate with direct current (DC) circuits, the need for an inverter with the WESS is likely eliminated. In addition, DC circuits don't have reactive power by definition. Therefore, it is unlikely that VAR support will be a significant benefit for a typical transit agency.

3.2.7 Phase Balancing

A third power quality issue that transit agencies may experience is phase balancing. A WESS can change load on a phase within a micro-grid or on a feeder based upon commands. This could alleviate phase imbalances on a feeder, transformer or line. This would provide an operational benefit as opposed to a direct economic savings or revenue. Phase balancing would be performed by smaller, single-phase storage devices using inverter technology, which would balance three-phase feeder loads, thereby improving voltage regulation, reducing losses, increasing capacity and enhancing protective relying functions, including avoiding nuisance tripping of relays due to imbalances. However, like reactive power, DC circuits eliminate the phase balance issues. Since most rail systems use DC power, this may not present a significant benefit.

3.2.8 Backup Power

Commercial and industrial facilities are exposed to a myriad of power quality problems and power outages, which can interrupt production processes, affect sensitive equipment, and cause downtime and capacity losses. As shown in FIGURE 5, the cost incurred across the U.S. for power interruptions is estimated to be $79 billion annually[16]. Depending on the system configuration and redundancy built into the system, transit agencies may experience reliability issues due to power outages. WESS can be used to provide temporary backup power to allow safe shut-down of equipment in the event of a sustained or major outage, after a power interruption event. A backup power device can also allow for a successful transfer to a backup generator. This could represent an operational benefit as well as an economic benefit if the transit agency could defer investment in a substation.



Source: Lawrence Berkeley National Laboratory

FIGURE 5 U.S. Cost of Power Interruptions

3.2.9 Peak Demand Reduction

The application of peak demand reduction assumes that the WESS would charge during off peak periods and discharge during on peak periods in order to reduce the load on central generation equipment, or transmission and distribution lines and equipment. A utility may benefit from reduced peak demand if they are able to defer a capacity upgrade to their equipment. While a transit agency would not install a WESS for this purpose alone since they would not receive the direct benefits (especially if they do not have a time-based rate structure), it may be possible to negotiate an arrangement with the utility to share the benefits. For example, if a transit agency owned a WESS for other primary purposes but made it available for discharge during peak demand, the utility may offer demand response revenue or some incentive such as other savings on their electricity bill. In this way, the transit agency could optimize their revenue associated with the WESS.

3.2.10 Renewable Energy Integration

Intermittent renewable energy resources and shifts in load often create short-term perturbations of one hour or less, thereby impacting the balancing of load and supply. At the distribution level, a high amount of intermittency on individual feeders can cause voltage regulation issues, as the time delay on load tap changing transformers or line regulators typically are not set to respond quickly enough to ensure voltages remain within prescribed limits (e.g., time delay can be up to one minute to avoid excessive contact wear). The unregulated voltage excursions can create power quality symptoms similar to those caused by “voltage flicker". WESS can buffer or mitigate the effects of both voltage regulation and non-economic operation of generating capacity to meet intermittency. This would provide an operational benefit to the utility. Again, a transit agency would be unlikely to invest in a WESS for this purpose, however, if a transit agency owned a WESS for another primary purpose but made it available for the utility to address issues associated with distributed intermittent renewable energy, the utility may provide revenue, savings, or other incentive.

3.2.11 Ancillary Services

Another application which WESS can provide is ancillary services such as frequency regulation. Virtually all power systems employ automated generation control systems (AGC) to maintain control area frequency. A control area is a section of the electric power grid where automated control systems monitor and schedule generation and inter-area power transfers, recognizing transmission constraints, to serve load and maintain frequency in compliance with the North American Electric Reliability Corporation (NERC) standards. The AGC system continually monitors differences between load and output, and adjusts generator power levels to respond to perturbations or mismatches between load and generation on a timescale of seconds to minutes.

Historically, frequency regulation service has been provided by generators which respond to AGC signals, ramping up or down to prevent the control area from deviating beyond NERC standards. WESS can be used, instead of or in addition to, generators to provide frequency regulation services. Several WESS technologies are more efficient at providing this service than generators, since they can respond rapidly to adjust power output levels up or down in response to an AGC signal.

These services vary between regulated and deregulated markets. In deregulated regions, owners of storage devices can receive payments for providing frequency regulation through the ancillary services market. In regulated regions, integrated utilities provide frequency regulation using their existing generation resources. Using storage to provide frequency regulation could yield ancillary service cost savings.

This could become a secondary application for transit WESS if market rules change and new business models are developed to provide an incentive to end users to make their WESS available for grid applications.

3.3 Technologies

Various WESS technologies can be considered for use in transit applications including:

- Batteries
  - Lead Acid (PbA) - conventional
  - PbA- advanced
  - Sodium Sulfur (NaS)
  - Lithium ion (Li ion)
- Flow Batteries
  - Zinc Bromide (ZnBr)
  - Vanadium Redox (VR)
- Flywheels (high speed or low speed)
- Ultracapacitors.

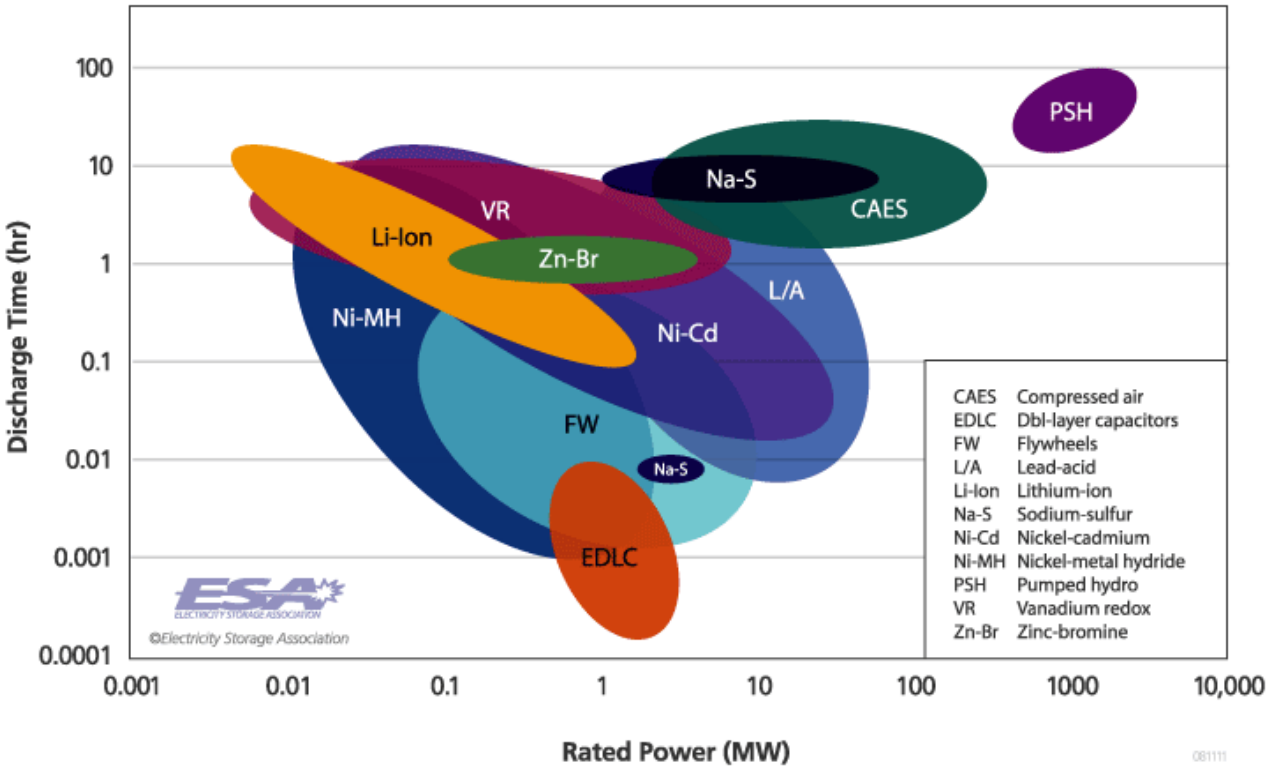
The most appropriate technology will vary depending on the application selected because each technology offers different characteristics. TABLE 3 shows some WESS technology characteristics rated on a scale of “1”, “4”, “7” or “10” (with a score of 10 representing the best score) for:

- Power (kW),
- Energy (kWh),
- Response time (seconds or minutes)
- Cycle life (cycles),
- Energy density (kWh/m3),

FIGURE 6 illustrates the power and energy ratings for various WESS technologies. TABLE 4 shows the commercialization status and primary vendors for each technology. TABLE 5 shows current cost estimates and forecasted trends in capital cost. Appendix A provides a description of the main WESS technologies being developed for stationary applications today.

TABLE 3 WESS Technology Characteristics

Technology	Characteristics				
	Power	Energy	Response Time	Cycle Life	Energy Density
PbA - Conventional	7	7	4	1	4
PbA - Advanced	7	7	4	4	4
NaS	10	7	4	7	10
Li ion	7	4	7	7	10
Flow Battery	10	10	7	7	4
Flywheel	10	1	10	10	1
Ultracapacitor	10	1	10	10	1



Source: Electricity Storage Association

FIGURE 6 Power and Energy Characteristics of WESS Technologies

TABLE 4 Commercialization Status and Vendors of WESS Technologies

Technology	Status	Primary Vendors
Lead Acid (Conventional and Advanced)	Commercial & Demonstration	• East Penn Manufacturing • Exide Technologies • EnerSys • Xtreme Power • Axion Power
Sodium Sulfur	Commercial	• NGK Insulators Ltd.
Lithium ion	Demonstration & Commercial	• A123 • Saft Battery • Altair Nanotechnologies • International Battery • Electrovaya • Dow Kokam • Mitsubishi Heavy Industries
Vanadium Redox	Demonstration & Commercial	• Prudent Energy
Zinc Bromide	Demonstration & Commercial	• ZBB • Premium Power • RedFlow
Flywheel	Demonstration & Commercial	• Beacon Power • Kinetic Traction Systems • Vycon • Piller • Active Power • Temporal Power
Ultracapacitor	Demonstration & Commercial	• Maxwell • Siemens

TABLE 5 WESS Cost Trends

Technology	Cost[1] ($/kW)	Future Cost Trends
Lead Acid	2000-4600	Conventional PbA batteries are a well established technology and the capital cost is already significantly lower than other battery types. However, advanced PbA batteries are under development to improve cycle life. The cost of the advanced lead acid technology is expected to decline slightly with broader commercialization.
Sodium Sulfur	3200-4000	The cost of a sodium sulfur system was estimated at $2600/kW installed in 2007. [20] Today, the estimate has increased due to high demand. However, increased manufacturing capacity and competition should reduce costs.
Lithium Ion	1800-4100	Industry stakeholders expect to see a 30-50% cost decline over the next five years as the market for lithium ion batteries in electric vehicles increases.
Vanadium Redox	3000-3310	Flow batteries are uniquely very easy to scale up in both power and energy, and thus draw significant development interest. Cost will likely decline with commercialization of new designs.
Zn/Br Flow	1670-2015	Flow batteries are uniquely very easy to scale up in both power and energy, and thus draw significant development interest. Cost will likely decline with commercialization of new designs.
Flywheel	1000-2200	Industry stakeholders expect a decline ~ 40-50% with economies of scale.
Ultra-capacitors	300-450	Ultracapacitors with the power and energy required for transit applications are unlikely to see a significant reduction in capital cost in the near-term.

[1] Capital Cost estimates for batteries and flow batteries are from EPRI December 2010. Flywheel costs estimates from EPRI December 2010 and conversations with industry stakeholders. Ultracapacitors from EPRI September 2008. [23]

3.4 Benefits

In this framework, benefits provided by WESS are categorized as Economic, Reliability, or Environmental. As shown in TABLE 6, these three benefit categories include 8 subcategories and 21 individual benefits. TABLE 7 shows which applications provide each of the potential benefits. The model monetized only the transit agency benefits which are highlighted in TABLE 7.

TABLE 6 List of Benefits

Benefit Category	Benefit Sub-category	Benefit
Economic	Market Revenue	▪ Arbitrage Revenue ▪ Capacity Market Revenue ▪ Ancillary Services Revenue ▪ Reduced Energy Cost
	Power System	▪ Reduced Peak Demand ▪ Reduced Peak Losses ▪ Reduced Reserve Margin Requirement ▪ Reduced Congestion Costs ▪ Reduced Ancillary Service Costs ▪ Improved System Performance
	T&D Capital	▪ Deferred Transmission Investments ▪ Deferred Distribution Investments
	T&D O&M	▪ Reduced Distribution O&M Cost ▪ Reduced Energy Cost
	Energy Efficiency	▪ Reduced Electricity Losses
Reliability	Power Interruptions	▪ Reduced Sustained Outages ▪ Reduced Major Outages
	Power Quality	▪ Reduced Momentary Outages ▪ Reduced Sags and Swells
Environmental	Emissions	▪ Reduced CO_2 Emissions ▪ Reduced Pollutant Emissions (e.g., SO_X, NO_X, PM-2.5)

TABLE 7 Applications and Benefits Matrix

Benefits			WESS Applications								
			Primary						Secondary		
			Time-Based Rate Management	Demand Charge Management	Regenerative Braking	Renewable Energy Optimization	Voltage/VAR Control & Phase Balancing	Backup Power	Peak Demand Reduction	Renewable Energy Integration	Ancillary Services
Economic	Market Revenue	Arbitrage Revenue							✓		
		Capacity Revenue							✓		
		Ancillary Service Revenue									✓
	Improved Asset Utilization	Optimized Generator Operation	✓	✓		✓			✓		
		Deferred Generator Capacity Investments	✓	✓		✓			✓		
		Deferred Ancillary Services Cost									✓
		Reduced Volt/VAR Support Cost					✓				
		Reduced Congestion Cost	✓	✓		✓			✓		
	T&D Capital Savings	Deferred Transmission Capacity Investments	✓	✓					✓		
		Deferred Distribution Capacity Investments	✓	✓		✓			✓		
		Reduced Equipment Failures					✓		✓		
	T&D O&M Savings	Reduced Distribution Equipment Maintence Cost		✓			✓		✓		
		Reduced Distribution Operations Cost									
	Energy Efficiency	Reduced Electricity Losses	✓	✓	✓	✓	✓		✓		
	Electricty Cost Savings	Reduced Electricity Cost	✓	✓	✓	✓	✓		✓		
	Revenue	Customer Revenue							✓	✓	✓
Reliability	Power Interruptions	Reduced Sustained Outages						✓			
		Reduced Major Outages						✓			
	Power Quality	Reduced Momentary Outages					✓	✓			
		Reduced Sags and Swells					✓				
Env.	Air Emissions	Reduced/Avoided CO2 Emissions	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Reduced SOx, NOx, and PM-10 Emissions	✓	✓	✓	✓	✓	✓	✓	✓	✓

3.4 Costs

The total estimated cost for each application and corresponding technology are based on two major components: 1) technology specific assumptions (e.g., capital cost, operations and maintenance (O&M) cost, cycle life) and 2) general financial assumptions (e.g., weighted cost of capital, discount rate). These assumptions are based on research, expert panel input, and Navigant estimates described in Section 4.0.

3.5 Value

The total value of the storage for an application can be calculated for a single calendar year based on assumptions such as the utility rate schedule, device technical constraints and transit system characteristics. After identifying and quantifying the costs and benefits, a cash flow and corresponding net present value (NPV) of the initial investment can be calculated. The benefits over the 15 year NPV analysis are assumed to remain constant. In addition, the non-capital costs are held constant such as debt service payments and O&M.

3.6 Combined Applications

Individual applications may not result in a positive business case. Therefore, where technically possible, applications can be combined to determine if they provide simultaneous benefit streams.

4.0 SIMULATIONS

A number of hypothetical simulations were modeled to quantify the value of WESS for a transit agency. Each simulation used the same standard assumptions which served as a "baseline" including:

1. Load Profile – A double peak profile for the morning and afternoon commute periods was developed.
2. Utility Rate Structure - A simplified utility rate structure included on-peak rates, off-peak rates, and a demand charge. These rates varied across two seasons. The summer season was defined as June 1st – September 31st and peak period was defined as 8:00 am – 8:00 pm during weekdays. Weekends used only off-peak rates.
3. Train Schedule
4. Transit System Characteristics
5. WESS Location - The baseline scenario assumed that the WESS serves a single train station or sub-station on the transit agency's side of the meter.
6. WESS Technology

The values modeled for each of these topics are presented in the FIGURE 7, FIGURE 8, and Tables 8 through 13.

The Analytica® modeling platform was used to build a fully customized technical and financial WESS simulation model from scratch. The simulation tool was designed to use annual 15-min profile data to accurately simulate storage technology performance on an annual basis. However, WESS technology specific performance parameters such as control system and data acquisition response times, physical/environmental factors such as temperature and power system constraints such as voltage limits were not considered. In addition, typical field installed WESS devices use a combination of near real-time sensing of local transit system electrical characteristics and additional external inputs such as weather and historical data to provide day-ahead, 1 hour ahead and minute-to-minute storage demand forecasts. Depending on the application, day-ahead forecasting can be particularly important to provide sufficient overnight charge for the coming day while optimizing for maximum benefits. Control algorithms and operational optimization continues to be a challenge even with today's cutting edge systems. Given the complexity of these algorithms, we made no attempt to replicate their capability. Instead we used a simplified storage device charging optimization method that perfectly follows load changes regardless of application based on the 15-min interval input load data. This simplification means that our performance results are likely the highest level of performance that could be expected with an actual field installed WESS unit.

The model optimizes the size of the device to be proportional to storage opportunities. This assumes that the device will be custom built to fit this application. However, it is likely that transit agencies will generally buy off-the-shelf storage devices that come in discrete unit sizes, and so this proportional scaling will not exactly occur.

FIGURE 7 Load Profile without WESS

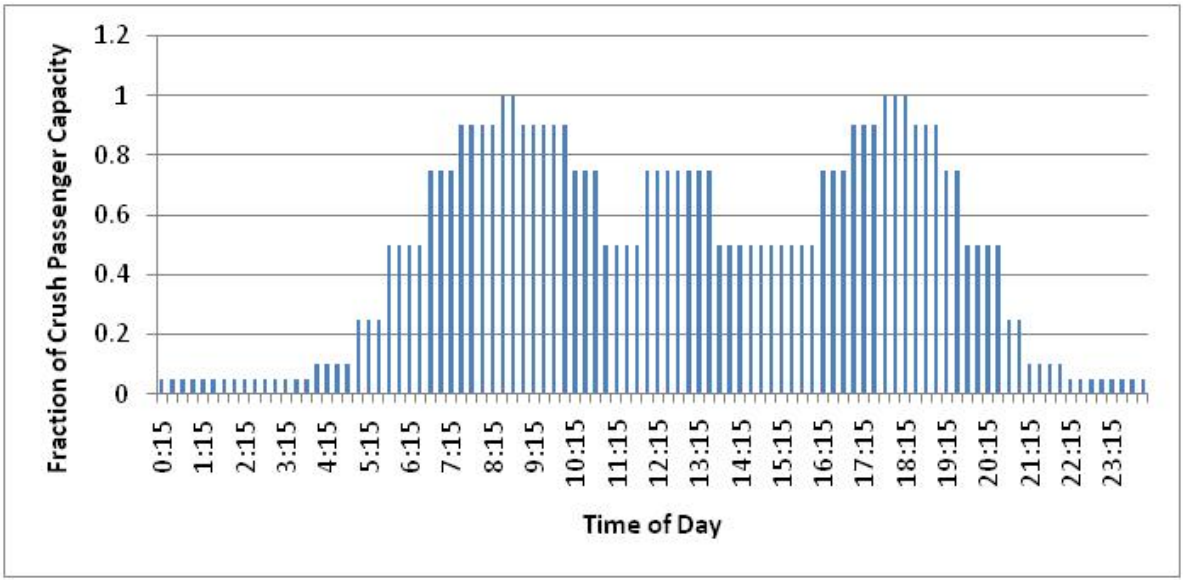


FIGURE 8 Estimated Passenger Load Curve

TABLE 8 Load Profile Characteristics

Load Profile Characteristics	Nominal Assumption
Time Between Peaks	9 hours
Peak Full Width Half Max	7 hours
Peak Load	425 kW
Peak Period Shapes	Morning = Evening
Minimum Load	50 kW
Mid Day Min Load	275 kW

TABLE 9 Electricity Rate Schedule

Charge	Summer	Winter
Energy off-peak	$0.05/kWh	$0.03/kWh
Energy on-peak	$0.07/kWh	$0.05/kWh
Demand charge	$8.00/kW	$5.00/kW

TABLE 10 Train Schedule

Parameter	Daily Average
Scheduled Daily Stops	400
Stops occurring within 30 seconds of another train (Stop Overlap)	15%

TABLE 11 Transit System Characteristics

Parameter	Standard Assumption	Units
Cars Per Train	2	cars/train
Car Weight	40,000	kilograms
"Crush" Passenger Capacity	180	passengers/car
Passenger Weight	81.5[2]	kilograms/passenger
Train Approach Speed	35	miles/hour
On-site renewable generation	3000[3]	kWh/day
Net metering with Storage[4]	Retail Rate	-

TABLE 12 Standard WESS Assumptions

Parameter	Lead Acid	Sodium Sulfur	Lithium Ion	Zn/Br Flow	Flywheel	Ultra-capacitor
Power Capacity Cost, $/kW	2000	3600	1800	1670	1000	300
Energy Capacity Cost, $/kWh	515	505	484	767	4000	25000
O&M Cost, $/year-kW [5]	30	36	18	25	10	3
Max Lifetime Cycles	4500	7500	7500	10000	150000	10000
Parasitic Load, kW	2	2	2	2	5	1
Roundtrip Efficiency, %	87.5	76	89.5	65	95	95

References:For batteries and flow batteries: Capacity Costs, Max Cycles, Roundtrip Efficiency: EPRI [19]; O&M Costs:Based on formula in EPRI [14]; Parasitic Load: Sandia [20]; For flywheels: Capacity Costs, Maximum Cycles: Navigant; O&M Costs: Based on EPRI [14]; Parasitic Load: Sandia [20]: For Ultracapacitors: O&M Costs: Based on EPRI [14]; All Other: Sandia [20]

[2] Center for Disease Control US adult average, assuming 50% female and 50% male
[3] Approximate generation from a 1000 kW_{DC} PV solar array
[4] Net metering regulation for storage is a heavily debated issue. For simplicity, it will be assumed that the power dispatched from the device can be sold at the current rate not the rate seen during charging.
[5] Annual O&M Costs are based on Power Capacity Costs, using the EPRI formula [14]

TABLE 13 Standard WESS Financial Parameters

Parameter	Units	Simulation Value	Definition
Energy Module Cost Per Replacement	%	50%	The cost of replacing the core storage modules of the storage device, as a percent of initial capital cost.
Loan Interest Rate	%	3.387%	The rate of interest on loans taken to purchase the storage device.
Percentage of System Cost Covered by Cash	%	40%	The percent of initial capital costs which the transit agency covers in cash, rather than by taking loans.

4.1 Simulation #1: Time-Based Rate Management and Demand Charge Management

For this simulation, the WESS energy capacity (shown in TABLE 14), a hypothetical utility rate structure (shown in TABLE 15) and load profile were varied while maintaining nominal assumptions for the train schedule, equipment and the WESS location and storage technology. The annual cost of electricity was simulated for both the base case (without storage) and with storage to calculate the NPV of a WESS investment for the time-based rate management and demand charge management applications together to achieve the electricity cost management objective. The combined electricity cost management application is intended to maximize the reduction in demand charges and costs due to time-based energy rates by leveling the overall substation load.

