FTA RESEARCH

FEDERAL TRANSIT ADMINISTRATION

WMATA Energy Storage Demonstration Project

Final Report

JUNE 2015

FTA Report No. 0086
Federal Transit Administration

PREPARED BY

Moustapha Ouattara
Washington Metropolitan Area Transit Authority (WMATA)

J. Gordon Yu
Gannett Fleming Transit & Rail Systems

U.S. Department of Transportation
Federal Transit Administration

COVER PHOTO

Courtesy of Edwin Adilson Rodriguez, Federal Transit Administration.

WMATA Energy Storage Demonstration Project

Final Report

JUNE 2015

FTA Report No. 0086

PREPARED BY

Moustapha Ouattara
Washington Metropolitan Area Transit Authority (WMATA)

J. Gordon Yu
Gannett Fleming Transit & Rail Systems

SPONSORED BY

Federal Transit Administration
Office of Research, Demonstration and Innovation
U.S. Department of Transportation
1200 New Jersey Avenue, SE
Washington, DC 20590

AVAILABLE ONLINE

http://www.fta.dot.gov/research

Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liter	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY	2. REPORT DATE June 2015	3. REPORT TYPE AND DATES COVERED 2013-2014

4. TITLE AND SUBTITLE WMATA Wayside Energy Storage Demonstration Project	5. FUNDING NUMBERS DC-26-7209

6. AUTHOR(S)
Moustapha Ouattara, J. Gordon Yu

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESSE(ES) WMATA CENI-Office of Chief Engineer, Infrastructure 4C-01 600 5th St. NW Washington, DC 20001	8. PERFORMING ORGANIZATION REPORT NUMBER FTA Report No. 0086
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Department of Transportation Federal Transit Administration Office of Civil Rights East Building 1200 New Jersey Avenue, SE Washington, DC 20590	10. SPONSORING/MONITORING AGENCY REPORT NUMBER FTA Report No. 0086

11. SUPPLEMENTARY NOTES [http://www.fta.dot.gov/research]

12A. DISTRIBUTION/AVAILABILITY STATEMENT Available from: National Technical Information Service (NTIS), Springfield, VA 22161. Phone 703.605.6000, Fax 703.605.6900, email [orders@ntis.gov]	12B. DISTRIBUTION CODE TRI-20

13. ABSTRACT
This report summarizes the experience and the test results from the Washington Metropolitan Area Transit Authority (WMATA) Energy Storage Demonstration Project, a project that was partially funded by the Federal Transit Administration (FTA). WMATA worked jointly with Kawasaki Rail Car, Inc., and Kawasaki Heavy Industries, Ltd., to implement the demonstration. Gannett Fleming Transit & Rail Systems served as the technical consultant. The installation was tested under normal revenue service conditions. The test results include energy saving, peak power reduction, and train voltage support that are provided by the 2MW Battery Power System (BPS) installation. In addition, the same installation was tested as an emergency power source to move trains to desired destinations when the traction power system is under a simulated blackout situation. Based on the obtained results and the prevailing electricity cost parameters, return-on-investment calculations were performed for the installation life times of both 10 years and 20 years

14. SUBJECT TERMS Regenerative braking energy recovery, energy savings for mass transit systems, emergency power for mass transit systems, energy storage applications in traction power systems	15. NUMBER OF PAGES 39

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

This report was developed for the Federal Transit Administration's Office of Technology. Special thanks to Roy Chen, Transportation Engineer, for his guidance and support. The demonstration project at WMATA would not have been possible without the support and cooperation of many people. The authors also thank the following:

WMATA

Ashton Robinson
Oscar Ravarra
Wayne Ficklin

Kawasaki Rail Car, Inc.

John Calvello
Willard Francis
Maurice Andriani

Kawasaki Heavy Industries, Ltd.

Shoichi Morioka
Takahiro Matsumura
Koki Ogura

ABSTRACT

This report summarizes the experience and the test results from the Washington Metropolitan Area Transit Authority (WMATA) Energy Storage Demonstration Project, a project that was partially funded by the Federal Transit Administration (FTA). WMATA worked jointly with Kawasaki Rail Car, Inc., and Kawasaki Heavy Industries, Ltd., to implement the demonstration. Gannett Fleming Transit & Rail Systems served as the technical consultant.