The simulation was designed to illustrate the impact that the utility rate structure, WESS sizing (i.e. storage capacity) criteria, and load profile variations have on WESS NPV. Given that actual utility rate structures are highly variable across transit authorities, the rate structures selected were meant to cover a wide range of rates that might actually be experienced. The system sizing criteria are defined as follows:

- Average Daily Max – This setting finds the maximum 15-min load for each day of a month, then finds the average max for each month, then finds the average across all months which normally results in the smallest system energy capacity.
- Annual Absolute Max - This setting finds the maximum 15-min load from the entire year which results in the largest system energy capacity.
- Avg. Monthly Max - This setting finds the maximum 15-min load for each day of a month, then finds the max daily 15 min interval for each month, then finds the average across all months which results in the medium system energy capacity.

TABLE 14 WESS Sizing Scenarios

Load Profile	Standard	Case 1	Case 2
Rated Energy Storage	Average Daily Max	Annual Absolute Max	Average Monthly Max

TABLE 15 Utility Rate Structure

Charge	Nominal Assumptions		High-Low	High-Low
	Summer	Winter	Summer	Winter
Energy off-peak	$0.05/kWh	$0.03/kWh	$0.03-0.05/kWh	$0.03-0.02/kWh
Energy on-peak	$0.07/kWh	$0.05/kWh	$0.10-0.08/kWh	$0.05-0.04/kWh
Energy critical-peak	-	-	$0.25-0.15/kWh	-
Demand charge	$8.00/kW	$5.00/kW	$10.00-5.00/kW	$5.00-3.00/kW

Before discussing the simulation results, it is important to understand the impact that the electricity cost management application has on a substation energy profile. FIGURE 9 shows the standard energy load profile for the substation without WESS. FIGURE 10 shows the average daily profile of energy stored in the WESS. Comparing FIGURE 9 to FIGURE 10, you can observe that due to the large drop-off in substation load from 0:15 to 6:15 AM, the WESS switches to a charge mode, increasing the amount of stored energy. As system load begins to rapidly increase after 6:15 AM, the WESS device begins to rapidly discharge the stored energy to lower the substation peak during the morning commute. Then, during the mid-day drop-off in load, the WESS begins to charge to prepare for the evening commute load. During the evening commute load, the WESS discharges completely down to its baseline level.

FIGURE 9 Load Profile Without WESS

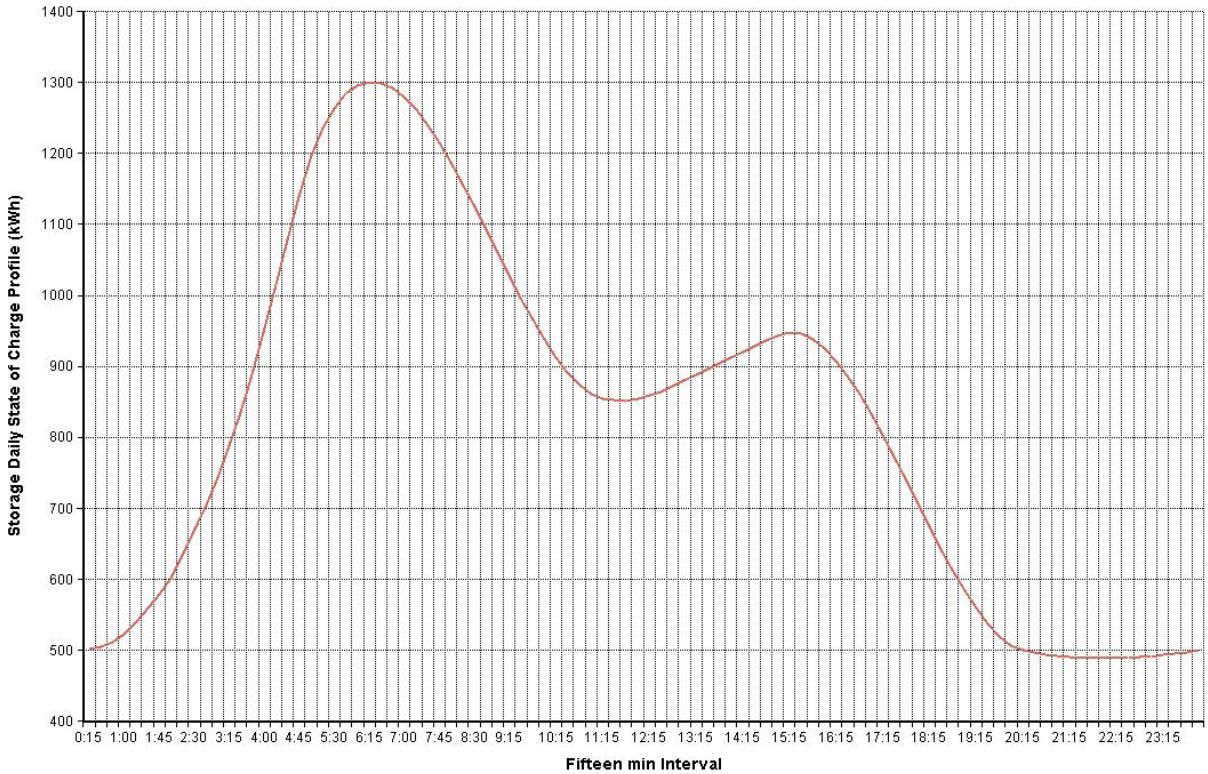


FIGURE 10 Daily State of Charge for WESS Device for Electricity Cost Management

As shown in FIGURE 11, the sizing assumption used to set the WESS capacity has a large impact on the overall NPV. The worst NPV corresponds to the scenario where the WESS capacity is sized to meet the absolute annual max. The NPV improves when the system is sized for the average monthly maximum load and achieves the best NPV (least negative) when the WESS is sized using the average daily max requirement. After seeing this result, we used the average daily max requirement sizing assumption for all additional simulations. While under-sizing the systems means that some of possible electricity cost management benefits are missed, the overall cost of the system is lowered resulting in an improved NPV.

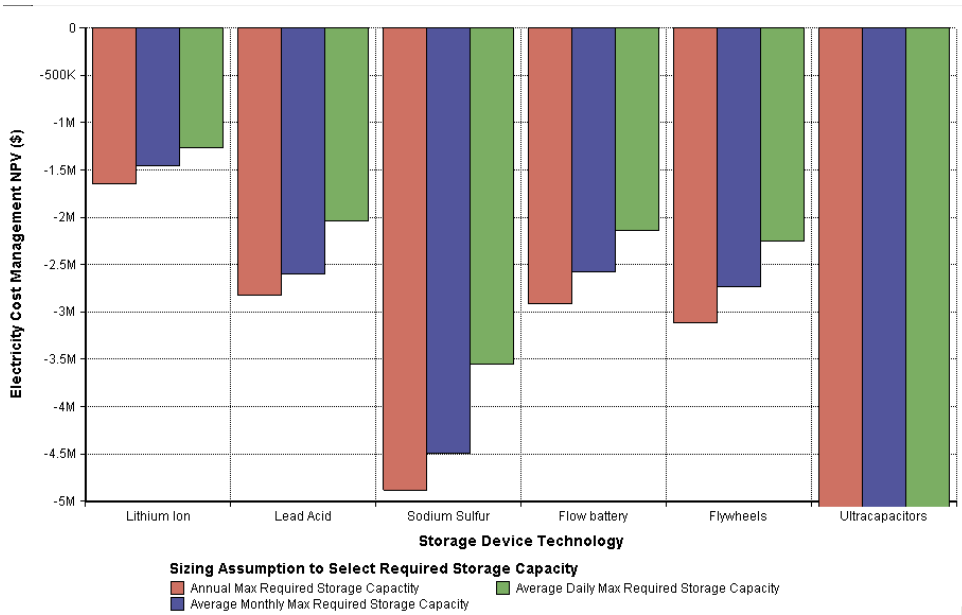


FIGURE 11 Electricity Cost Management NPV by Sizing Assumption and Technology

As one would expect, FIGURE 12 illustrates that the best NPV occurs when the highest energy and demand rate profile is selected. However, an unexpected result was the relatively low sensitivity of this assumption on the NPV. More than doubling (increase of 100%) the rate from the "low" scenario to the "high" only improves the NPV by 10-15%. As previously mentioned, we used the average daily max requirement sizing assumption for this simulation.

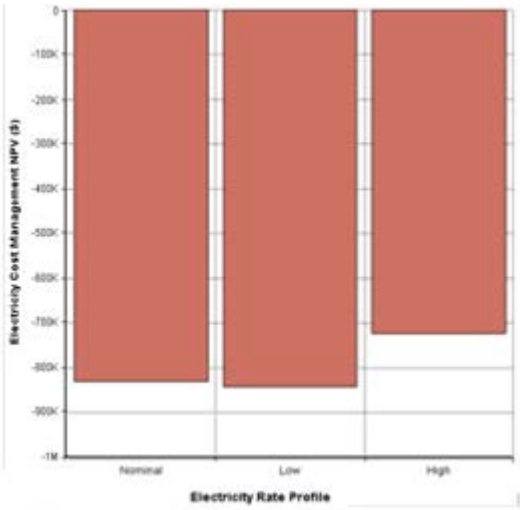


FIGURE 12 Electricity Cost Management NPV by Rate Profile

A detailed sensitivity analysis was conducted to further identify the most sensitive inputs. FIGURE 13 shows that WESS cost is far more important than other parameters such as electric rates when considering WESS investment. This suggests that in order for the NPV to improve most rapidly, the WESS cost must come down from today's levels to make WESS cost effective.

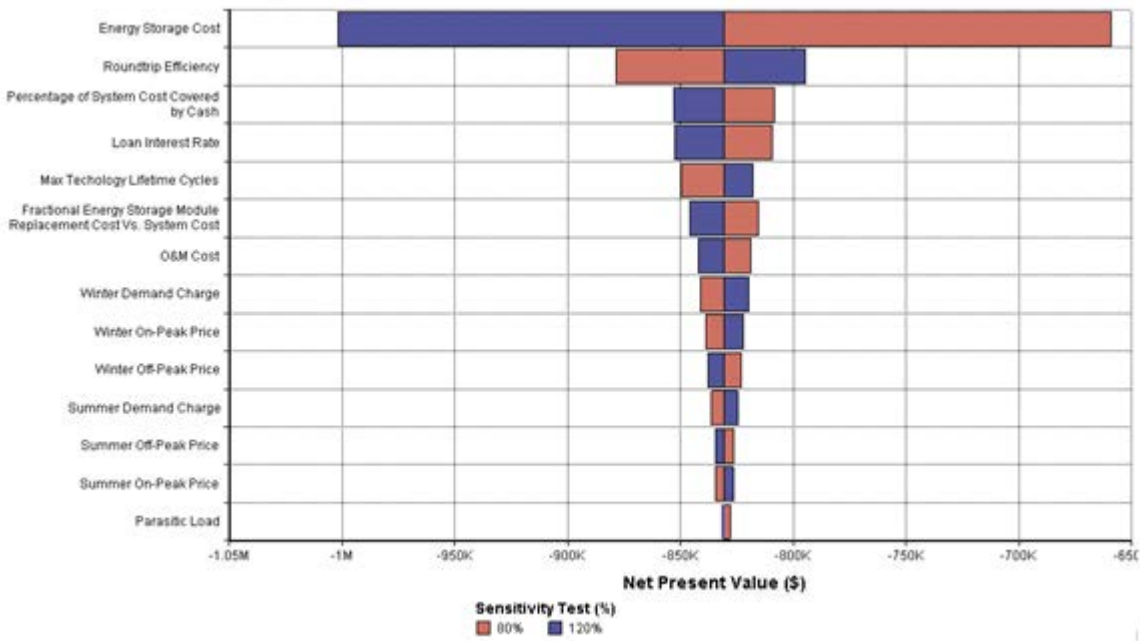


FIGURE 13 Electricity Cost Management Sensitivity Analysis for Lithium Ion WESS

TABLE 16 presents the low, standard, and high time difference between peaks used to vary the load profile. FIGURE 14 shows the resulting three load profiles while the results in FIGURE 15 demonstrate that as the time between peaks increases, electricity cost management becomes more effective.

TABLE 16 Characteristics of Load Profiles to be Modeled

Load Profile Characteristics	Standard	High	Low
Time Between Peaks	9 hours	11 hours	7 hours

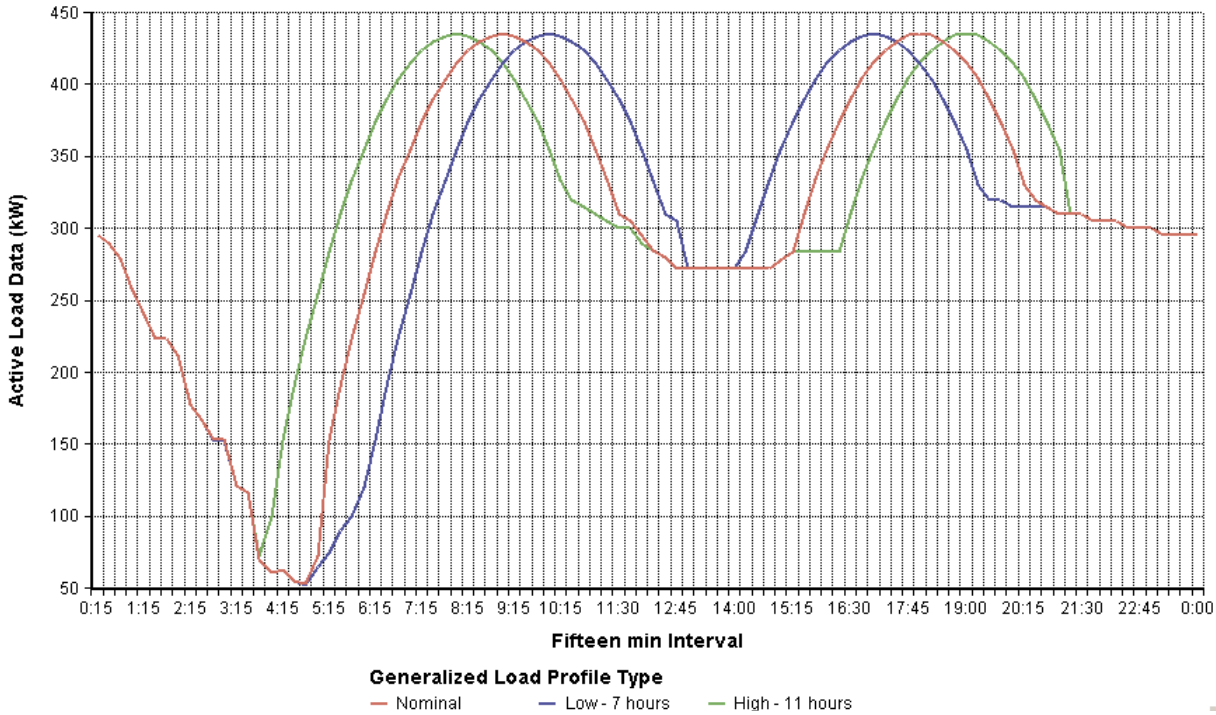


FIGURE 14 Electricity Cost Management Load Profiles

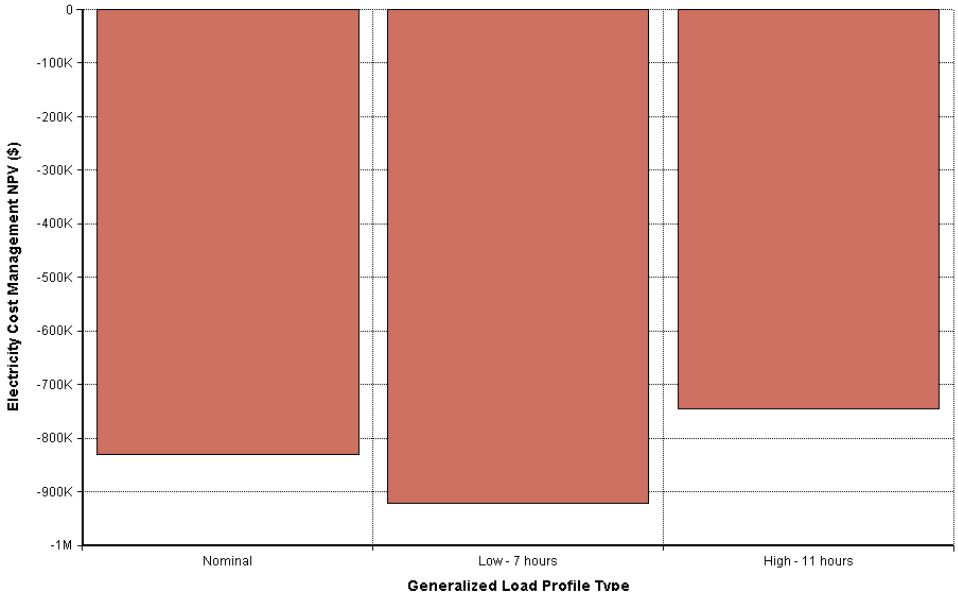


FIGURE 15 Electricity Cost Management NPV for Each Load Profile

The overall electricity cost management NPV results are shown in FIGURE 16 and TABLE 17. Flywheels and ultracapacitors were excluded from this analysis since they did not meet the technical specifications for hour-scale energy storage. The standard assumptions described in Section 4.0 were used to generate these results. Overall, lithium ion based WESS device has the best NPV.

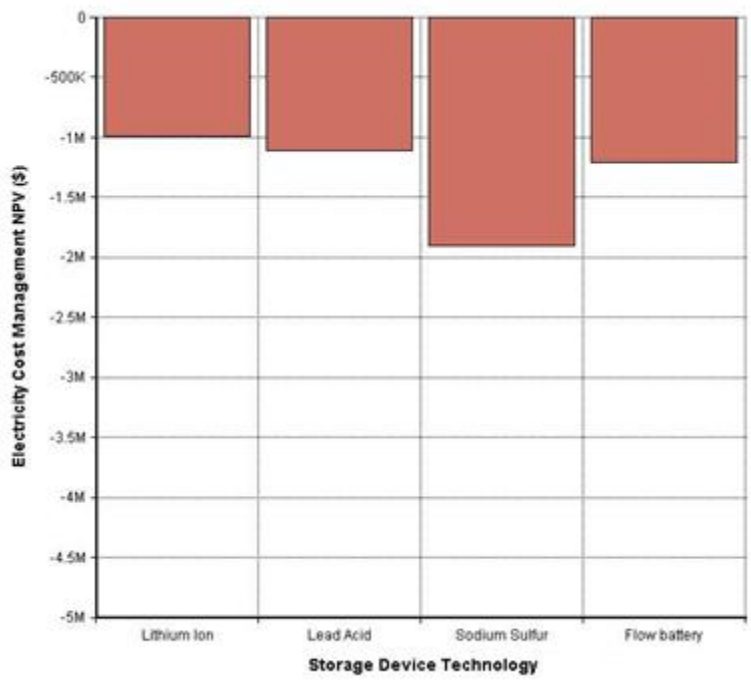


FIGURE 16 Electricity Cost Management NPV by Technology

TABLE 17 Electricity Cost Management NPV by Technology

Technology	NPV
Lithium Ion	-$991,340
Lead Acid	-$1,107,269
Sodium Sulfur	-$1,900,776
Flow battery	-$1,209,127

4.2 Simulation #2: Regenerative Braking

For this simulation, the train schedule and system equipment were modeled as shown in TABLES 18 and 19 while maintaining standard assumptions for the rate structure, train schedule/equipment and the WESS location and storage technology. The annual electricity use was simulated for both the base case (without storage) and with storage to calculate the benefit of regenerative braking via WESS.

TABLE 18 Technology-Specific Parameters for Regenerative Braking Sensitivity Analysis

Sensitivity Test Inputs	Units	Li Ion	Lead Acid	Flow battery	Flywheel	Ultra-capacitor
Roundtrip Efficiency	%	90%	88%	65%	95%	95%
Power Capacity Cost	$/kW	1800	2000	1670	1000	300
Max Technology Lifetime Cycles	cycles	7,500	4,500	10,000	150,000	10,000
O&M Cost	$/kW-year	18	30	25	2.5	3

TABLE 19 Transit System Parameters for Regenerative Braking Sensitivity Analysis

Sensitivity Test Inputs	Units	Simulation Value	Definition
Train Velocity On Approach	m/s	15.65	The velocity of the train when it begins braking, on approach to a station.
Line Receptivity	%	80%	The amount of energy which the overhead line can accept from braking trains.
Wheel to Line Regen Efficiency	%	80%	The portion of physical braking energy which the train captures as electricity.
Daily Storage Opportunities	opps/day	400	Number of storage opportunities provided by braking trains in each day.
Total Train and Passenger Weight	kg	91,896	The total weight of the train, with passengers on board.
System Size Reduction	%	65%	The total WESS size is adjusted to store this portion of total peak braking energy, assuming the remaining energy can be used directly on the line.
Length of Stopping Event	s	20	The length of time between the start of braking and complete stop at a station.

When train arrivals/departures are synchronous, generation (from dynamic braking) from one train may be transferred to a train that is simultaneously leaving the station, avoiding the need for direct storage. Therefore, WESS regenerative braking opportunities occur only when trains arrive and leave a station asynchronously. The maximum theoretical regenerative braking opportunity (assuming no wind resistance and other losses) is governed by the available kinetic energy in a moving train which is defined as:

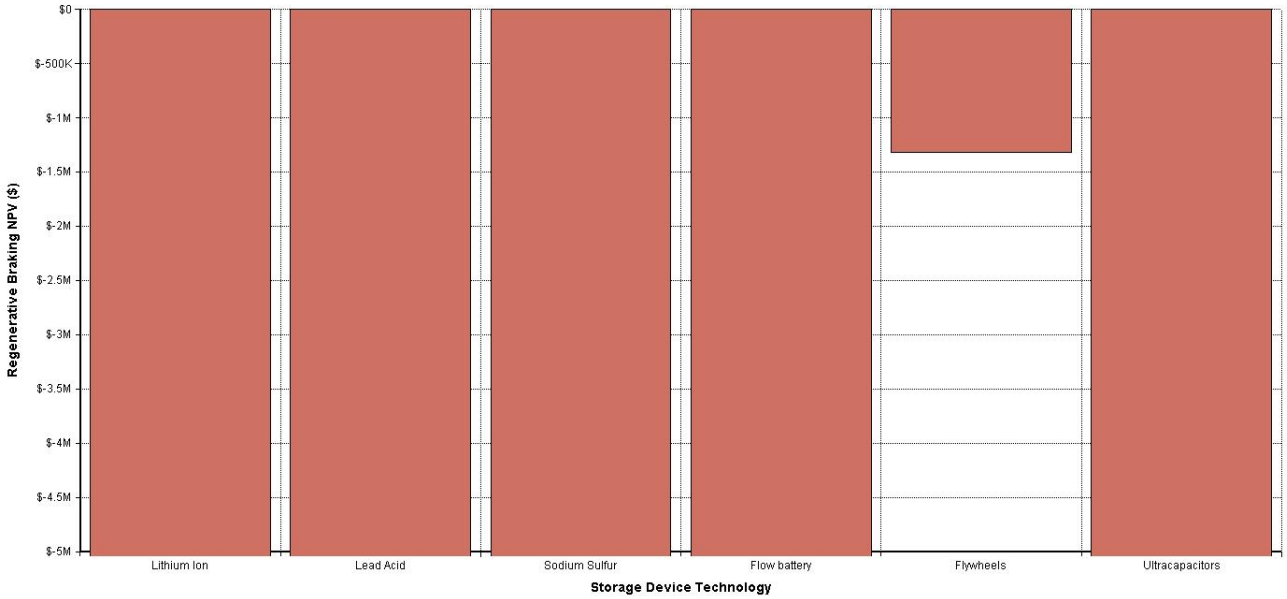


FIGURE 17 Regenerative Braking NPV by Technology

TABLE 20 Regenerative Braking NPV by Technology

Technology	NPV
Flywheels	-$1,317,000
Ultracapacitors	-$5,055,000
Flow battery	-$19,750,000
Lithium Ion	-$38,560,000
Sodium Sulfur	-$65,550,000
Lead Acid	-$69,620,000

One might expect the sensitivity analysis for regenerative braking to show that the most sensitive parameter is the approach train velocity followed by the total mass. However, these are only a few of the technical assumptions that can impact the NPV analysis. There are also many financial assumptions that impact the NPV. The results of the sensitivity analysis for the flywheels are shown in FIGURE 18 below. As expected, the train velocity is the most critical variable followed by the wheel to line regenerative efficiency, the total car and passenger weight, and the system size reduction assumption. This is because each parameter is directly proportional to the kinetic energy. Wheel to line regenerative efficiency represents the mechanical and electrical losses that occur as the kinetic energy of the moving train is transferred from the car drive train, motors, and power conditioning devices to the overhead catenary. This is meant to represent the conversion losses that occur before the regenerative electricity enters the WESS device. The capital cost based on power also impacts the NPV.

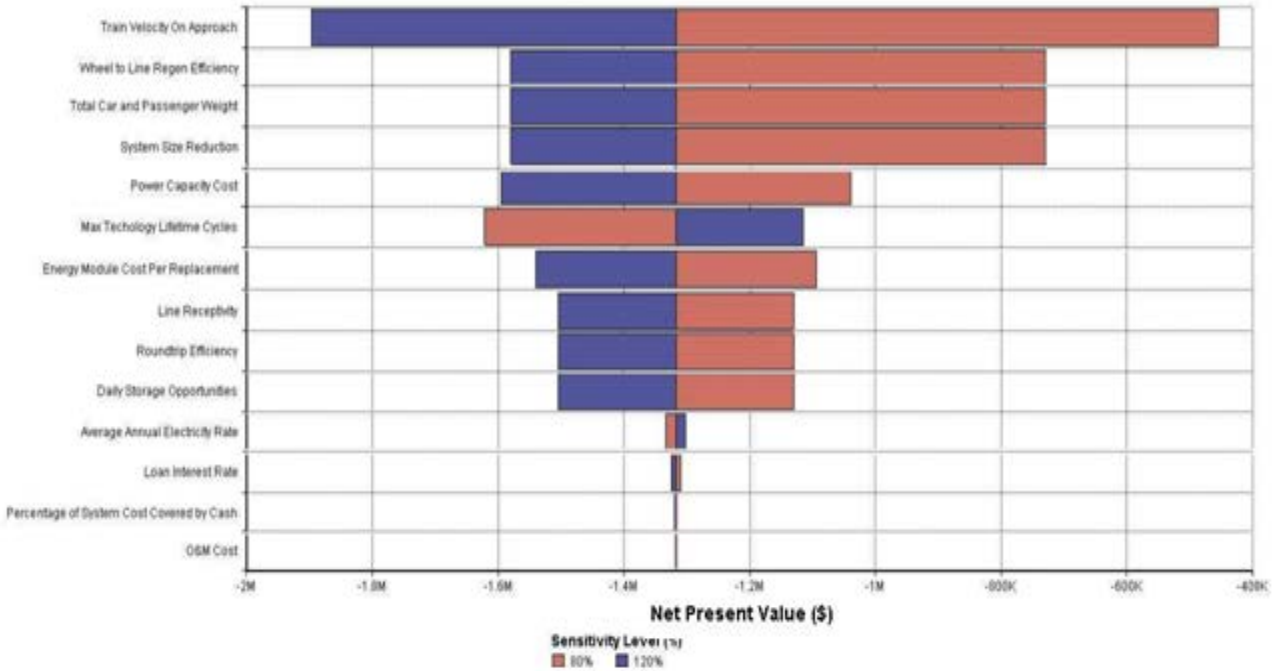


FIGURE 18 Regenerative Braking Sensitivity Analysis for Flywheel WESS

4.3 Simulation #3: Renewable Energy Optimization

For this simulation, the utility rate structure was varied with both a WESS device and 1 MW solar array connected in close proximity to the traction power substation (TPSS). The annual cost of electricity was simulated for both the base case (without storage) and with storage to calculate the overall increase in electricity costs. We assumed that the array is connected directly to the transit system DC line close to the tracking power substation. This had the added benefit of eliminating solar inverter losses normally incurred when converting from DC to alternating current (AC) for traditional net metering. A solar load profile for a 1MW array was simulated with the National Renewable Energy Laboratory's (NREL) System Advisory Model (SAM) using weather data from the population weighted geographic center of the US. Ten–year average, 30 min interval weather data (solar radiation, temperature, cloud cover etc) was used to produce a solar generation profile for every 30 min interval of a single calendar year. The final average annual profile is shown in FIGURE 19.

We used a simulated rate schedule (TABLE 15) to determine the NPV for electricity cost management application, combined with a solar array, using various types of WESS unit. The results are shown in FIGURE 20 below. When the transit agency has a solar array, the WESS unit operates with one cycle per day, rather than two cycles when there is no solar array. This is due to the high availability of solar energy during the morning peak, which results in the WESS unit being used only for the evening peak load. Lead acid batteries perform better than lithium ion batteries in this simulation, a change from the electricity cost management application without solar. Lead acid batteries have a shorter cycle lifetime than lithium ion devices but lower capital costs. Therefore, since the number of cycles required is approximately half of what was required in the electricity cost management simulation, lead acid batteries look more attractive.

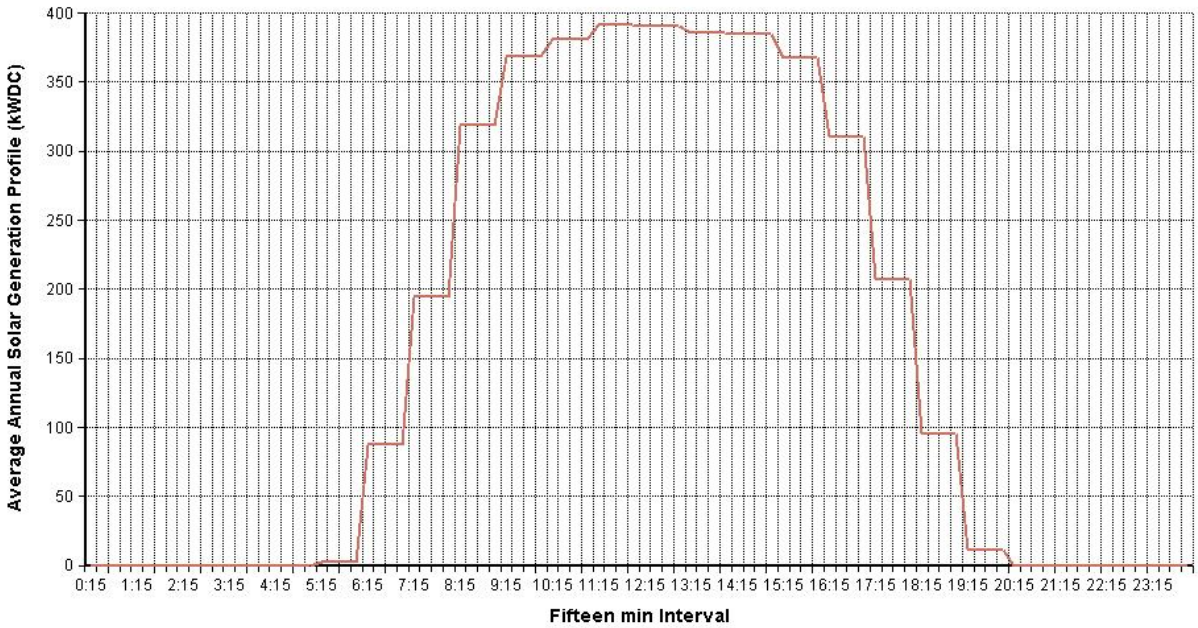


FIGURE 19 Annual Average Daily Solar Profile

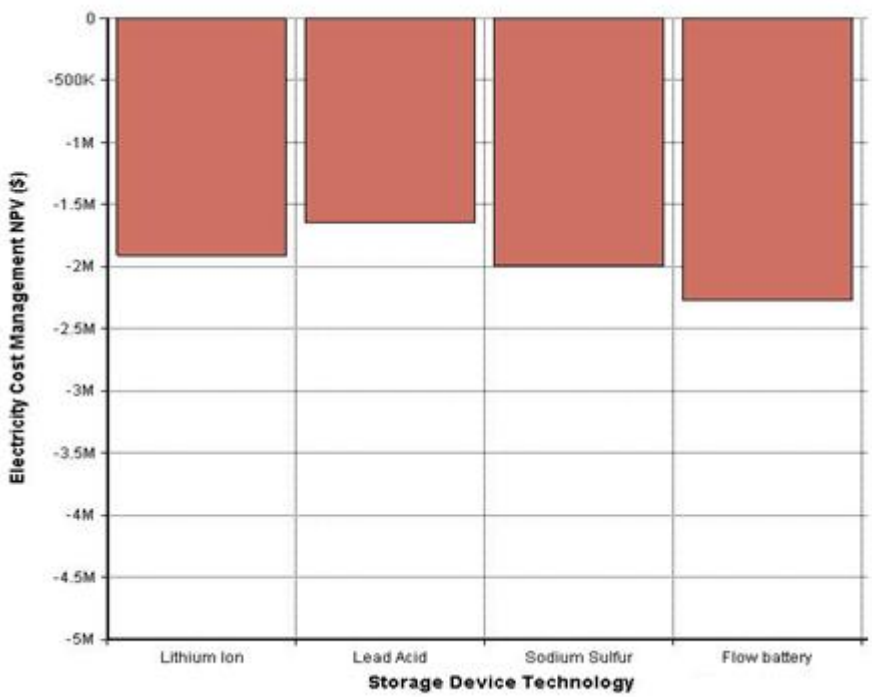


FIGURE 20 Renewable Energy Optimization NPV by Technology

For each utility rate structure, the addition of WESS reduces the annual cost of electricity with renewable energy. The storage allows the solar generation to be shifted to a time of the day when the rates are higher, reducing the overall annual cost for both demand and energy charges. The change is best illustrated by the difference between the daily storage profile with and without solar as shown in FIGURE 21 and FIGURE 22, respectively. The WESS delays charging until approximately 8:15AM, when the solar output begins to rapidly

increase. Then, the WESS begins to rapidly discharge due to the demand of the evening commute and the drop-off of the solar resource as the sun begins to set.

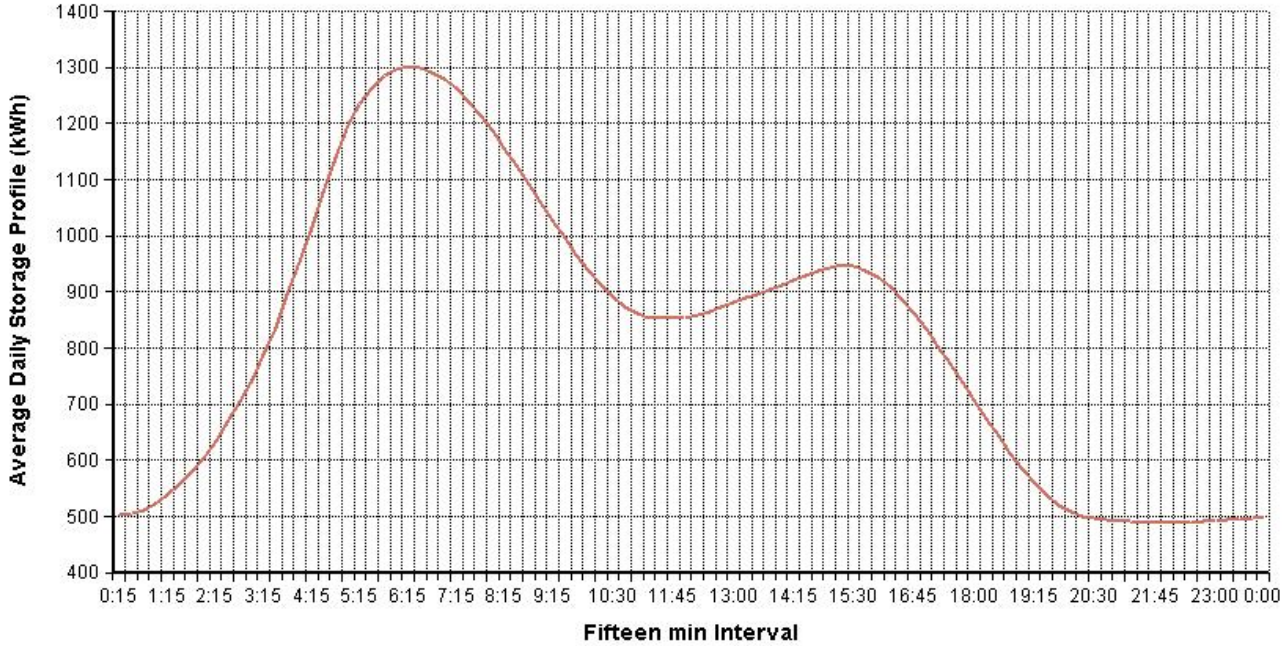


FIGURE 21 Nominal WESS Storage Profile without Solar Array

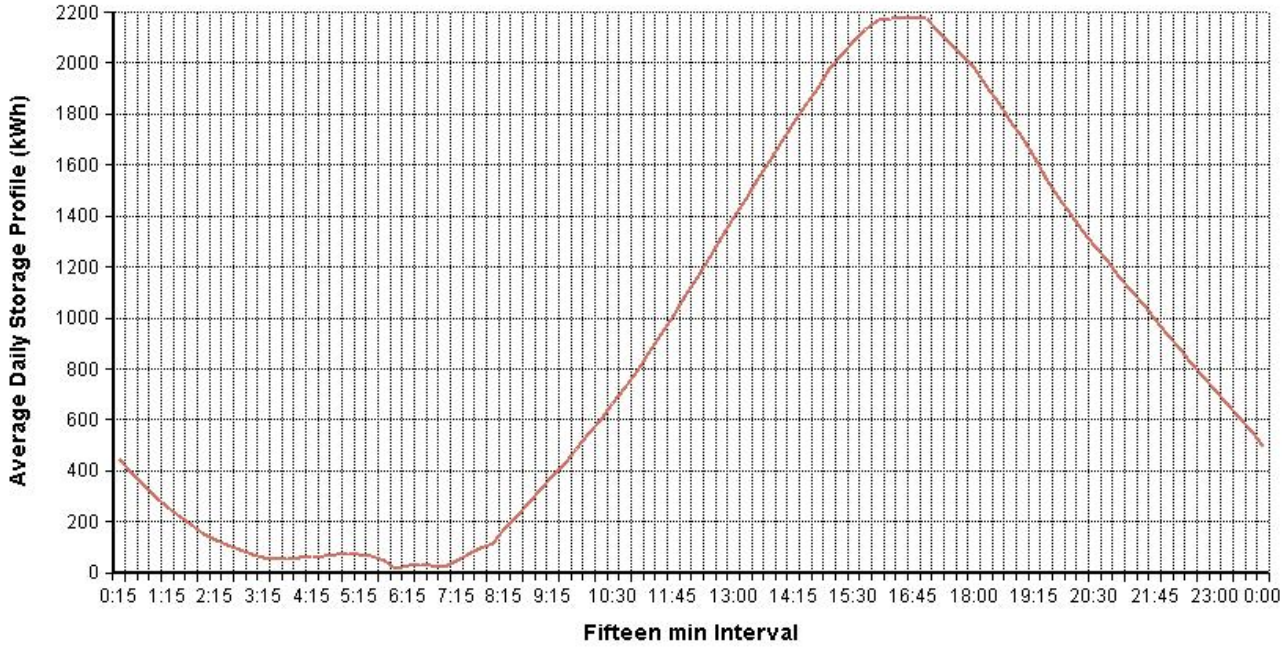


FIGURE 22 Nominal WESS Storage Profile with Solar Array

4.4 Simulation #4: Voltage Support

WESS can be used for local voltage support by injecting power into the system during low voltage events or absorbing power during high voltage excursions. Since most rail systems are DC, if instantaneous demand exceeds the available line power capacity, the voltage drop will be directly proportional to the extra demand. Voltage drop also increases linearly per unit distance from a supporting substation due to line losses. Therefore, there are two voltage support opportunities for WESS: 1) Areas of high load, such as a large hill or overpass, or a very busy station or 2) when a train is operating at a great distance from a substation. Transit systems typically include redundant or strategically placed substations to avoid low voltage conditions from ever occurring. If WESS was included in the planning process it may be possible to avoid or defer investment in costly substations. In order to calculate the value of this avoided investment, the cost of the replacement WESS device must be included. Since voltage support needs are normally very short duration events, the WESS would likely need high power but low storage capacity. The absolute power requirements are highly dependent on specific transit authority needs. The cost of a TPSS is also highly dependent on local construction issues, utility interconnection requirements, and available right-of-way. Given the variability of TPSS costs, we used a triangular probability distribution for the assumed cost of $800/kW, $1000/kW, and $1500/kW. This distribution resulted in the statistics shown in TABLE 21 below.

TABLE 21 TPSS Cost Statistics with Triangular Distribution

TPSS Cost Statistics	($/kW)
Minimum	982
Median	1285
Mean	1307
Max	1732
Standard Deviation	175

The same cost assumptions for each technology (capital, O&M, storage module replacement etc) were used to compare the 15 year NPV for a TPSS and for a WESS system. The results are shown in FIGURE 23 below. For all technologies, except ultracapacitors, a WESS installation is a better investment than a traditional TPSS based on our assumptions. Of all of the simulations discussed thus far, it appears that using WESS for voltage support application is a good investment.

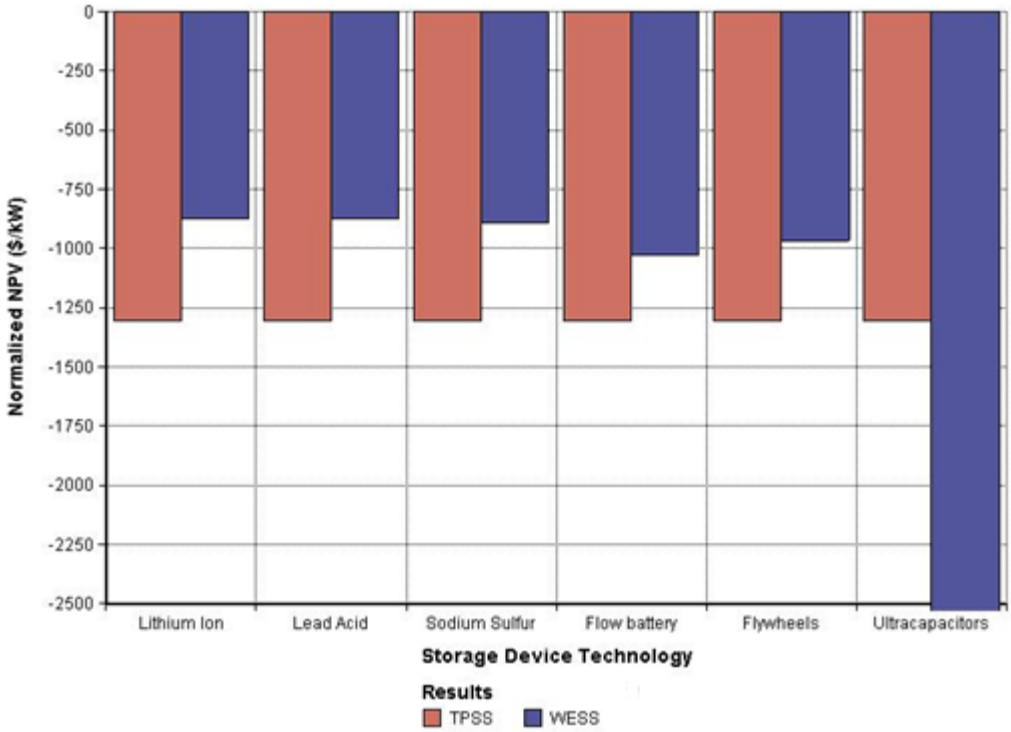


FIGURE 23 Voltage Support NPV Compared to TPSS

4.5 Simulation #5: Backup Power

For this simulation, the required WESS characteristics were varied (as shown in TABLE 22) while maintaining standard assumptions for the load profile, rate structure, train schedule, and storage technology. The focus was on avoided capacity investments and/or lower cost system design by eliminating or reducing the number of system substations that are normally built for backup purposes. Since the specific backup power requirements for a given transit are variable, we simulated both a low and a high scenario for the maximum required power.

TABLE 22 System Requirements for Backup Power

Variables	Low	High
Available WESS Capacity (kW)	25% of Substation	100%
Required Energy Storage (kWh)	1 hour at max Power	1 hour at max Power

In FIGURE 24 we show the normalized rated energy capacity versus the type of WESS technology. In order for a given technology to be technically capable of being used as backup power, the normalized rated energy capacity (or ratio of kWh to kW must exceed 1.00 for the high case and 0.25 for the 25% case. If only 25% (the low case) is required, then all technologies except Ultracapacitors would be technically suitable for backup power. However, in the high case where 1 hour of storage at 100% power is required, then only battery technologies have the proper technical characteristics to meet the requirement.

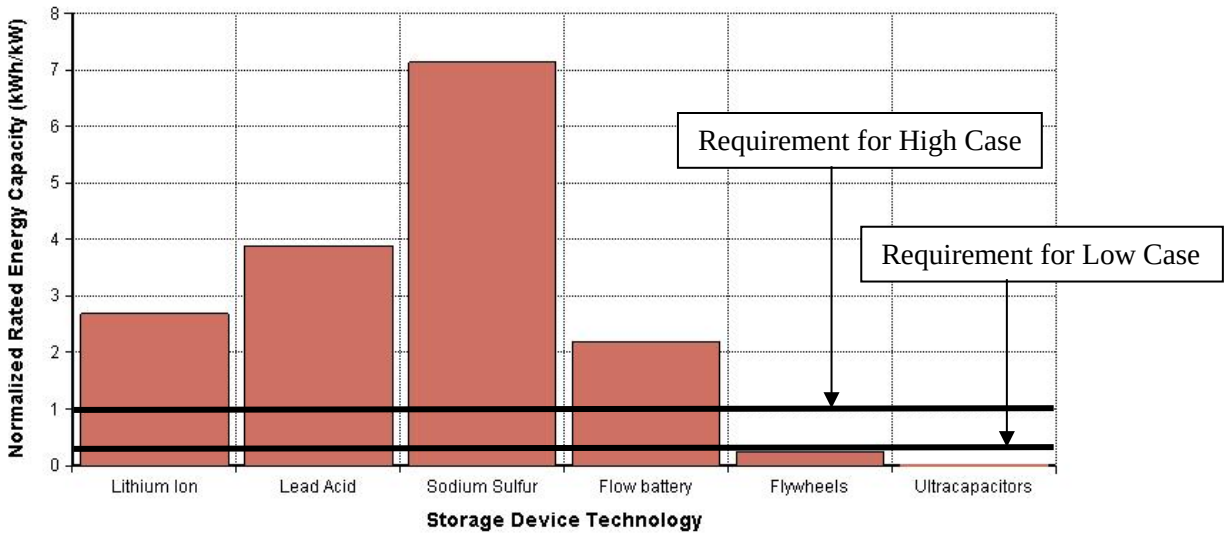


FIGURE 24 Normalized Rated Energy Capacity by Technology

After learning which technologies are technically capable of providing backup needs, we completed a similar analysis as was conducted for the voltage support application. Since traditional backup power is provided by TPSS, a WESS installation would allow a transit authority to avoid investment in a TPSS by using a WESS unit. Using the same TPSS cost assumptions as the previous section, the relative cost for each relevant technology is shown in FIGURE 25 below. The results suggest that using a lithium ion, lead acid, sodium sulfur or flow battery WESS for backup power would be more cost effective than installing a traditional TPSS for the same purpose.