The installation was tested under normal revenue service conditions. The test results include energy saving, peak power reduction, and train voltage support that are provided by the 2MW Battery Power System (BPS) installation. In addition, the same installation was tested as an emergency power source to move trains to desired destinations when the traction power system is under a simulated blackout situation. Based on the obtained results and the prevailing electricity cost parameters, return-on-investment calculations were performed for the installation life times of both 10 years and 20 years.

EXECUTIVE SUMMARY

This report presents the results of the WMATA Energy Storage Demonstration Project.

The rail cars in the WMATA Metrorail system use regenerative braking to recover a substantial amount of energy that otherwise would have been wasted. The ratio of the recovered energy over the available energy (defined as the receptivity of the system) depends primarily on the service frequency, among other factors. An energy storage system helps with the additional recovery of the braking energy. It also helps reduce peak power demands from substations and reduce the voltage drops to motoring trains. WMATA decided to install a demonstration unit and collect in-service data to quantify the benefits of such a system and determine the return on investment. Such data are not only useful to WMATA, but also to other rail agencies. FTA partially sponsored this demonstration project so that the experience gained from this demonstration can be shared in the wider industry.

A 2MW Battery Power System (BPS) was installed in West Falls Church Yard on the Orange Line of the WMATA metro network. The system uses the high-capacity Nickel-metal Hydride GIGACELL technology by Kawasaki Heavy Industries, Ltd. The objective of the demonstration was to assess the suitability and effectiveness of the system in a mass rapid transit rail environment.

Electronic data recorders have been used to collect the real-time performance data. This report contains the analysis of the test results.

Three scenarios were tested:

- Scenario A – West Falls Church substation with 6MW rectifiers
- Scenario B – West Falls Church substation with 3MW rectifiers
- Scenario C – West Falls Church substation without any rectifier, acting as a tie-breaker station

In each scenario, the BPS was turned off for one week and then turned on for the next week to assess its effects. The results from the available test data are summarized as follows:

- Energy saving – Equivalent annual energy saving between 7.2% (Scenario A) and 15.4% (Scenario C) was achieved. (Energy saving for Scenario B was not calculated because the data were incomplete due to train operational anomalies during the test.)
- Peak power shaving – Peak power shaving between 121 kW (Scenario A) and 436 kW (Scenario C) was achieved.
- System voltage improvement – Voltage stabilization effect between 42 V (Scenario A) and 139 V (Scenario C) was achieved.

- Emergency power – Powered by the BPS alone, a 6-car train without passengers (AW0 load) started from standstill and moved 2,800 feet at a speed limit of 10 mph. This train movement consumed 4% of the BPS energy capacity. If the train had been loaded at crush load (AW2 load at 175 passengers per car), the same train movement would have consumed 5.24% of the BPS energy capacity. From this test, it was calculated that the fully-charged BPS can support 19 such train movements at AW2 load in succession if the BPS is not used to supply any other load.

The test results demonstrate that the when the BPS is installed at a tie-breaker station, it yields better results than an equivalent installation in a traction power substation for the same battery system configuration.

Return-on-investment (ROI) calculations were performed based on the following parameters:

- Average electricity price of $0.124/kWh for the Washington-Baltimore area [4]
- National average electric energy price increase from 2013 to 2040 of 2.4% per year [3].
- Maintenance cost of BPS assumed to increase by 2% per year.

For a 10-year installation, the following results were obtained:

- For Scenario A, equipment cost (offset by additional benefits and cost for displaced investment) needs to be at or less than $730,000 for the system to achieve a positive financial return.
- For Scenario C, equipment cost (offset by additional benefits and cost for displaced investment) needs to be at or less than $1,870,000 for the system to achieve a positive financial return.

For a 20-year installation, the following results were obtained:

- For Scenario A, equipment cost (offset by additional benefits and cost for displaced investment) needs to be at or less than $410,000 for the system to achieve a positive financial return.
- For Scenario C, equipment cost (offset by additional benefits and cost for displaced investment) needs to be at or less than $2,650,000 for the system to achieve a positive financial return.

Additional benefits that may be realized from a BPS include the following:

- Voltage support for trains so that the traction power system can support the desired train service levels more effectively.

- Emergency power to trains in traction power blackout situations—this is particularly valuable in tunnel environments where the requirements for safety evacuation of passengers are more demanding than in an open-track environment.
- Significant capital cost savings if a BPS can be installed in place of one or more traditional rectifier units.
- Where the site conditions do not permit installations of traditional rectifier units, a BPS may be a viable option.