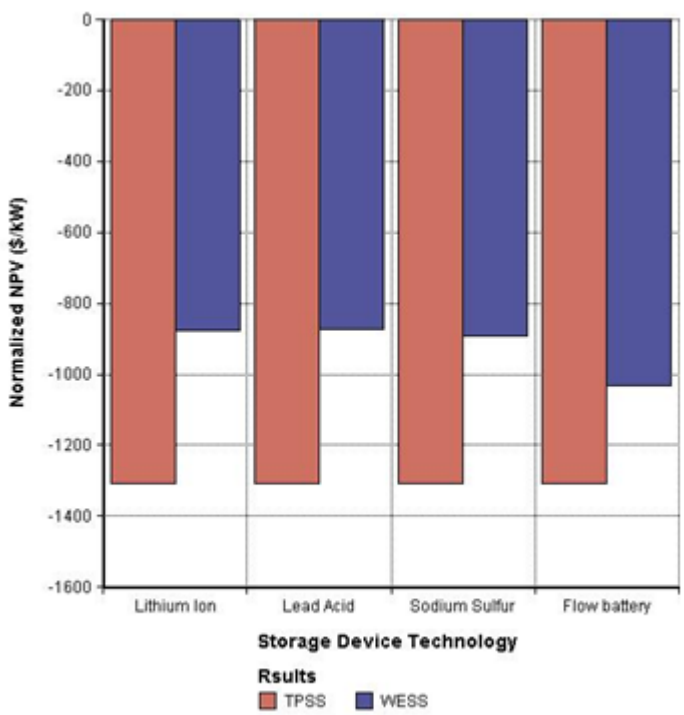


FIGURE 25 Backup Power NPV Compared to TPSS

4.6 Simulation #6: Backup Power, Time-Based Rate Management, and Demand Charge Management

Since the WESS requirements for electricity cost management and backup power are so similar (high energy storage capacity with low to moderate power needs), they are ideal candidates for a combination. By moderately oversizing the storage requirements to ensure that the necessary backup energy is available when needed, a device designed for electricity cost management can easily provide backup power. Since lithium ion showed the best NPV for electricity cost management, it was selected as a candidate for a combination with backup power. FIGURE 26 shows the results from the combination. With the benefits from backup power included, the resulting NPV is positive for a 15 year analysis with lithium ion.

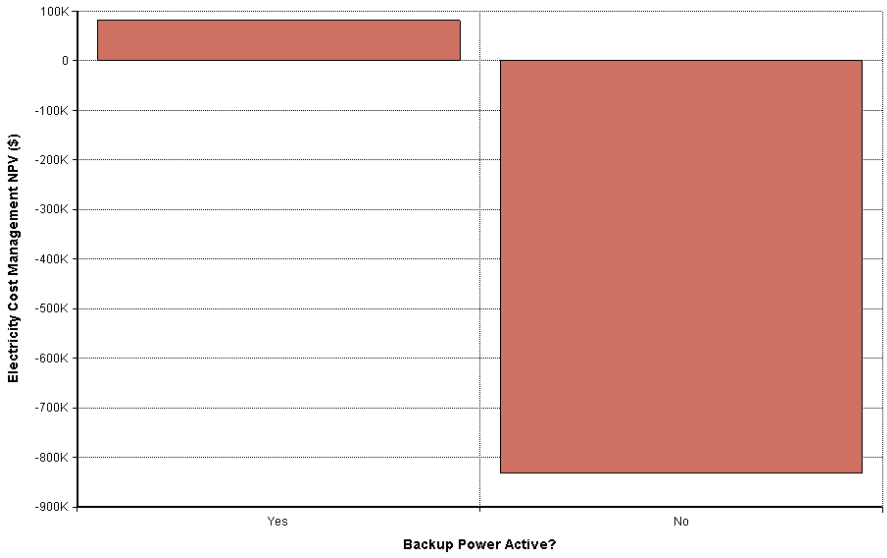


FIGURE 26 Backup Power and Electricity Cost Management NPV for Lithium Ion WESS

4.7 Simulation #7: Voltage Support and Regenerative Braking

Likewise, the device requirements for both regenerative braking and voltage support are very similar making them good candidates for combination. Voltage excursions (either above or below nominal voltage levels) occur when available power is mismatched with load. When load exceeds the local substation capability the voltage drops. Conversely, when load is far lower than available substation power, the voltage can spike. Regenerative braking inherently provides voltage support by absorbing energy when it is available and discharging rapidly when it is needed. If a particular site is known to have voltage support issues and a new substitution is being considered to correct the issue, a transit authority should carefully considered WESS instead of a traditional substation. WESS may be able to fully address the voltage issue while simultaneously accruing regenerative braking benefits. Assuming that a 400kW substation would have been necessary to correct the voltage support issue, using the estimated triangular distribution substation costs, and combining the avoided substation investment benefit with regenerative braking, the result is a drastically less negative NPV as shown in FIGURE 27 below.

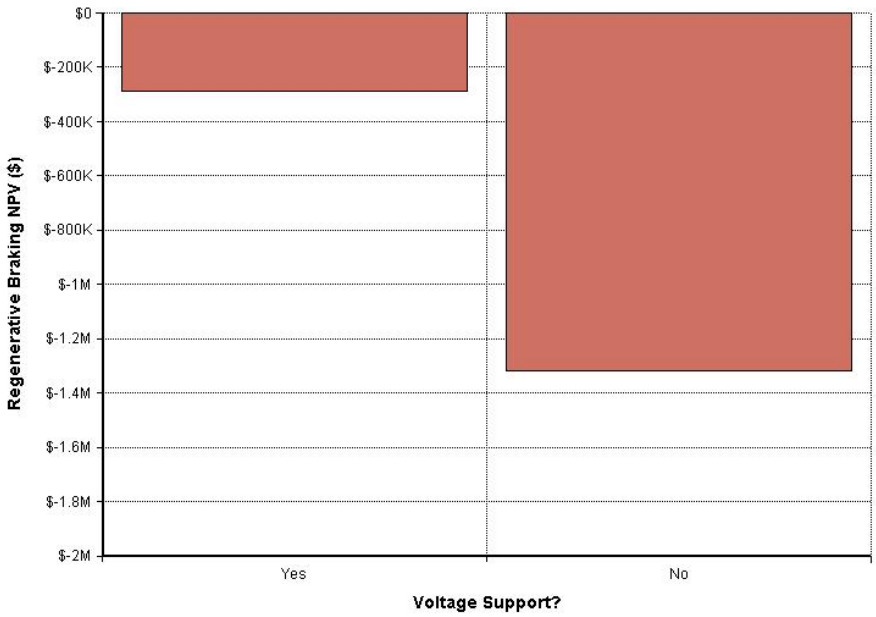


FIGURE 27 Voltage Support and Regenerative Braking NPV for Flywheel WESS

4.8 Secondary Applications

WESS can provide benefits to electric utilities through the applications of peak demand reduction, renewable energy integration, and ancillary services. The quantitative value of these benefits was not analyzed in the Navigant WESS model, due to extensive technical and regulatory uncertainty about the potential use of WESS for utility applications.

The peak demand reduction application involves a utility using WESS to store grid energy during low-demand periods, and then discharging to the grid during periods of peak load. This allows the utility to effectively reduce peak demand at the urban site of major loads, resulting in reduced demand for peak generation, transmission, and distribution. This application could result in numerous benefits for the utility, including: deferred expansion costs for generation, transmission, and distribution; reduced wear on distribution equipment; reduced costs from avoided peak power energy purchases; and reduced greenhouse gas and criteria pollutant emissions from peak power generation.

The renewable energy integration application involves a utility using WESS to store grid energy during periods of high renewable resource availability and low demand, and then to discharge to the grid during high demand periods. Intermittent renewable generation can also be smoothed by using a storage device. A WESS, located within an urban area, may be especially useful when used to help integrate distributed renewable energy from sites within the city. Renewable energy integration can offer the utility significant benefits, primarily including reduced greenhouse gas and criteria pollutant emissions by avoiding the use of fossil fuel generation.

The ancillary services application involves a utility using WESS to store grid energy during low cost periods, and then discharging to provide rapid frequency regulation or reserve services. The need to maintain electric grid stability currently requires utilities to purchase these ancillary services at high cost, from non-renewable power plants. Many WESS, including all of the technologies evaluated in the Navigant WESS model, can provide various types of ancillary services with response times superior to those of conventional ancillary resources, such as gas combustion turbine power plants. By using a WESS device to provide rapid

ancillary services, a utility could gain the following benefits: reduced ancillary services costs; deferred ancillary resource investments; and reduced greenhouse gas and criteria pollutant emissions from avoided non-renewable generation.

Despite these extensive potential applications and benefit streams for utilities from WESS operations, there are significant regulatory and financial barriers to the utilization of a WESS device by a utility, in addition to the transit agency. The regulatory structure for market participation from energy storage devices remains incomplete and uncertain even for energy storage systems installed on the main electrical grid, let alone for those sited in and operated by a transit agency. There is no established or expected model for the ownership and financing structure for a WESS providing both utility and transit agency applications, and any such projects will likely involve a highly specialized and specific arrangement.

The utilization of a WESS for both utility and transit agency applications faces further barriers in the technical operations of the device. Most storage devices can only serve charge and discharge functions at separate times, and require time to respond and ramp to full performance. The balance-of-system, power conversion, and grid integration equipment of the WESS device will provide further complications to operation for multiple applications during a single time period. Many transit WESS applications will not align perfectly with the timing of utility applications, potentially requiring independent storage modules and balance-of-system equipment for operation within a single time period. Utilities will generally want to use WESS applications of peak demand reduction and ancillary services during peak daily periods of electrical load, from midday to evening, which are largely concurrent with the peak times of WESS operation for transit applications of regenerative braking and electricity cost management. It thus remains highly uncertain whether a WESS device could provide both utility and transit agency applications within a given day peak period. If a WESS would only be used for one type of application at a time, then using a WESS for utility applications would require a complex structure for judging the highest-priority and highest-value application for the near-term operations profile.

It is feasible that a WESS device could be owned and operated by a transit agency and operated primarily for transit applications, but could offer ancillary services and other utility applications during critical peak periods. This arrangement would require a technical interface between the WESS device and the electric grid, as well as a decision-making interface between the utility and the transit agency. Although the potential benefits of occasional WESS usage for utility applications, the additional costs and complications of this arrangement are very uncertain.

5.0 CASE STUDIES

5.1 Denver RTD

The Denver RTD operates a light rail system with 5 lines, 36 rail stations, 39.4 miles of track, and 35 traction power substations. The existing lines connect parts of downtown Denver with southeastern and southwestern suburbs, and meet along a central corridor directly south of downtown. A new light rail line is under development to extend to the western suburbs of Denver, and is planned for completion by 2013. FIGURE 28 presents the Denver RTD Light Rail Map.

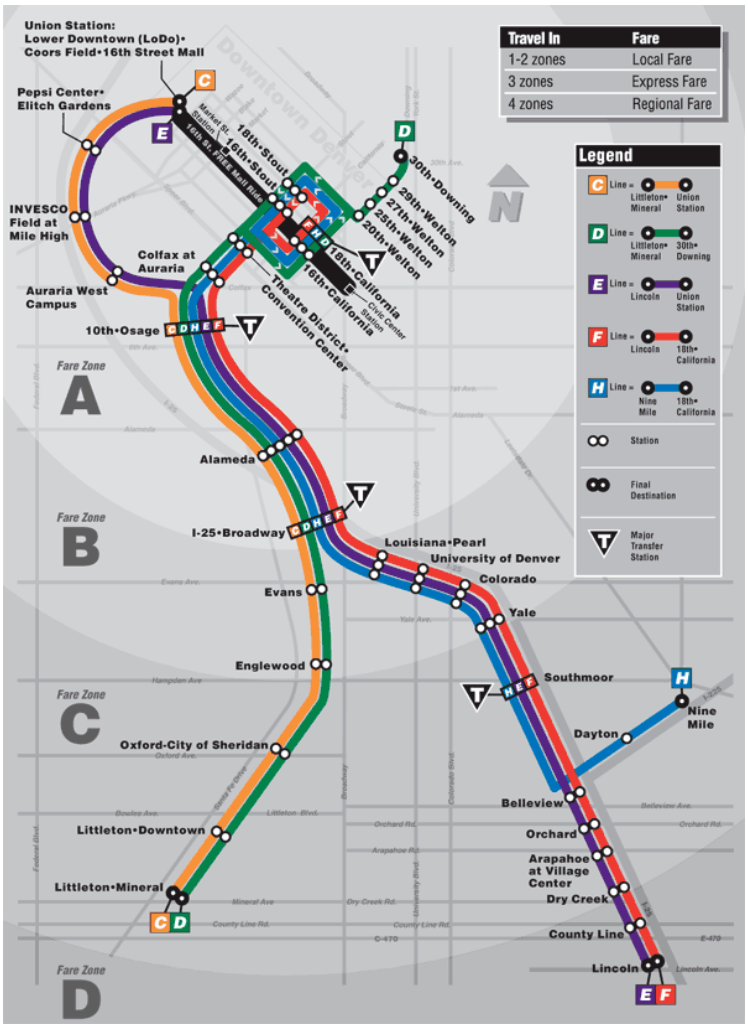


FIGURE 28 Denver RTD Light Rail System Map

The light rail system uses traction power substations and rectifiers to deliver DC electricity. A portion of their train car fleet use brushed DC motors for propulsion while a group of more modern cars operate with on-board inverters to allow them to run AC motors. Electricity is purchased from Xcel Energy, with charges based largely on overall energy consumption and the maximum power demand reached for a month. The 35 substations, with one exception, are each situated adjacent to a single train station, and each substation primarily provides electric service to that single station and its nearby railway.

Denver RTD staff identified two WESS applications that they believe represent high value for the system: demand charge management, and regenerative braking. These applications were identified for their ability to reduce electricity costs. This benefit is maximized for the areas of the system with the highest train traffic and the highest variability between peak and off-peak traffic. Denver RTD staff also identified some voltage sag challenges in the Central Corridor (between Broadway &I-25 TPSS and Evans TPSS), and in the West Corridor under construction. However, Denver RTD estimated these voltage sag challenges to be of smaller value than the demand charge management and regenerative braking.

Based on these goals and the available system energy data, Navigant and Denver RTD identified the Central Corridor as the best area to evaluate WESS benefits. This section of the system has very high rail traffic, with peaks in usage during weekday morning and evening commute hours. The transit agency substations in this part of the system have historical load data recorded at 15 minute intervals.

To evaluate the potential for demand charge management at stations in the central corridor, Navigant conducted a preliminary analysis of substation load profiles. The benefit potential is highest when power requirements are exhibited in narrow intervals. Based on this analysis, Navigant initially selected the substation supporting the I-25 & Broadway light rail station, at the southern base of the central corridor, shown in FIGURE 29. The peaks at this substation occur during the morning and afternoon commute periods. However, these peaks are quite broad, with high demand levels lasting for over two hours. (See FIGURE 30.) Therefore, Navigant determined that this load profile at the I-25 & Broadway station is unlikely to be highly valuable for demand charge management alone.

FIGURE 29 Denver RTD I-25 & Broadway Light Rail Station Map

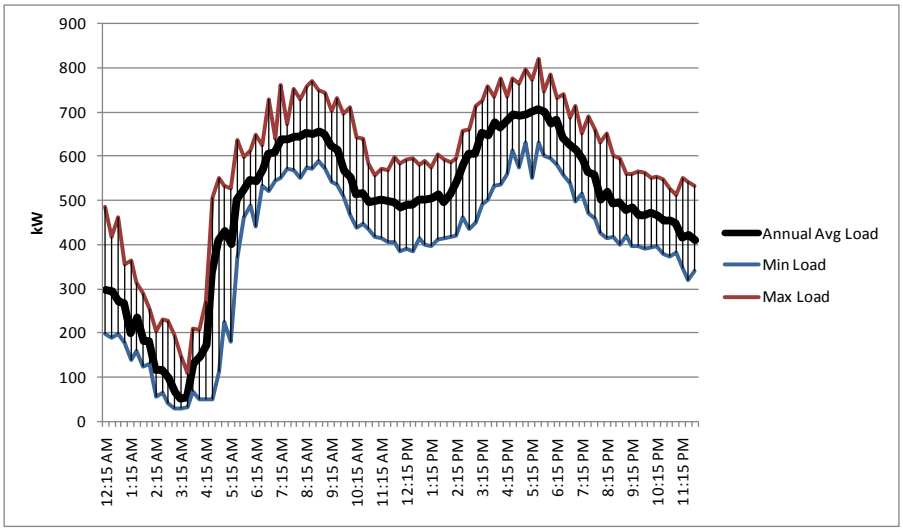


FIGURE 30 Denver RTD I-25 & Broadway Substation Load Profile for 2010

Navigant then conducted an evaluation of regenerative braking potential at the I-25 & Broadway station based on the station's train schedule. The analysis identified the frequency of train stops at this station during different times of day, and distinguished between two types of train stops: 1) "synchronous" stops that occurred within one minute of another scheduled stop on a parallel line, and 2) "asynchronous" stops that occurred with a gap of 2 minutes or higher with the nearest stop. The analysis made this synchronicity distinction to identify the potential for WESS to provide regenerative braking support, and estimate the associated energy savings. Synchronous stops may allow for an incoming braking train to provide power directly to an outbound accelerating train. This direct transfer reduces the potential energy for WESS to store and reuse. Asynchronous stops have a larger potential for WESS to charge with braking energy, store the energy, and then supply power to an accelerating train many minutes later.

The results of the schedule analysis are shown in FIGURE 31, FIGURE 32, FIGURE 33, and FIGURE 34. The I-25 & Broadway station, with three independent tracks, has 605 individual train stops distributed through a weekday, including 370 asynchronous stops on a standard weekday schedule. This high number of asynchronous stops appears to provide high potential for WESS regenerative braking support. Additionally, the frequency of asynchronous stops increases during periods of peak power demand, meaning that it there is potential for WESS to support regenerative braking, reducing energy use, and thus lowering peak power demand charges.

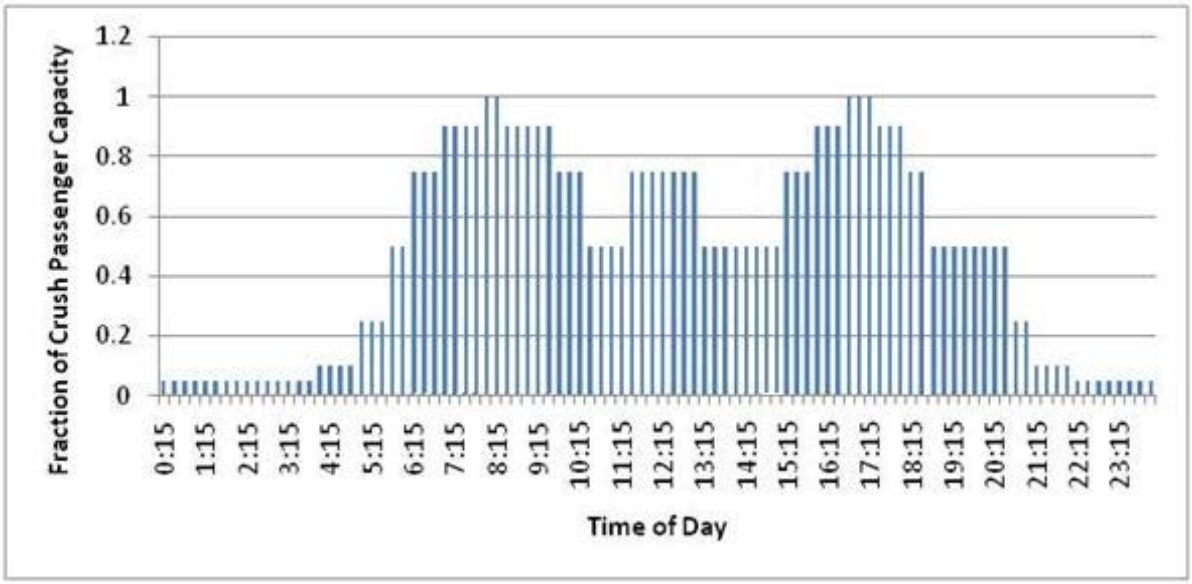


FIGURE 31 Denver RTD Estimated Daily Passenger Load by Time of Day

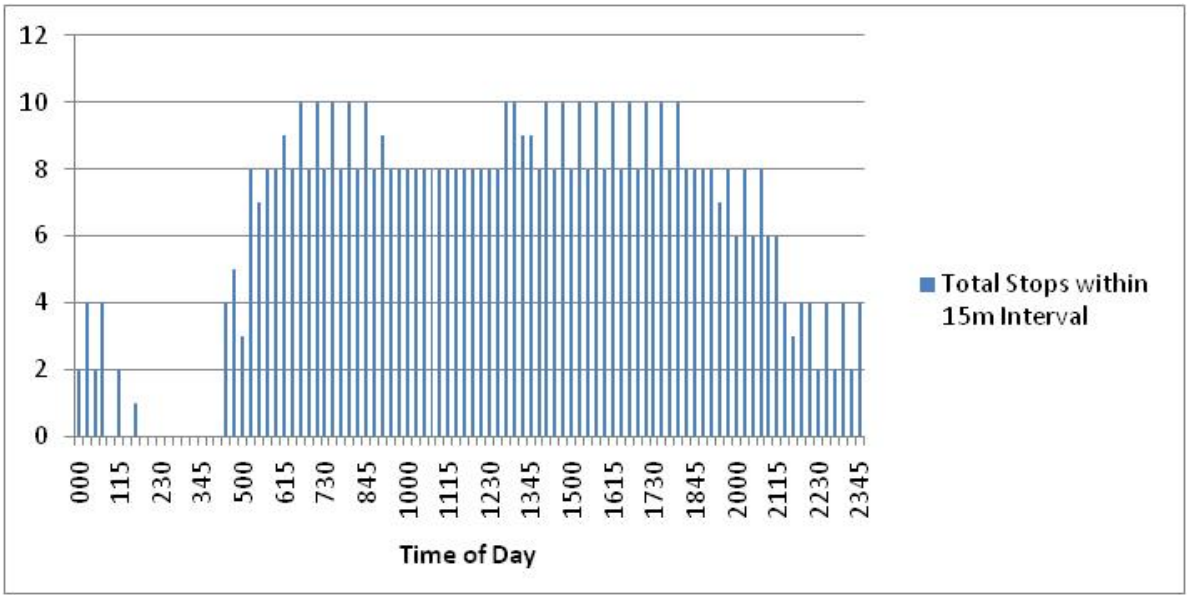


FIGURE 32 Denver RTD Weekday Frequency of All Scheduled Stops at I-25 & Broadway Station

Source: Denver RTD Schedule Data

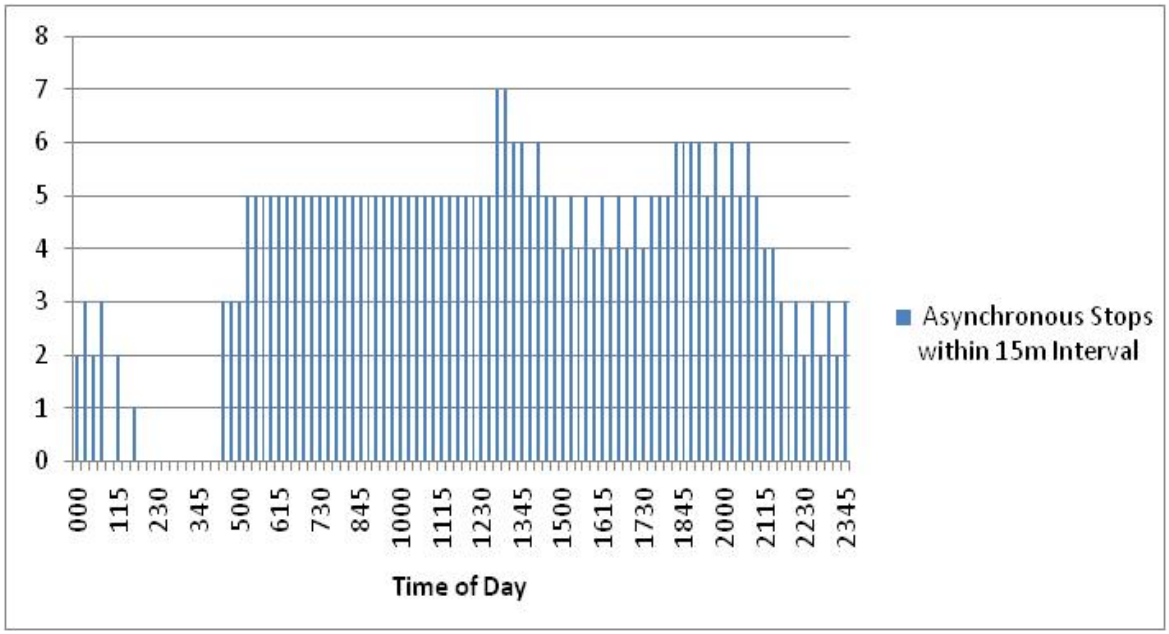


FIGURE 33 Denver RTD Weekday Frequency of Asynchronous Stops at I-25 & Broadway Station
Source: Denver RTD Schedule Data

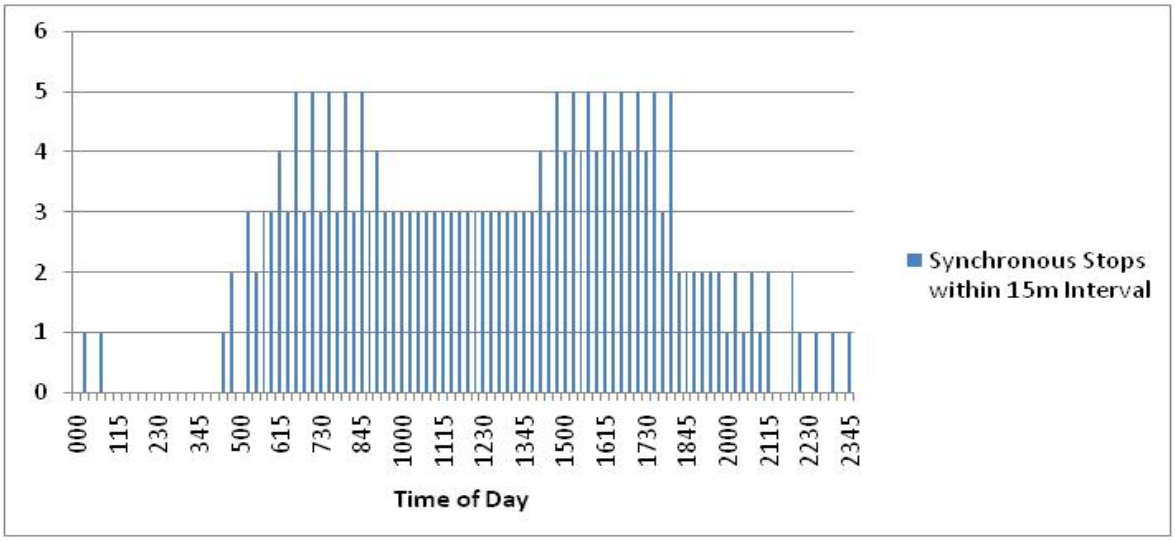


FIGURE 34 Denver RTD Weekday Frequency of Synchronous Stops at I-25 & Broadway Station
Source: Denver RTD Schedule Data

Based on this analysis of load profiles and train schedules at the I-25 & Broadway station, Navigant and Denver RTD decided to model WESS at this location, optimized primarily for regenerative braking support, and secondarily for demand charge management. During the construction of the model, the case studies for Denver RTD were slightly modified. These two applications were separated completely in the analysis instead of modeling WESS devices to perform both applications from one device. This separation was made primarily due to the severe differences in power and energy capacity requirements between the applications. Due to these differences, all WESS technologies studied are specialized only to a single application, and are extremely cost-prohibitive for the other application. Another key change was made to the demand charge reduction application. Initially, Navigant and Denver RTD expected that a

WESS device could separately optimize demand charges and time-based energy use charges. However, the simulation modeling analysis (discussed in Section 4) showed significantly higher benefits for a WESS application that optimized both applications. This more inclusive, combined application was renamed as electricity cost management. Therefore, the model analyzed the value of WESS for the specific applications of electricity cost management and regenerative braking support separately. TABLE 23TABLE 23 Operational Parameters for Denver RTD Case Study presents the parameters used in the model.

TABLE 23 Operational Parameters for Denver RTD Case Study

Variables	Value	Reference
Weight per Train Car, kg	39,920	Denver RTD
Cars per Train	2-4	Denver RTD
Passengers Crush Capacity per Car	171	Denver RTD
Weight per Passenger, kg	81.5	U.S. Centers for Disease Control
Receptivity, %	80	Navigant Estimate
Train Approach Speed, m/s	15.65	Navigant Estimate
Summer Off-peak Energy Charge, $/kWh	$0.02218	XCEL
Summer On-peak Energy Charge, $/kWh	$0.03438	XCEL
Summer Demand Charge, $/kW	$8.30	XCEL
Winter Off-peak Energy Charge, $/kWh	$0.03	XCEL
Winter On-peak Energy Charge, $/kWh	$0.0348	XCEL
Winter Demand Charge, $/kW	$5.50	XCEL

FIGURE 35 shows the total value of benefits from each type of WESS device for the electricity cost management application at the I-25 & Broadway station. These benefits are based on optimization of the light rail station's electric load, by shifting large amounts of load to lower demand charges and peak time rates. These total benefits are reduced by losses in the WESS device, such as parasitic loads and roundtrip inefficiency. The overall benefits are highest for devices which have the largest effective energy storage capacity, based on roundtrip efficiency and nominal energy storage capacity. The Navigant WESS model builds storage devices to meet a constant power capacity requirement, depending on the application. The nominal energy storage capacity varies between different WESS technologies based on the technical power to energy ratio (kW/kWh). Lead acid and sodium sulfur batteries have more energy capacity than other technologies, so these devices create more savings than other options.

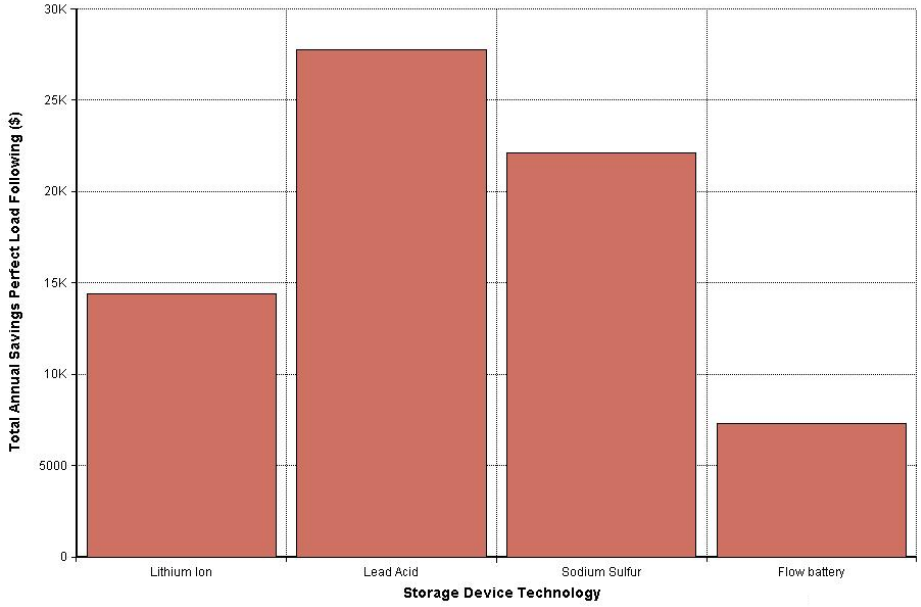


FIGURE 35 Denver RTD Total Annual Benefits for Electricity Cost Management

FIGURE 36 shows the results of Net Present Value (NPV) analysis for the four WESS technologies evaluated, for the specific application of electricity cost management at the I-25 & Broadway station. Ultracapacitors and flywheels are not shown since they do not meet the technical specifications for energy. None of the technologies evaluated resulted in a positive NPV for this application under the modeled assumptions. Lithium ion batteries, while built in this model with less nominal energy capacity, are shown in the NPV analysis to be the most attractive WESS technology for electricity cost management due to the better cycle life and reduced O&M costs compared to lead acid batteries.

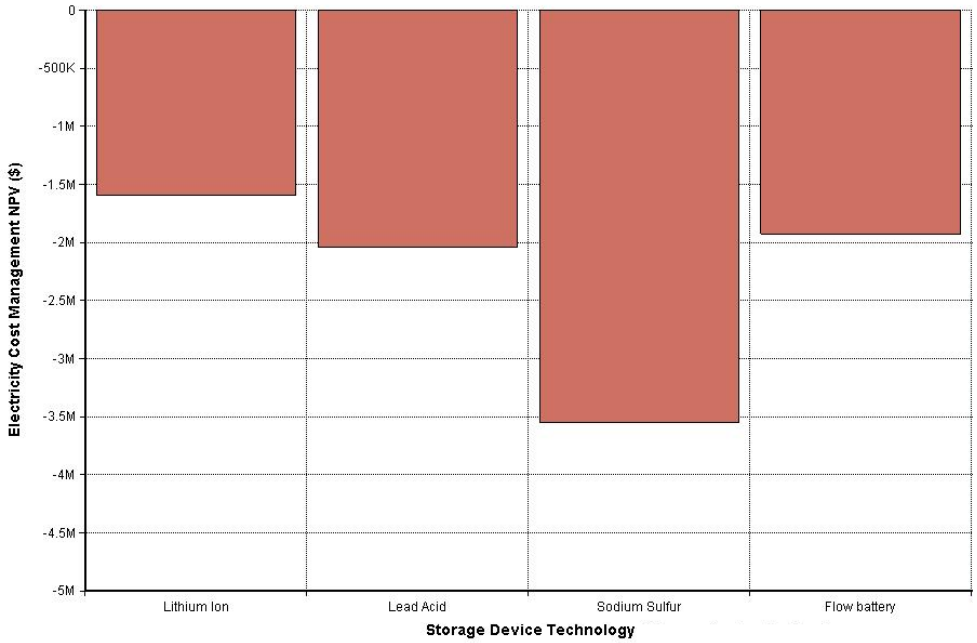


FIGURE 36 Denver RTD Electricity Cost Management NPV by Technology

FIGURE 37 shows NPV sensitivity analysis for a lithium ion WESS for the electricity cost management application. This analysis shows how changes in input variables affect the overall value of the WESS device. For all devices in this application, WESS cost is by far the most sensitive variable. This indicates that a change in the capital expense of the WESS device would have a greater effect on the overall NPV than an equivalent change in any other variable. While FIGURE 36 shows that no WESS device currently achieves a positive NPV for electricity cost management, the NPV sensitivity analyses for this application show that potential future improvements in WESS capital costs would bring the technologies far closer to a positive value proposition.

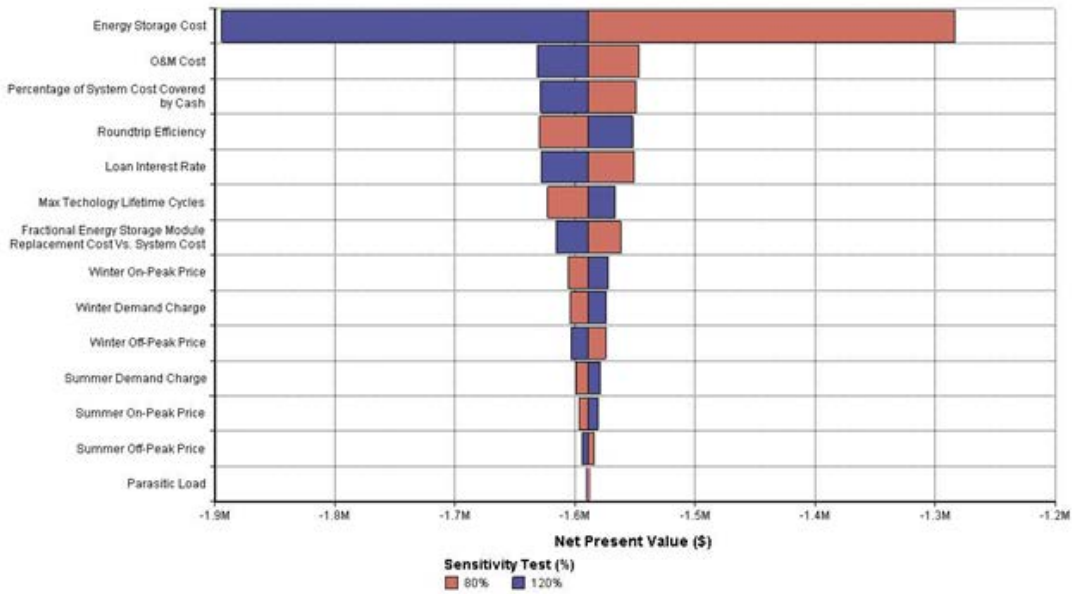


FIGURE 37 Denver RTD Sensitivity Analysis for Electricity Cost Management for Lithium Ion WESS

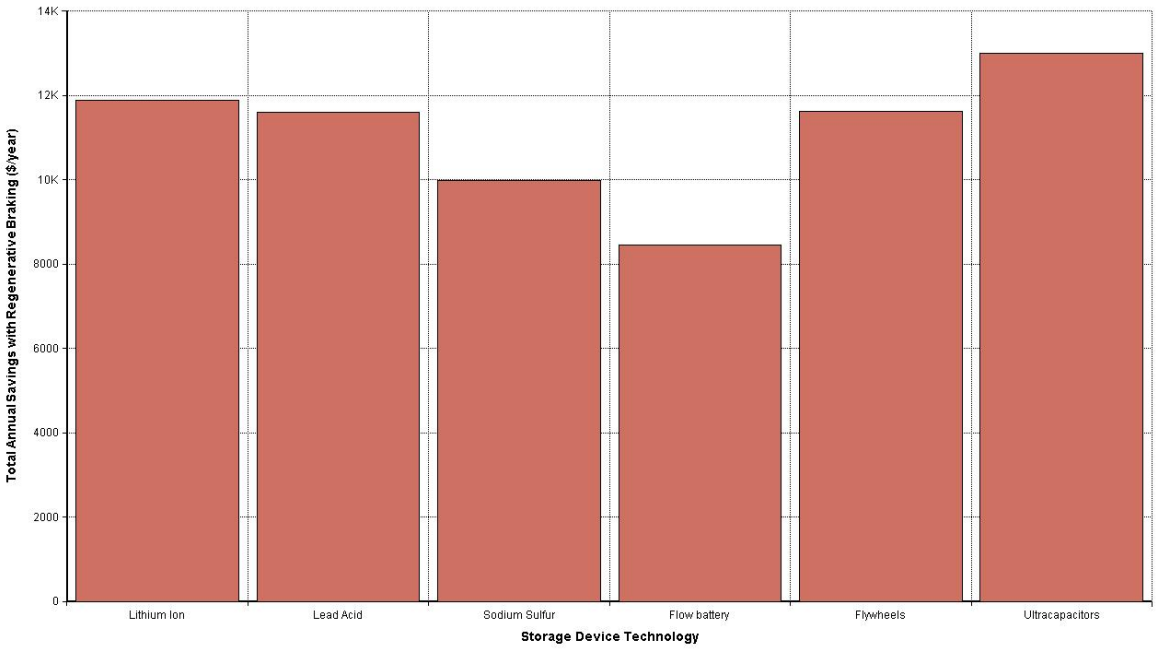


FIGURE 38 shows the value of electric cost savings, or total benefits, from each type of WESS device, for the regenerative braking application at the I-25 & Broadway station for Denver RTD. Total regenerative braking

benefits are based on storage of braking energy that would otherwise be lost as trains enter the station, during periods when this braking energy cannot be sent on the line to a train accelerating out of the station. By charging the WESS device with this braking energy, the overall electric load can be reduced during each discharge of braking energy to an accelerating train, thus reducing both demand charges and energy charges.

All of the WESS devices achieve a positive level of benefits from regenerative braking at the I-25 & Broadway station. Total electric cost savings are reduced by losses in the WESS device, such as parasitic loads and roundtrip inefficiency. The overall benefits are highest for devices which can deliver the most power with the least losses such as flywheels and ultracapacitors.

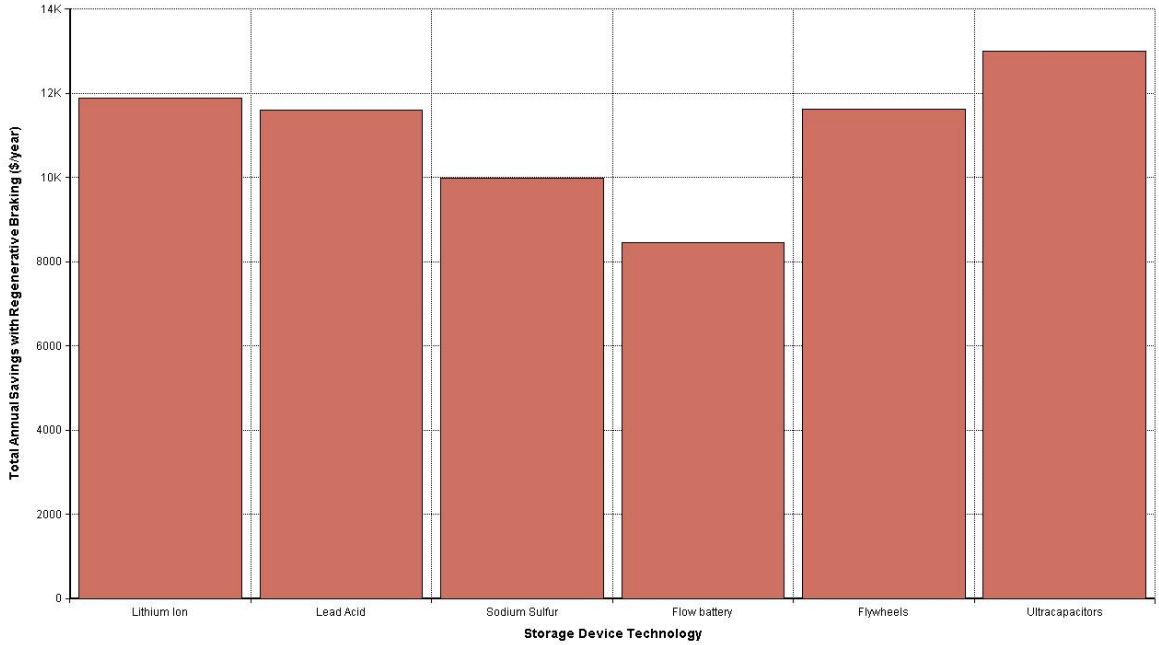


FIGURE 38 Denver RTD Total Annual Benefits for Regenerative Braking

FIGURE 39 shows the results of the NPV analysis for all technologies for the regenerative braking application at the I-25 & Broadway station. All technologies evaluated have a negative NPV for this application. Unlike electricity cost management, the cost of regenerative braking support is dominated by the cost of WESS power capacity. The technologies with the highest power capacity per cost have a higher NPV. Flywheels are more attractive than the other technologies by a significant margin. In particular, the flywheel WESS device has a significantly higher value than all other devices evaluated, with a nearly positive NPV. A flywheel WESS appears uniquely well suited to provide regenerative braking based on its relatively low power capacity costs and high number of lifetime cycles. An ultracapacitor WESS has similar advantages compared to battery technologies, but has significantly higher energy capacity costs than flywheels.

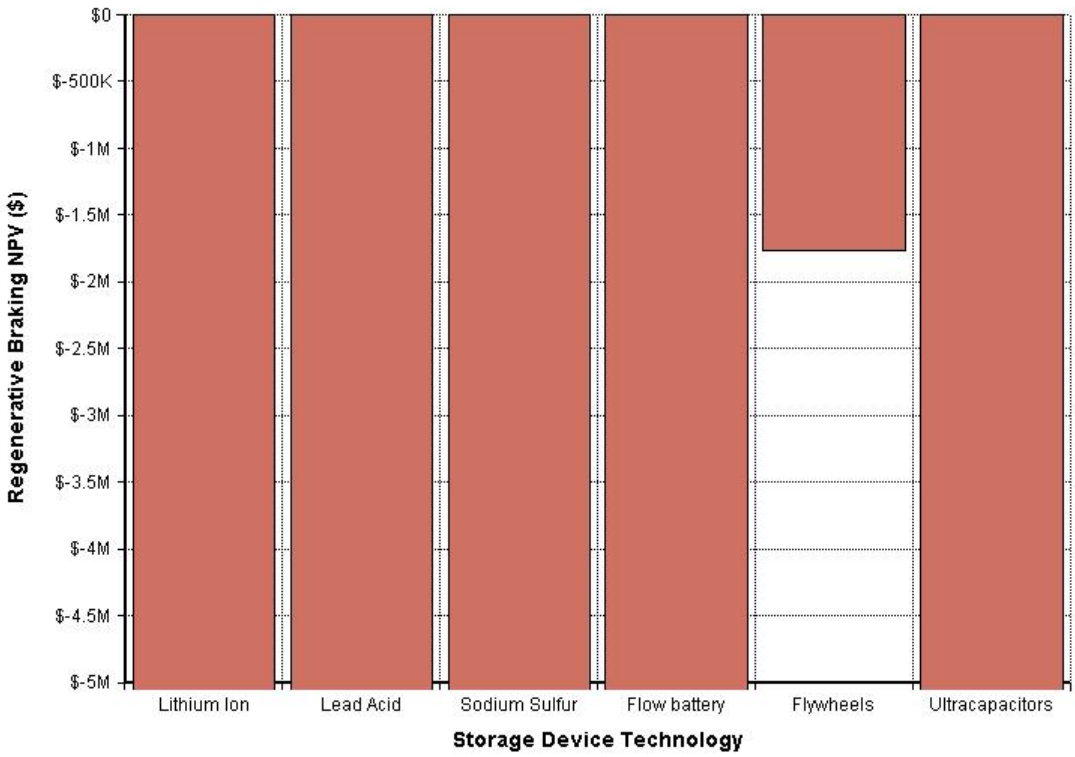


FIGURE 39 Denver RTD Regenerative Braking NPV by Technology

FIGURE 40 shows NPV sensitivity analysis for a flywheel WESS for the regenerative braking application. This analysis shows how changes in input variables affect the overall value of the WESS device. For all devices in this application, train velocity on approach is the most sensitive variable. Since required power is directly related to system cost, the length of each stopping event has a big impact on overall NPV. The sensitivity of these variables indicates that WESS NPV for regenerative braking is greatly affected by the frequency and size of regenerative braking opportunities. The consistent high sensitivity of system size reduction, power capacity costs, energy module cost per replacement, and the efficiency and receptivity variables shows that the NPV of the WESS is significantly affected by changes in the needed capacity and overall cost of the WESS.

While FIGURE 39 shows that no WESS device currently achieves a positive NPV for the regenerative braking application, the NPV sensitivity analyses show that different operational characteristics and future reductions in WESS cost could bring flywheel technologies much closer to a positive value proposition.

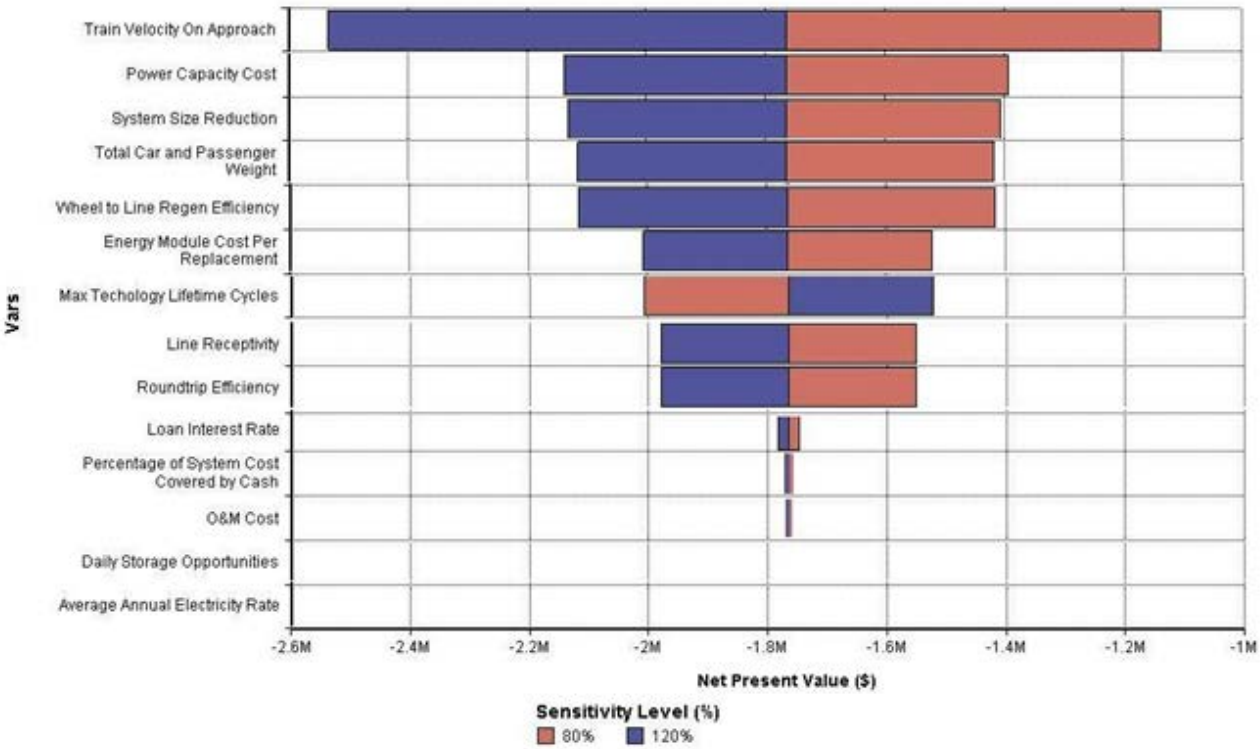


FIGURE 40 Denver RTD Sensitivity Analysis for Regenerative Braking for Flywheel WESS

Each type of storage device has a different ratio of power to energy, and the amount of actual energy storage capacity built is highly dependent on this ratio. Ultracapacitors have a very low amount of energy per unit of power. Regenerative braking support from a WESS requires rapid cycling with high power loads and relatively small amounts of energy stored and discharged. Battery devices thus require significant over-built energy capacity to achieve the same regenerative braking capabilities of a flywheel or ultracapacitor WESS. This over-built energy capacity results in lower cost-effectiveness for battery units in the regenerative braking application, shown in their less attractive NPV in FIGURE 39.

Flywheels are the best technology option for regenerative braking at the Denver RTD I-25 and Broadway station, yielding an NPV of -$1,765,000. Regenerative braking provides steady time-based rate savings, combined with smaller demand charge savings, which total about $11,500 per year in benefits. Flywheels are the most attractive technology due to low power capacity costs, high efficiency, and a very high cycle lifetime compared to other technologies. The NPV of flywheels for regenerative braking is highly sensitive to the size and frequency of regenerative braking opportunities, which are in turn highly dependent on train operation patterns. Capital cost for flywheels is the most significant cost contributing to the negative NPV. It is feasible that significantly improved capital costs and different train operation patterns, to increase the velocity and frequency of train stops, could make flywheel WESS a positive investment for a transit system. Transit systems and stations with large and frequent braking events would require a larger WESS for regenerative braking.

Electricity cost management, with lithium ion battery WESS, results in a less negative NPV than regenerative braking at the Denver RTD I-25 and Broadway station, largely due to the smaller system capacity requirements for the electricity cost management application. Electricity cost management offers higher annual benefits than regenerative braking. A lithium ion WESS results in roughly $14,000 annual savings in electricity costs when applied to provide electricity cost management at the I-25 and Broadway

station, with an NPV of -$1,590,000. Denver RTD uses a two-tiered time-of-use rate schedule and relatively high demand charges, which increases the annual benefits from electricity cost management.

As both modeled applications resulted in a negative NPV, Denver RTD development of WESS appears to require reduced system capital costs, as well as increased electric rates, before it will provide a positive value for the transit agency. This system cost reduction can come through improvement in technology manufacturing, or from public grants and cost-share measures. Increases in demand charges and in the peak rate charges will increase the benefits from a WESS for electricity cost management and regenerative braking alike. Based on the NPV sensitivity analysis performed for electricity, the model indicates that lithium ion WESS would gain a positive NPV when capital costs reach $1000/kW, down from the current $1800/kW, demand charges rise by about 500%, and peak energy rates rise by about 400%. Public grants could reduce initial costs and help make WESS a positive investment for Denver. A 50% cost-share could make a lithium ion WESS feasible with $1400/kW capital costs, and only 300% increases in demand and peak energy charges.

5.2 GCRTA

The regional transit authority for the greater Cleveland, OH area includes a heavy rail Red Line, as well as the light rail Green and Blue Lines illustrated in FIGURE 41. Navigant was asked by GCRTA to focus on the operation of the light rail lines, which have 18 miles of track, 34 stations, and 6 dedicated and 2 joint traction power substations. The light rail lines extend from the eastern suburbs of Cleveland to the city center and then turn to extend east along the waterfront.

FIGURE 41 GCRTA Rail System Map

The GCRTA light rail system operates at 600V DC using overhead catenary system. The Illuminating Company provides electricity for the GCRTA system at 8 substations. Three of these substations are backup power substations, and most substations are built at or adjacent to a rail station. All substations are daisy-chained to provide backup power during a nearby substation outage. The Illuminating Company historically was located within the Midwest Independent System Operator area. On June 1, 2011, the PJM Interconnection took regional system operator authority over the area, which will lead to some minor changes in GCRTA rates. Currently, GCRTA purchases the generation portion under various flat rates for all times of day, with a utility charge for the power demand peak.

GCRTA staff reviewed the potential functions of WESS, and identified demand charge management and regenerative braking as the functions of highest interest. Navigant reviewed electricity metering and route maps for GCRTA stations, to find the location with the theoretically highest potential for WESS functions of demand charge management, and regenerative braking. GCRTA provided Navigant with substation electric metering data at 5 substations showing energy use and power demand, at thirty minute intervals, for each day from October 2010 through March 2011 (FIGURE 42).

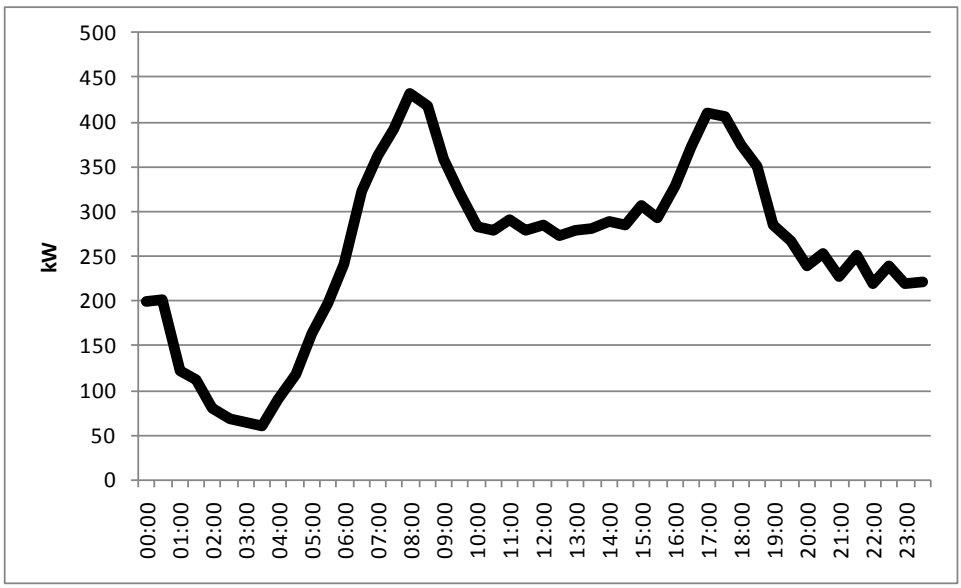


FIGURE 42 GCRTA Average Load Profile of the Tower City Substation

Navigant evaluated the substations for their potential for demand charge management, identifying the stations with the highest peaks and variations in demand. Navigant also used this data to identify the stations with the highest overall energy usage and the highest number of lines using the station, which would likely signify the highest need for regenerative braking.

Based on the evaluations of electricity data and route maps, Navigant identified the substation for Tower City station (highlighted in FIGURE 43) as the location with the highest potential for demand charge management and regenerative braking. The Tower City station is centrally located in the GCRTA system, serving both light rail lines and the single heavy rail line. This station receives a high load of rail traffic, and its energy use has major peaks during the morning and evening commute periods, with high power demand enduring for at least an hour.

FIGURE 43 GCRTA Tower City Rail Station Focus Map

Navigant then conducted a preliminary evaluation of regenerative braking potential at the Tower City station, based on analysis of the station's train schedule. The analysis identified the frequency of train stops at this station at different times of day, and distinguished between two types of train stops: 1) "synchronous" stops that occurred within one minute of another scheduled stop on a parallel line, and 2) "asynchronous" stops that occurred with a gap of 2 minutes or higher with the nearest stop. The analysis made this distinction to identify the potential for WESS to provide regenerative braking support, and associated energy savings. Synchronous stops will often allow for an incoming braking train to provide power directly to an outbound accelerating train. This direct transfer reduces the potential energy for WESS to store and reuse. Asynchronous stops have a larger potential for WESS to charge with braking energy, store the energy, and then supply power to an accelerating train seconds later.

The results of the schedule analysis are shown in FIGURE 44, FIGURE 45, FIGURE 46, and FIGURE 47. The Tower City station, on a standard weekday schedule, has 195 individual train stops, including 178 asynchronous stops. This high number of asynchronous stops appears to provide a high potential for WESS regenerative braking support. Additionally, the frequency of asynchronous stops increases during periods of peak power demand. This indicates that there is potential for WESS to reduce peak power demand charges while providing regenerative braking support.

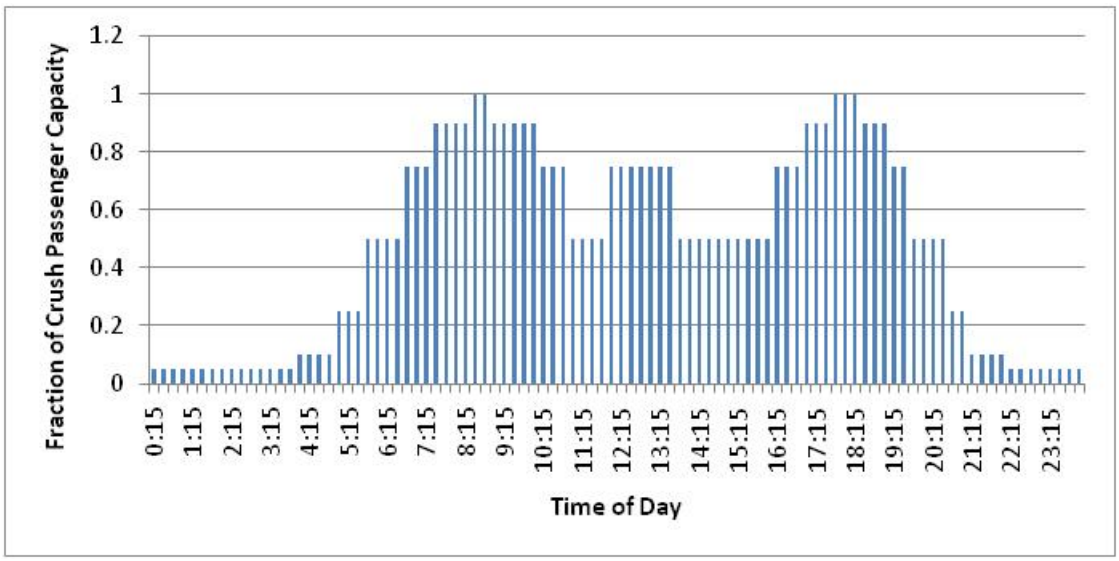


FIGURE 44 GCRTA Estimated Daily Passenger Load by Time of Day

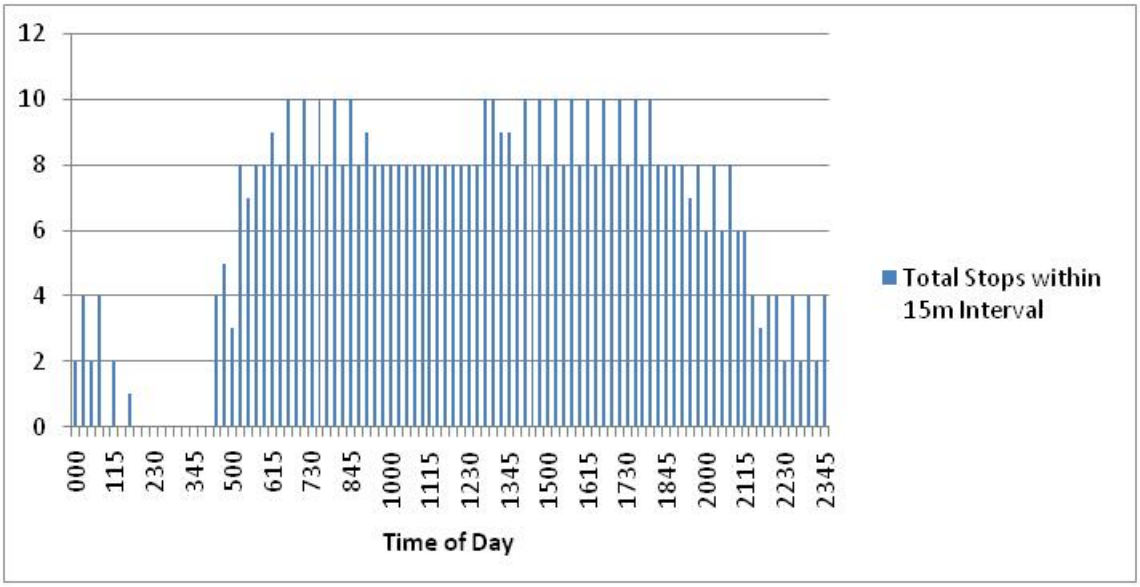


FIGURE 45 GCRTA Weekday Frequency of All Scheduled Stops at Tower City Station
Source: GCRTA Schedule Data

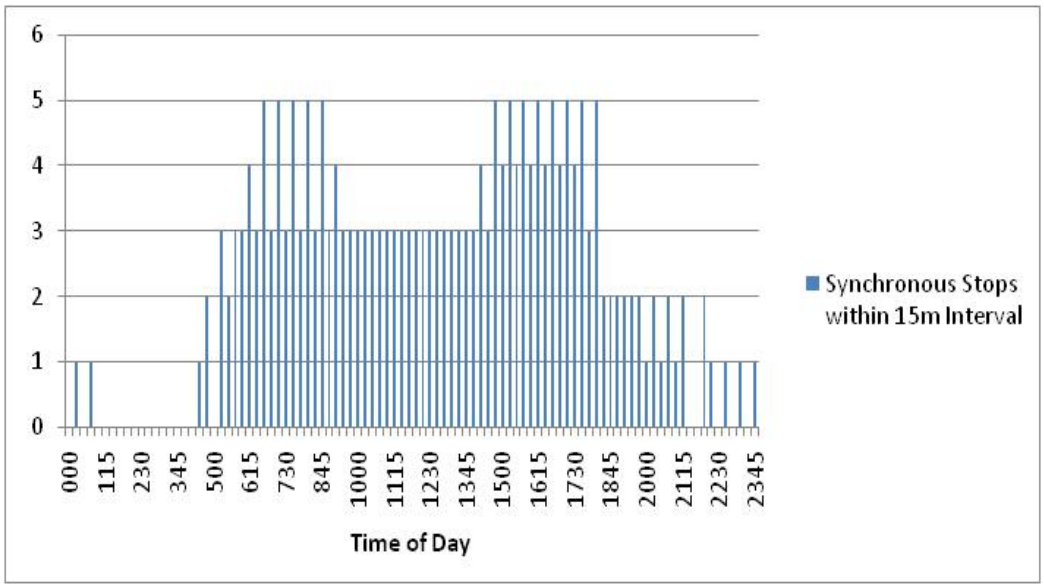


FIGURE 46 GCRTA Weekday Frequency of Asynchronous Stops at Tower City Station
Source: GCRTA Schedule Data

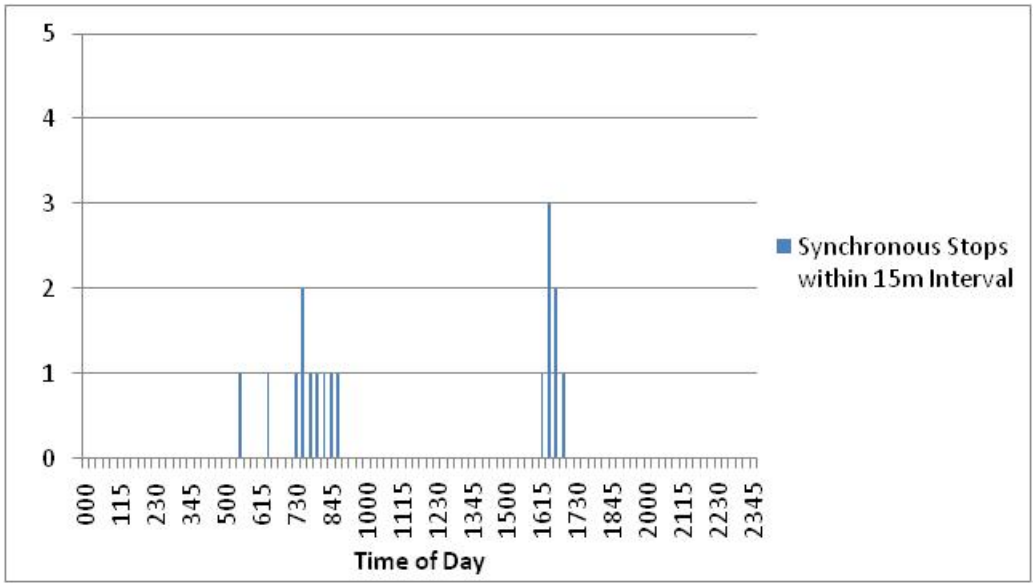


FIGURE 47 GCRTA Weekday Frequency of Synchronous Stops at Tower City Station
Source: GCRTA Schedule Data

Based on this analysis of load profiles and train schedules, Navigant and GCRTA decided to model a WESS installation at the Tower City station, optimized primarily for regenerative braking support and secondarily for demand charge management. During the construction of the model, the case studies for GCRTA were slightly modified. These two applications were separated completely in analysis instead of modeling WESS devices to perform both applications from one device. This separation was made due to the severe differences in power and energy capacity requirements between the applications. Due to these differences, all WESS technologies studied are specialized only to a single application, and are extremely cost-prohibitive for the other application. Demand charge management was renamed to electricity cost management for symmetry, though GCRTA does not use time-based energy rates and this application remains solely applied to reduction of demand charges. Operational parameters for the GCRTA case study are presented in TABLE 24.

TABLE 24 Operational Parameters for GCRTA Case Study

Variables	Value	Reference
Weight per Train Car, kg	44,000	GCRTA
Cars per Train	2-3	GCRTA
Passenger Crush Capacity per Car	175	GCRTA
Weight per Passenger, kg	81.5	US Centers for Disease Control
Receptivity, %	80	Navigant Estimate
Train Approach Speed, m/s	15.65	Navigant Estimate
Summer Energy Charge, $/kWh	$0.0726	The Illuminating Co.
Winter Energy Charge, $/kWh	$0.0757	The Illuminating Co.
Demand Charge, $/kW	$0.9718	The Illuminating Co.

FIGURE 48 shows the total value of benefits from each type of WESS device, for the electricity cost management application for GCRTA. These benefits are based on optimization of the light rail station's electric load, by shifting large amounts of load to lower demand charges. These total benefits are reduced by

losses in the WESS device, such as parasitic loads and roundtrip inefficiency. The overall benefits are highest for devices which have the largest effective energy storage capacity based on roundtrip efficiency and nominal energy storage capacity. Flywheels and ultracapacitors are not applicable to electricity cost management because they do not meet the technical specifications for energy capacity. Lithium ion batteries are the most attractive technology overall for electricity cost management.

The low demand charges for GCRTA and flat rate schedule result in consistent losses for electricity cost management with all WESS technology types, except for lithium ion. The electric load pattern at the Tower City Station varies significantly from day to day and month to month, with some periods offering only very small demand "peaks" for the storage device to manage and reduce. With small potential demand charge benefits, and no potential time-based rate benefits, three of the applicable WESS devices result in higher overall electric costs, due to the electric losses created by device inefficiencies. As expected and shown in FIGURE 48, the size of negative benefits is directly related to a given technologies round trip efficiency. Since flow batteries, on a relative basis, have the lowest efficiency they result in the fewest benefits. Lithium ion has the highest round-trip efficiency of the applicable technologies.

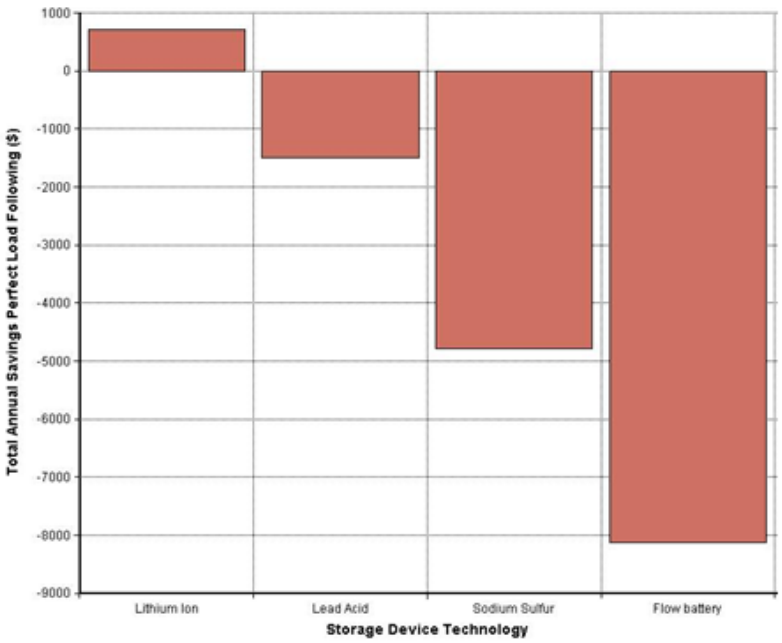


FIGURE 48 GCRTA Total Annual Benefits for Electricity Cost Management

FIGURE 49 shows the results of NPV analysis for the five WESS technologies evaluated for electricity cost management. All technologies evaluated have a negative NPV for this application. Lithium ion batteries are the most cost effective technology, with an NPV of approximately -$960,000.

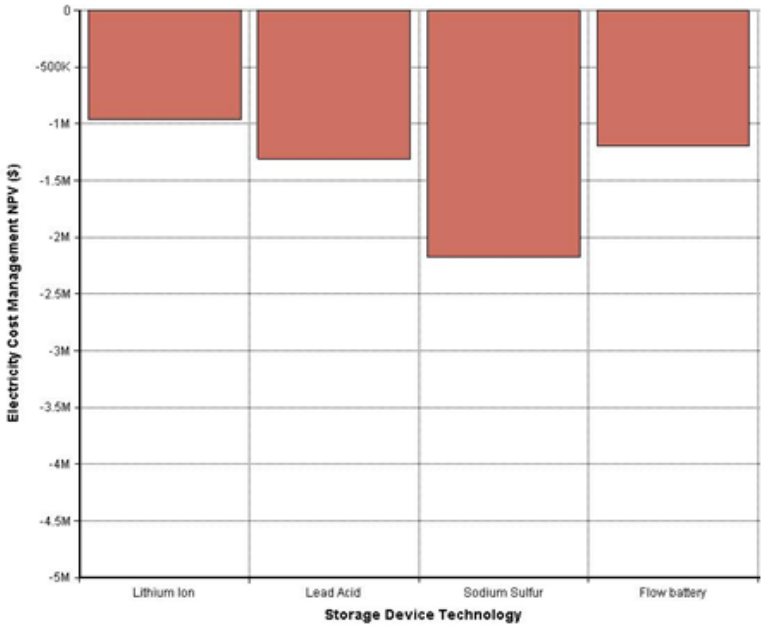


FIGURE 49 GCRTA Electricity Cost Management NPV by Technology

FIGURE 50 shows the NPV sensitivity analysis for a lithium ion WESS for the electricity cost management application for GCRTA. This analysis shows how changes in input variables affect the overall value of the WESS. For all devices in this application, WESS cost is by far the most sensitive variable. This indicates that a change in the energy capacity capital expense of the WESS device would have a greater effect on the overall NPV than an equivalent change in any other variable. While no WESS currently achieves a positive NPV for electricity cost management, the NPV sensitivity analyses for this application show that potential improvements in WESS capital cost would bring the technologies far closer to a positive value proposition.

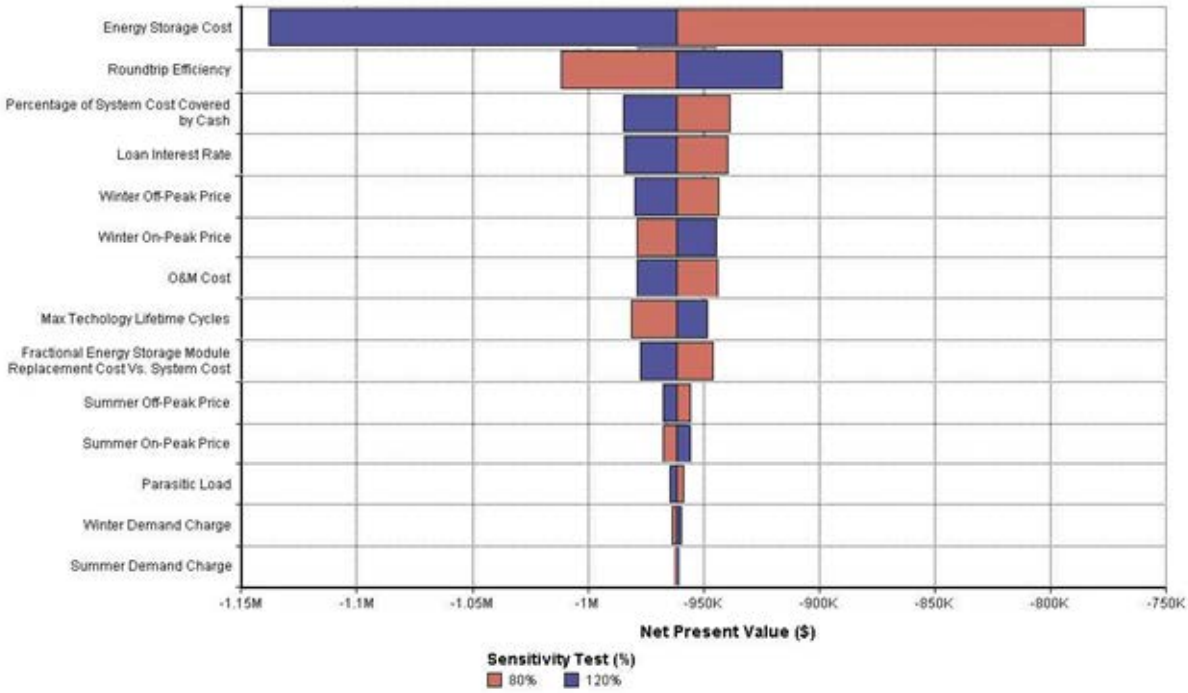


FIGURE 50 GCRTA Sensitivity Analysis for Electricity Cost Management for Lithium Ion WESS

FIGURE 51 shows the value of total benefits from each type of WESS for the regenerative braking application. These benefits are based on storage of braking energy that would otherwise be lost as trains enter the Tower City station during periods when this braking energy cannot be sent on the line to a train accelerating out of the station. By charging the WESS with this braking energy, the overall electric load can be reduced during each discharge of braking energy to an accelerating train, thus reducing both demand charges and energy charges.

All of the WESS technology types achieve a positive level of benefits from regenerative braking at the Tower City station. Total electric cost savings are reduced by losses in the WESS device, such as parasitic loads and roundtrip inefficiency. The overall benefits are highest for devices which can deliver the most power with the least amount of losses such as flywheels and ultracapacitors.

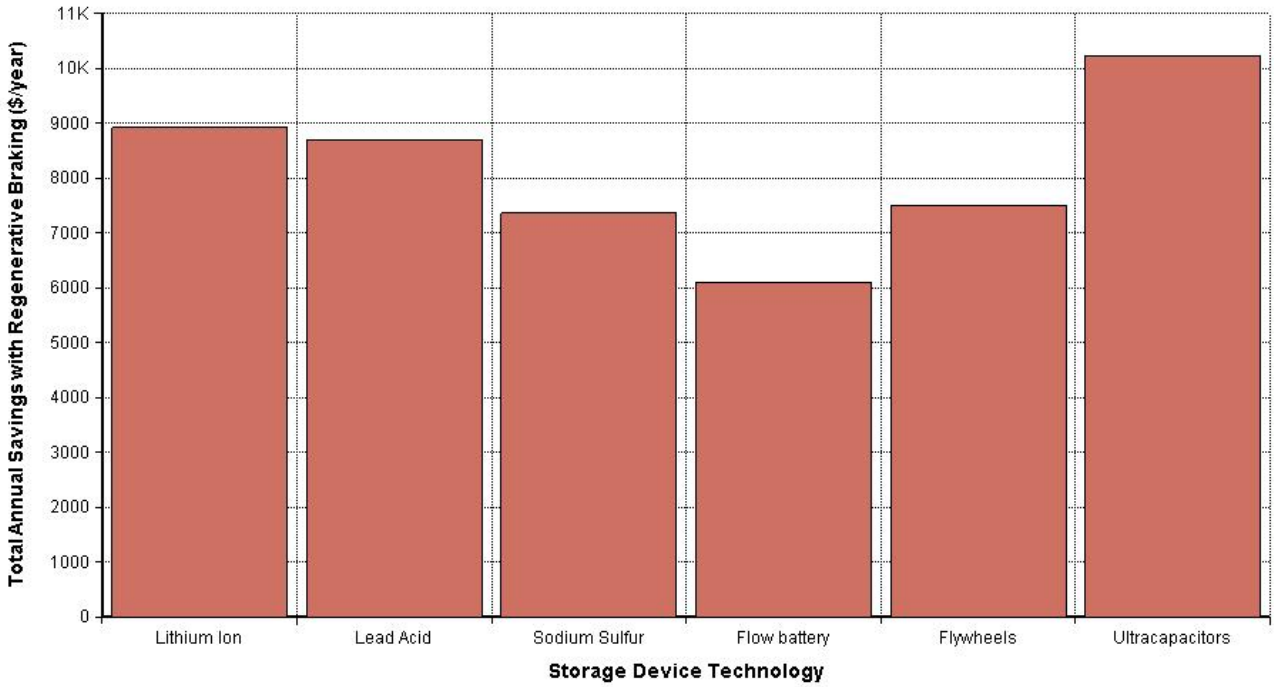


FIGURE 51 GCRTA Total Annual Benefits for Regenerative Braking

FIGURE 52 shows the results of the NPV analysis for all technologies for the regenerative braking application at the Tower City station. All technologies evaluated have a negative NPV for this application. Unlike electricity cost management, the cost of regenerative braking support is dominated by the cost of WESS power capacity. The technologies with the highest power capacity per cost have a higher NPV. Flywheels and ultracapacitors are more attractive than the battery technologies considered. In particular, the flywheel WESS device has a significantly higher value than all other devices evaluated, with a nearly positive NPV. A flywheel WESS is uniquely well suited to provide regenerative braking based on its relatively low power capacity costs and high number of lifetime cycles.

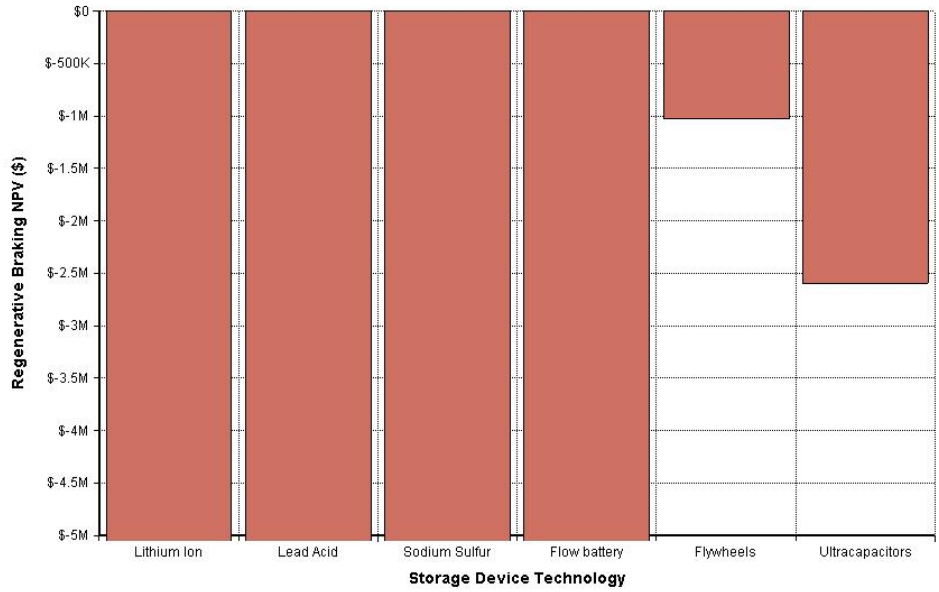


FIGURE 52 GCRTA Regenerative Braking NPV by Technology

FIGURE 53 shows the NPV sensitivity analyses for a flywheel WESS in the regenerative braking application for the Tower City station. This analysis shows how changes in input variables affect the overall value of the WESS device. For all devices in this application, train velocity on approach is the most sensitive variable. The sensitivity of these variables indicates that WESS NPV for regenerative braking is greatly affected by the frequency and size of regenerative braking opportunities. The consistent high sensitivity of system size reduction, power capacity cost, energy module cost per replacement, and the efficiency and receptivity variables shows that the NPV of the WESS device is affected by changes in the necessary capacity and overall cost of the WESS. While, no WESS currently achieves a positive NPV for the regenerative braking application, the NPV sensitivity analyses for this application shows that different operational characteristics and future improvements in WESS costs could bring flywheel technologies much closer to a positive value proposition.

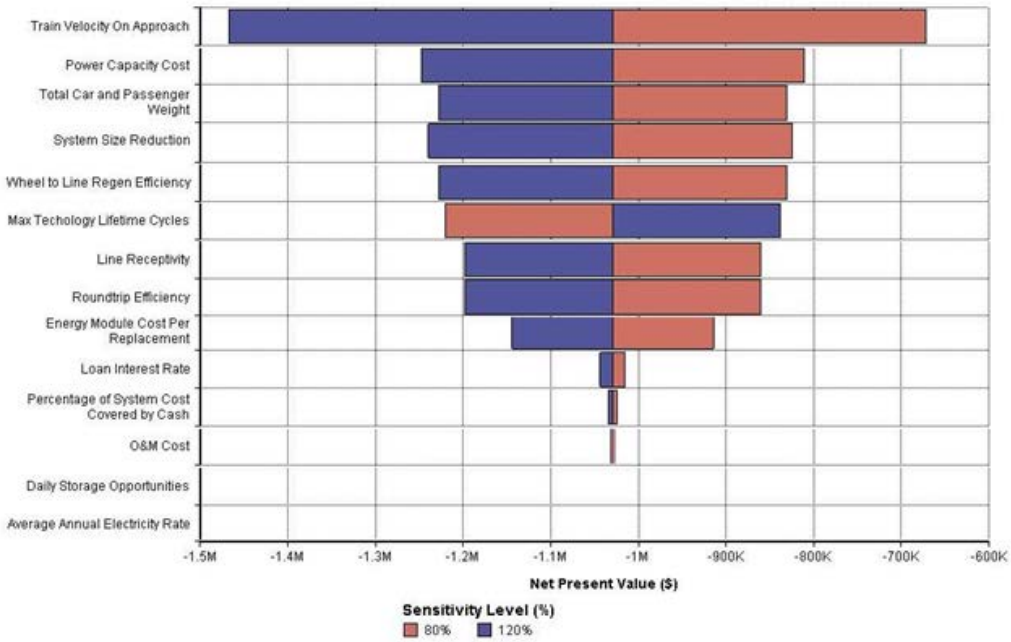


FIGURE 53 GCRTA Sensitivity Analysis for Regenerative Braking for Flywheel WESS

Regenerative braking support from a WESS requires rapid cycling with high power loads and relatively small amounts of energy stored and discharged. Ultracapacitors have a very low amount of energy capacity per unit of power capacity. Battery technologies, on the other hand, have a large amount of energy storage capacity for a relatively small power capacity. Battery devices thus require significantly over-built energy capacity to achieve the same regenerative braking power capabilities of a flywheel or ultracapacitor WESS. This over-built capacity results in lower cost-effectiveness for battery units in the regenerative braking application.

Flywheels are the best technology option for regenerative braking at the Tower City station, yielding an NPV of -$1,029,000. Regenerative braking provides steady energy charge savings, combined with smaller demand savings, which total to about $7,500 per year in benefits. Flywheels are the most attractive technology due to low power capacity costs, high efficiency, and a very high cycle lifetime compared to other technologies. The NPV of flywheels for regenerative braking is highly sensitive to the size and frequency of regenerative braking opportunities, which are in turn highly dependent on train operation patterns. Capital cost for flywheels is the most significant cost contributing to the negative NPV. It is feasible that significantly improved capital costs and different train operation patterns, to

increase the velocity and frequency of train stops, could make flywheel WESS a positive investment for a transit system. Transit systems and stations with large and frequent braking events would require a larger WESS for regenerative braking.

Electricity cost management, with lithium ion battery WESS, results in a less negative NPV than regenerative braking at the GCRTA Tower City station, largely due to the smaller system capacity requirements for the electricity cost management application. However, electricity cost management offers very small annual benefits in reduced electric costs, due to the WESS roundtrip efficiency losses, GCRTA flat rate schedule, and very low demand charges. A lithium ion WESS results in roughly $1,000 annual savings in electricity costs when applied to provide electricity cost management for the Tower City station, with an NPV of -$960,000.

As both modeled applications resulted in a negative NPV, GCRTA development of WESS appears to require reduced system capital costs, as well as increased electric rates, before it will provide a positive value for the transit agency. This system cost reduction can come through improvement in technology manufacturing, or from public grants and cost-share measures. Increases in demand charges and in the peak rate charges will increase the benefits from a WESS for electricity cost management and regenerative braking alike. Based on the NPV sensitivity analysis performed for electricity, the model indicates that lithium ion WESS would gain a positive NPV when capital costs reach $1000/kW, down from the current $1800/kW, and demand charges increase to about $40 in summer and $30 in winter. Public grants could reduce initial costs and help make WESS a positive investment for GCRTA.

6.0 CONCLUSIONS

In this project, Navigant explored the use of WESS in transit systems to achieve economic and technical benefits as shown in TABLE 25. In addition to achieving their primary objectives, transit agencies may be able to realize additional revenue or other economic benefits as a secondary objective by using the WESS for utility applications.

TABLE 25 Transit Agency Rationale, Objectives, and Applications for WESS

Rationale	Primary Objective	Transit Application
Economic	Electricity cost management	Time-Based Rate Management
		Demand Charge Management
	Energy efficiency & resource optimization	Regenerative Braking
		Renewable Energy Optimization
Technical	Power quality improvement	Voltage Control
		VAR Control
		Phase Balancing
	Reliability improvement	Backup Power
Rationale	**Secondary Objective**	**Utility Application**
Economic	Revenue optimization	Peak Demand Reduction
		Renewable Energy Integration
		Ancillary Services

Navigant modeled the costs and benefits of various applications using hypothetical simulations as well as case studies using real data from our transit agency partners Denver RTD and GCRTA. The simulations were individual applications or combinations of applications listed in TABLE 25 including:

1. Simulation #1: Time-based rates and demand charge management
2. Simulation #2: Regenerative braking
3. Simulation #3: Renewable Energy Optimization
4. Simulation #4: Voltage Control
5. Simulation #5: Backup Power
6. Simulation #6: Backup power with time-based rate management and demand charge management
7. Simulation #7: Voltage Support with regenerative braking

Simulations

Investing in a single system that can be used for multiple applications and provide a variety of benefits will result in the most attractive NPV. WESS power and energy requirements as well as when the WESS is required to operate for each application dictate which applications can be combined. Based on these restrictions, energy applications were combined in Simulation #6 and power applications were combined in Simulation #7.Simulation #6: Backup power with time-based rate management and demand charge management resulted in an NPV of about $80,000.

However, all the other simulations did not result in a positive NPV using the standard assumptions. Combining time-based rate management and demand charge management for electricity cost management in Simulation #1 indicated that benefits can be captured for each technology studied. However, when the capital and O&M costs were considered, electricity cost management did not result in a positive NPV over a 15 year period under the assumptions and parameters modeled. The sensitivity analysis showed that capital cost is the most important variable and as technology costs decline, this may become a more attractive option.

Simulation #2 for regenerative braking also showed that benefits can be realized, however, it did not result in a positive NPV. Once again the sensitivity analysis showed that capital cost is one of the important variables and as technology costs decline, this may become a more attractive option. In contrast to the electricity cost management application, where various technologies are competitive options, flywheels were more attractive than other technologies evaluated on an NPV basis. Flywheels appear to have the best combination of performance characteristics such as cycle life and ratio of power to energy storage capacity. High cycle life is crucial for regenerative braking since annual cycles can easily exceed 100 cycles per day for an typical transit schedule. Unlike electricity cost management, regenerative braking benefits are almost completely dependent on energy cost. The higher the electricity rate ($/kWh) that a transit authority pays for energy, the greater the regenerative braking benefit. Industry stakeholders believe that the capital cost for a flywheel system can be reduced by 40% with economies of scale.

Simulation #3 indicated that the annual electricity cost would decline if a WESS were added to a renewable energy system. However, the benefits from shifting renewable energy from off-peak to on-peak did not outweigh the capital and O&M costs associated with the WESS.

Simulation #7 indicated that combining voltage support with regenerative braking is promising but did not provide a positive NPV with the parameters modeled.

Simulations #1 through #3 and #7 represent the applications with an economic rationale so the NPV for these applications is an important decision criterion. Technology capital cost or other parameters would have to change in order for these to be attractive applications.

However, Simulations #4 and #5 represent applications that would be implemented for technical reasons (i.e., the transit agency must invest in a technology to address a power quality or reliability issue). In this situation, the transit agency may consider implementation even if it required an economic investment in order to resolve the technical issue. The NPV of the WESS compared to an alternate technology is more important than whether the NPV is positive. In Simulations #4 and #5, the results of the model indicated that implementing a WESS was more attractive than implementing a traction power substation (TPSS).

Case Studies

The Denver RTD case study considered electricity cost management (time-based rate management and demand charge management) as well as regenerative braking. The GCRTA case study considered electricity cost management (demand charge management only) as well as regenerative braking. In both cases, electricity cost management was slightly more attractive than regenerative braking using a flywheel, but neither provided a positive NPV with the assumptions modeled.

The annual benefits from regenerative braking are largely determined by the electricity rate schedule for each transit agency. GCRTA’s electric rates are 2 to 3 times higher than Denver RTD’s electric rates, but Denver RTD faces significantly higher demand charges and has more regenerative braking opportunities than GCRTA. Therefore, the total annual regenerative braking benefits for Denver RTD are slightly more than those accrued by GCRTA.

The electricity cost management application provided significantly more benefits for Denver RTD than for GCRTA. This is primarily due to the fact that GCRTA does not have time-based rates and cannot take advantage of these benefits. GCRTA’s electricity cost management case study included only demand charge management. In addition, GCRTA pays demand charge rates that are only 10% to 20% of the rates faced by Denver RTD.

These two case studies underscore the importance of transit system operational characteristics in any WESS analysis. The results vary widely based on the assumptions used, particularly for electric load patterns.

Changes in electricity rate schedules to increase demand charges and peak energy charges would greatly increase the value of WESS for both electricity cost management and regenerative braking.

The value proposition for WESS would be substantially improved by federal grants or other incentives. Incentives are used as a means to accelerate market adoption for early stage technologies that have higher costs and are not fully proven operationally. Public grants or loan guarantees effectively reduce the initial capital costs or loan rates for WESS projects.

In summary, the key findings were:

1) Combining applications provides benefits that result in the most attractive NPV. Simulations #6 modeled a combination of applications that resulted in a positive NPV.

2) Applications that solve a technical problem, such as to address a power quality or reliability issue, may be attractive to a transit agency even if the NPV is not positive. This was the case in Simulations #4 and #5. The important consideration is whether WESS is less expensive than the alternative technology.

3) The results for each of the applications could be improved with a reduction in WESS capital cost, which is expected for most technologies over the next few years as they become commercially available and are produced in larger quantities.

4) The financial value proposition for WESS would be improved by federal capital grants or other incentives. This project analyzed the value of WESS as an investment made solely by the transit agency without capital funds from other sources.

5) This analysis considered the business case for a transit agency and therefore monetized on the benefits that accrue to the transit agency. However, if a societal perspective had been modeled and other benefits were monetized, WESS would likely be much more attractive in these applications.

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LIST OF ACRONYMS

AC	Alternating current
APTA	American Public Transportation Association
DC	Direct current
EIA	U.S. Energy Information Administration
EPRI	Electric Power Research Institute
ESRC	Energy Storage Research Consortium
GCRTA	Greater Cleveland Regional Transit Authority
Li ion	Lithium ion
MTA	New York Metropolitan Transit Authority
MiMH	Nickel Metal Hydride
NPV	Net present value
NYCT	New York City Transit
O&M	Operations and maintenance
NaS	Sodium Sulfur
PbA	Lead Acid
PbC	Carbon Modified Lead Acid
RTD	Regional Transportation District
SRT	Sacramento Rapid Transit
TOU	Time of use
TRB	Transportation Research Board
VRB	Vanadium Redox Battery
WESS	Wayside energy storage systems
ZnBr	Zinc Bromide

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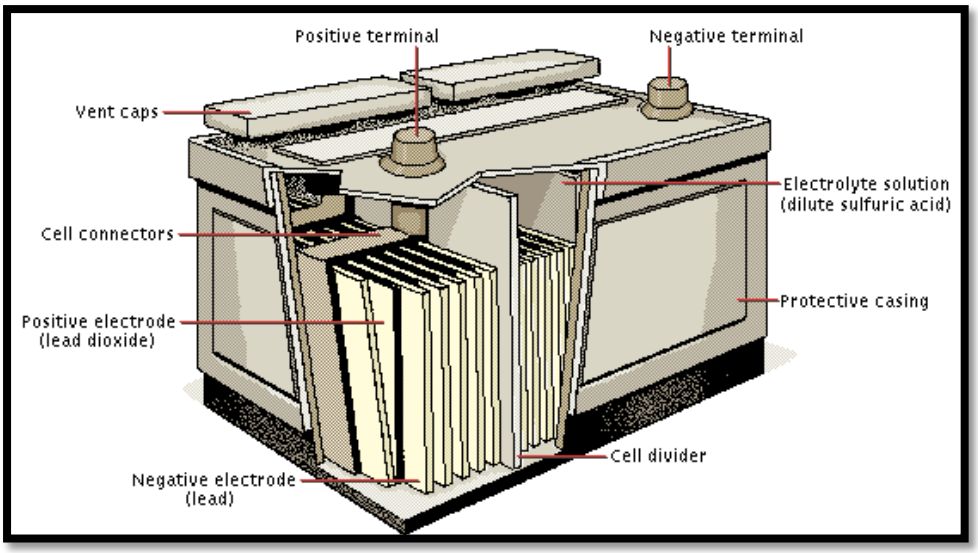
APPENDIX A: DESCRIPTION OF WESS TECHNOLOGIES

A.1 Lead Acid (PbA) Battery

Lead acid (PbA) batteries are one of the oldest and most developed battery technologies for ES and they are one of the most inexpensive battery technologies available. Each cell contains electrodes of lead metal and lead dioxide in an electrolyte of sulfuric acid. In the discharged state, both electrodes turn into lead (II) sulfate. The electrolyte then loses its dissolved sulfuric acid and becomes primarily water. (See FIGURE 54.) Since PbA batteries contain strong acids and lead, they are environmentally unfriendly. In addition, limitations of the lead-acid chemistry restrict the voltage of a single cell to a little more than 2 volts DC. Nonetheless, it is possible to produce systems with higher voltage by electrically linking cells in series.

There are two main types of conventional lead acid batteries: flooded lead acid cell and valve-regulated lead acid (VRLA). VRLA has internal gas recombination that minimizes electrolyte loss over the life of the battery and allows for mounting in any position. This technology offers a limited number of full discharge cycles. On the other hand, PbA batteries have relatively low maintenance requirements, no memory effect, and high discharge rates. PbA batteries are relatively inexpensive compared to other battery types. Though less expensive compared with other battery technologies, conventional lead acid batteries will be able to compete in few utility applications due to their limited number of full discharge cycles, their material toxicity, and their required footprint. However, they may be used for long duration, non-cyclic discharge activities. Several large-scale ES devices have been demonstrated using conventional PbA batteries such as those located in Chino, CA (10 MW), Puerto Rico (20 MW), and Germany (18 MW). There are several large players in the PbA market including East Penn Manufacturing Company, Exide Technologies, and EnerSys.

Carbon modified lead acid (PbC) and Advanced PbA batteries have recently emerged for utility applications. The carbon modified device contains a traditional lead-acid battery positive electrode and an activated carbon negative electrode. The research emerged in an effort to improve the performance of lead-acid batteries under conditions similar to those required for hybrid electric vehicle operation (high-rate partial state-of-charge operation). The addition of carbon has shown to slow or prevent negative plate sulfation, which deteriorates battery performance of conventional PbA devices over time. Other advanced PbA batteries incorporate an ultracapacitor to handle their short duration needs.



Source: http://www.reuk.co.uk

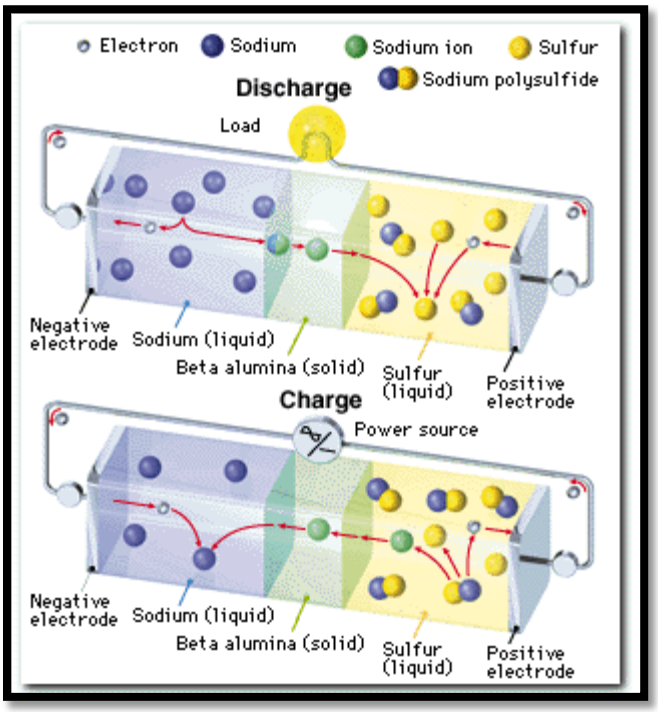
FIGURE 54 PbA Battery

A.2 Sodium Sulfur (NaS) Battery

The sodium sulfur (NaS) battery, illustrated in FIGURE 55, consists of a beta alumina conductive ceramic that separates and permits ions to flow between the positive electrode (sulfur) and the negative electrode (sodium). It can be used continuously because of its reversible charging and discharging system. This type of battery is heated to approximately 300°C to reduce the internal resistance, and requires an installation area that is smaller than that for a flow battery and approximately one third for that of a lead acid battery. The typical efficiency of NaS batteries is 75-80% and the lifetime is 12-15 years with more than 2,500 cycles.

There are currently several demonstration and commercial installations in the U.S. and worldwide, despite the fact that NaS batteries remain very expensive on a per kW basis. Scaling of NaS systems is more expensive than scaling of flow batteries, and NaS-based ES projects cost approximately $2,500/kW - 3,000/kW, installed[21]. Given the backlog that NGK Insulators has in orders, the price appears to be increasing instead of decreasing over time.

In the 1960s, Ford Motor Company developed the basic NaS principles, and by the 1990s, Ford was using NaS batteries for its electric prototype vehicles. In the 1980s, Tokyo Electric Power Company (TEPCO) began NaS technology development, and by 1998, a Joint R&D effort with NGK Insulators, Ltd. (NGK) in Japan led to a 6 MW NaS battery system at TEPCO's Ohito Substation[22]. After 50 demonstrations in Japan, NaS batteries were offered for commercial sale in Japan in April 2002, with 40 MW produced in 2003 and 65 MW in 2004. In July 2004, the largest NaS to date was installed by TEPCO with a capacity of 9.6 MW (57.6 MWh) project for daily load shifting. In September 2002, American Electric Power (AEP) hosted the first US demonstration of a NaS battery (100 kW, 375 kWh) and by July 2006, AEP began operating a 1MW NaS battery, the first commercial-scale application outside Japan[22]. As of 2008, approximately 200 large-scale demonstrations totaling 270 MW had been installed worldwide. NGK is currently the only vendor of NaS batteries but POSCO, a Korean steel company, has announced plans to begin development of a sodium sulfur battery with commercial production by 2015.



Source: NGK Insulators, LTD

FIGURE 55 NaS Battery

A.3 Lithium Ion (Li ion) Battery

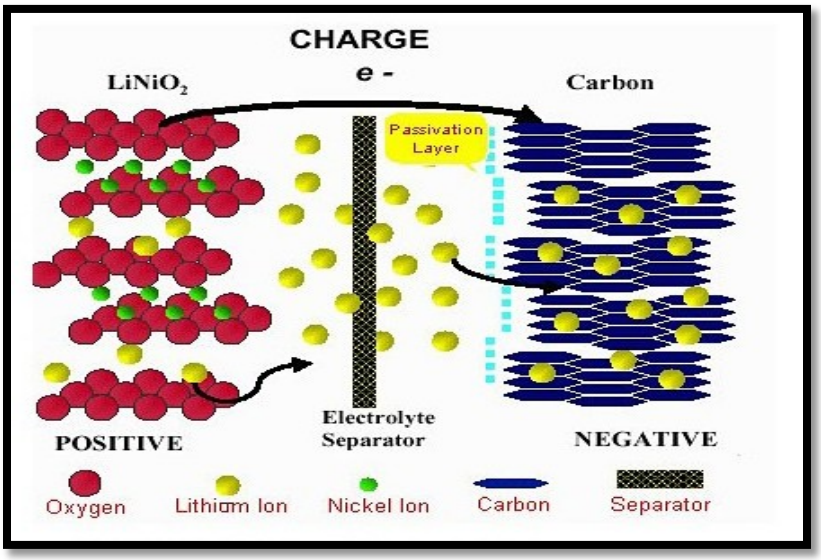
Li ion batteries are amongst the newest rechargeable batteries, but within just a few years of their introduction, small Li ion batteries have taken over 50% of the small portable power market, displacing nickel metal hydride (NiMH) batteries. The characteristics of the Li ion battery make it ideal for commercial and residential applications including load shifting, photovoltaic integration, and electric vehicles. They are currently undergoing demonstration testing in utility applications.

Energy costs are currently higher than other battery technologies at ~ $2,000/kWh. However, at high production volumes, the estimated manufacturing cost could be reduced significantly. Li-ion R&D expenditures worldwide are around $1 B per year and technological advances may drive the price lower[23]. While relatively expensive on a per kWh basis, Li ion batteries could gain substantial market share if prices can be reduced.

When a Li ion battery charges, as illustrated in FIGURE 56, lithium atoms in the cathode become ions and migrate through the electrolyte toward the carbon anode where they combine with external electrons and are deposited in the anode as lithium atoms. The process is reversed during discharge. Lithium ion batteries can have a variety of anode and cathode materials, which impacts the battery energy density and voltage. Lithium Iron Phosphate is considered to be the most mature of the new lithium ion chemistries, and is being pursued by major storage vendors in the utility-application space, including A123 and International Battery.

In 2007, KEMA successfully tested a Li ion prototype developed by Altairnano Technologies for frequency regulation at a US substation. The system consisted of two 1 MW batteries based on lithium titanate battery cells. Each unit was designed with enough capacity to deliver 1 MW to a 480V electric distribution system for the duration of 15 minutes. Unit efficiency was relatively high, with application efficiencies in the low 90% range.

Developers are currently focusing on electric vehicles as a key target application for more research. This is highly desirable for utilities, as it will help to develop higher energy densities that can store more energy in smaller, lighter packages. Furthermore, Li ion is currently being developed for use in HEVs, which may eventually displace NiMH from its current dominance in this market. In 2008, Sanyo and Volkswagen AG announced that they would develop Li ion batteries for hybrid electric vehicles (HEVs), and hoped to use them by 2010[24].



Source: www.saftbatteries.co

FIGURE 56 Li ion Battery

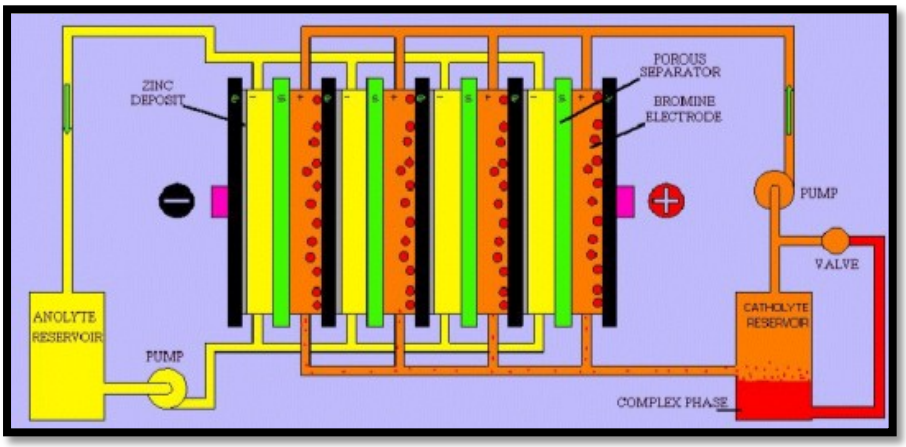
A.4 Zinc Bromide (ZnBr) Flow Battery

As FIGURE 57 shows, ZnBr batteries consist of an aqueous solution of zinc bromide circulated through the compartments of the cell from two separate reservoirs. The electrolyte stream in contact with the positive electrode contains bromide, which is maintained at the desired concentration by equilibrating with a bromide storage medium.

Flow batteries are capable of storing and releasing energy through a reversible electrochemical reaction between two salt solutions (electrolytes). Since they offer power and energy with a high cycle life at any depth of discharge, they are well-suited for moderate to high power, long discharge duration applications such as load shifting. The capacity of a flow battery is determined by the size of the electrolyte storage tanks, while the power of the system is a function of the size of the cell stacks. At a high-level, the difference between types of flow batteries is the composition of the electrolyte solution used.

This technology has reached the demonstration stage with some small-scale products commercially available. For applications beyond 3 hours, the cost of flow batteries is more attractive than the conventional lead acid batteries by a factor of 2 to 3. Within the next 5 years, flow batteries utilizing Zinc Bromide (ZnBr) or Vanadium Redox technologies will likely become the technology of choice for these applications since costs are expected to be significantly lower than that of NaS batteries.

Premium Power, ZBB, and Red Flow are the main vendors and ZnBR flow batteries for utility applications. All three companies have commercially available small-scale products and are demonstrating several large-scale projects.



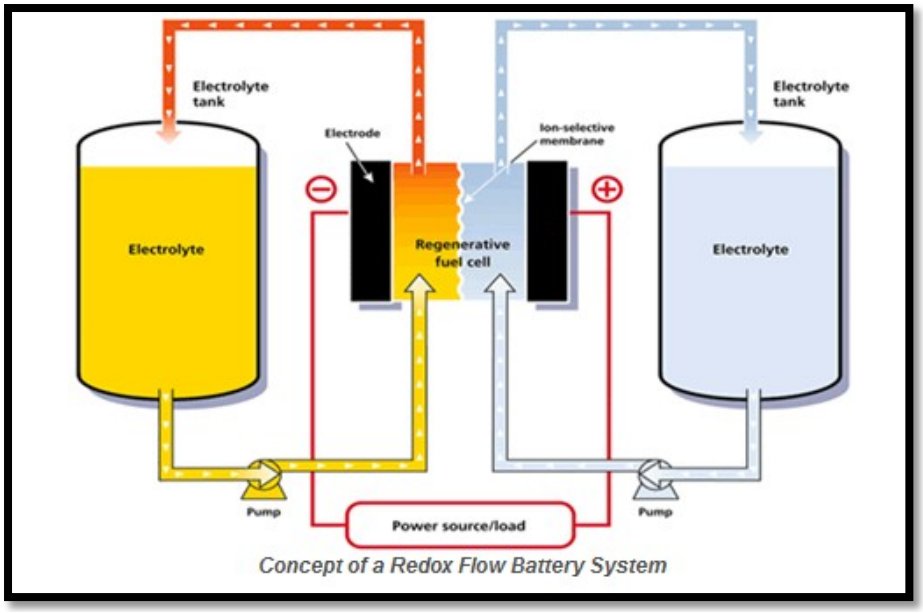
Source: www.ZBBenergy.com

FIGURE 57 ZnBr Flow Battery

A.5 Vanadium Redox (VR) Flow Battery

Prudent Energy is the top industry player for the VR technology. Ashlawn Energy is also currently developing a vanadium redox battery for demonstration. VR stores energy by employing vanadium redox couples (V2+/V3+ in the negative and V4+/V5+ in the positive half-cells) that is stored in mild sulfuric acid solutions (electrolytes). (See FIGURE 58.)

As mentioned for ZnBR, flow batteries are capable of storing and releasing energy through a reversible electrochemical reaction between two salt solutions (electrolytes). Since they offer power and energy with a high cycle life at any depth of discharge, they are well-suited for moderate to high power, long discharge duration applications such as load shifting. The capacity of a flow battery is determined by the size of the electrolyte storage tanks, while the power of the system is a function of the size of the cell stacks. At a high-level, the difference between types of flow batteries is the composition of the electrolyte solution used.



Source: www.pdenergy.com

FIGURE 58 VR Flow Battery

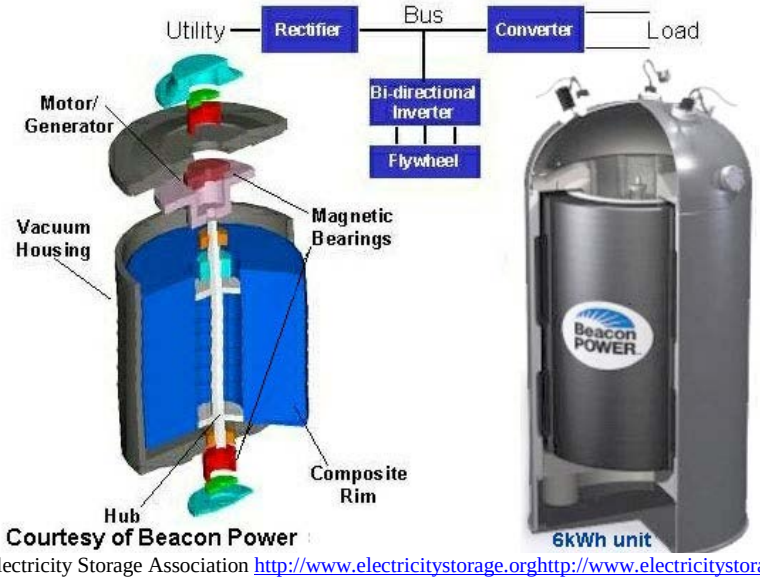
A.6 Flywheel

Flywheels store energy in a rotating mass and release it over a very short amount of time. A flywheel ES system draws electrical energy from a primary source such as the utility grid, and stores it in a high-density rotating flywheel. The flywheel system is actually a kinetic, or mechanical, battery spinning at very high speeds to store energy that is instantly available when needed. (See FIGURE 59.) Upon power loss, the motor driving the flywheel acts as a generator. As the flywheel continues to rotate, the generator supplies power to the customer load. There are two major categories of flywheel ES systems: low-speed systems (<10,000 RPMs) and high-speed systems (>30,000 RPMs).

Low-speed systems consist of a high mass flywheel and power electronics to convert between DC and AC voltages. High-speed systems rely on magnetic bearings, vacuum chambers, and permanent magnet motor/generator to provide high efficiency operation and high energy density storage capability.

Despite high cycle life, flywheels are one of the most expensive technologies on a per KW basis. Current estimated capital costs for higher energy flywheels are approximately $2,000/kW. Beacon Power, the dominant flywheel provider in the market, has a cost target for its next 20 MW facility of $1,250-1,500/kW[25].Flywheels that offer lower energy (1 to 10 seconds) have significantly lower costs. Some flywheel products are commercially available, but advanced flywheel technologies are still under development. Flywheels are best suited for high power, low energy applications such as frequency regulation and power quality.

Beacon Power and Active Power are leaders in the industry. A third industry leader, Pentadyne, recently sold its uninterruptible power supply assets to Phillips Service Industries and Kinetic Traction Systems, Inc. was formed which focuses on flywheels for transit applications. Active Power, Phillips, and Kinetic Traction Systems offer lower energy (1 to 10 seconds) flywheel-based power quality technologies commercially available, and Beacon Power offers higher energy (15 minute) utility-scale flywheel systems currently being demonstrated to provide frequency regulation services. The Beacon Power flywheel design includes an integrated system of 100 kW flywheels, interconnected in a matrix to provide ES for utility-scale applications. The Beacon system is designed to deliver megawatts of power for minutes, providing frequency and voltage regulation capabilities for increased grid reliability. Velkess and Temporal Power are also currently researching advanced flywheel systems for utility applications.



Source: Electricity Storage Association http://www.electricitystorage.orghttp://www.electricitystorage.org

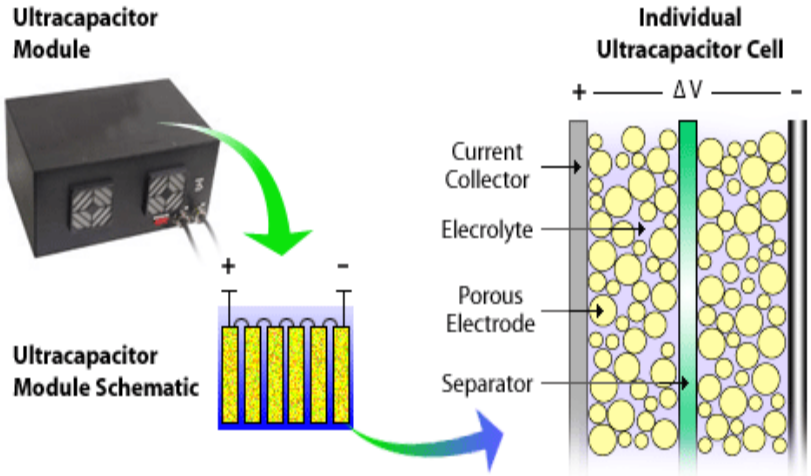
FIGURE 59 Flywheel

A.7 Ultracapacitor

Ultracapacitors (*also called supercapacitors or electrochemical double layer capacitors*) polarize an electrolytic solution to store energy electrostatically and release it quickly. (See FIGURE 60.) Though it is an electrochemical device, no chemical reactions take place. This mechanism is highly reversible, and allows the Ultracapacitor to be charged and discharged hundreds of thousands of times[26]. The amount of energy stored is very large compared to a standard capacitor. However, it stores a much smaller amount of energy than a battery does.

Ultracapacitors offer high cycle life and high power density, but their low energy density limits the number of appropriate applications. Ultracapacitors can release energy much more quickly (with more power) than a battery that relies on slower chemical reactions[26]. Ultracapacitors release their stored energy over a very short period of time of roughly 1 to 10 seconds. Their cycle life is estimated to be over 500,000 cycles. Since they are inherently low voltage devices, hundreds of cells must be series-connected to meet requirements of a utility application. Failure of just one cell can lead to failure of the entire storage system. While total capital costs in terms of power are in the range of $250/kW to $350/kW, energy costs are extremely high, ranging from $20,000/kWh to $30,000/kWh. Currently, most applications for ultracapacitors are focused on transportation, but there are several demonstrations of interest to the utility industry.

The Palmdale water district in California has deployed a Maxwell ultracapacitor system with 450 kW/30 seconds capacity, to maintain high power quality on protected loads at all times, provide power to protected load in case of utility sag or outage, meet the ITI (CBEMA) curve during power quality events, and resynchronize with backup power or grid as necessary. Testing and operation began in 2008[27] [28] Sacramento municipal light rail also uses this storage technology in wayside application, with a 1 MW ultracapacitor bank that absorbs braking energy to relieve overloading, reduce voltage sags, and increase train capacity. Testing and operation for the Sacramento WESS began in 2008[28].



Source: NREL: Energy Storage – Ultracapacitors. http://www.nrel.gov/vehiclesandfuels/energystorage/ultracapacitors.html.

FIGURE 60 Ultracapacitor