Quantification of these additional benefits is dependent on the actual situation, and the realization of these benefits may significantly improve the ROI calculation results. This is consistent with the findings from a previously-published study by the Transit Cooperative Research Program [5]: an energy storage installation in a rail transit environment is most practical when it realizes more than one benefit simultaneously rather than focusing the application primarily on solving any one problem alone.

SECTION 1 Introduction

The WMATA Metrorail System (Washington Metro) is the second busiest rapid transit system in the United States. The network is made up of 6 lines, including more than 117 route-miles of track and 91 passenger stations. The system map is shown in Figure 1-1.

Figure 1-1

Map of Washington Metrorail Network

At present, WMATA operates a mixture of 6-car and 8-car trains on its 6 lines. The Metro's train fleet consists of 6 types of rail cars, numbered as 1000-series to-6000 series. New 7000-series cars are being tested and will be introduced into service in 2015.

The trains are powered by more than 100 traction-power substations across the network through a 3rd rail 700 V dc distribution system. There are also more than 100 tie-breaker stations. A tie-breaker station normally is located between two adjacent substations and provides an electrical connection of the two parallel third rails associated with the power supply to the inbound and outbound tracks, so that the two tracks can share the loads and thus minimize the voltage drops to the trains.

The traction power system consumes about 500,000 MWh (MegaWatt-hours) per year, at a cost of approximately $48 million. (As a comparison, the average annual electricity consumption for a U.S. residential utility customer is approximately 11 MWh in 2013, according to the U.S. Energy Information Administration [2]. The traction power system energy consumption is equivalent to 45,450 U.S. homes.)

All cars in operation are capable of regenerative braking, which has benefitted WMATA in energy saving and reduction in energy cost. As the amount of energy saving is dependent on the chances that trains demanding power are near trains that are generating power, a significant amount of energy is lost as heat dissipates to the surrounding environment by braking resistors. Therefore, there is a lot of potential to achieve more energy savings through the adoption of new technologies and innovations.

Furthermore, as the volume of passengers has steadily increased on the system over the years, WMATA has formulated strategic plans to meet the rising service demands by migrating to 8-car trains as a uniform standard and operating more frequent services in the future. Consequently, the traction power system needs to be upgraded to support the increased power demands.

Research has shown that wayside energy storage substations can help capture more regenerative braking energy and increase the amount of energy saving. They also can help reduce peak power demands and provide voltage support to trains. Installation of wayside storage substations also may help delay or defer some of the need for capital investment in the upgrade of the traction power system. However, since this technology is relatively new with limited operational history, WMATA decided to evaluate its effectiveness through a demonstration project.

WMATA conducted an extensive initial assessment of different wayside energy storage technologies, including flywheels, electrochemical capacitors, and batteries. Subsequently, WMATA focused on the battery technology. After discussions with several battery vendors, WMATA selected GIGACELL battery for this demonstration project.

SECTION

2

Battery Power System (BPS) Technical Parameters and Installation

GIGACELL Battery Technology

GIGACELL is a state-of-art high capacity Nickel-metal Hydride (Ni-MH) battery developed by Kawasaki Heavy Industries, Ltd [1]. It has the following features:

- High scalability – Bipolar 3D design increases both the number and capacity of cells
- Rapid charge and discharge – Low internal resistance enables fast charging and discharging capability
- Excellent cycle durability – Designed to withstand frequent cycles of short, rapid charging and discharging requirements
- Simplicity and safety – Low operating temperature, water-based electrolyte eliminates risk of fire
- Environment-friendly – No use of lead, mercury, cadmium, or other toxic materials
- Ease of recycling – Easy to disassemble for recycling since no welding is used

Based on the GIGACELL battery, Kawasaki has developed the BPS technology specifically for rail and transit applications. A number of demonstration and commercial installations have been in operation in the rail and transit environment, including Osaka Municipal Transportation Bureau, Tokyo Monorail, East Japan Railway, and New York City Subway.

The fundamental element of the battery is a cell. Each individual cell has a nominal voltage of 1.2V. The cells are arranged in series to form a module. For the WMATA BPS installation, the Type 30-K5 module is used. This module has 30 cells connected in series, with a nominal voltage of 36V.

Specifications for the Type 30-K5 module are shown in Figure 2-1.

Figure 2-1
GIGACELL Specifications (Type 30-K5)

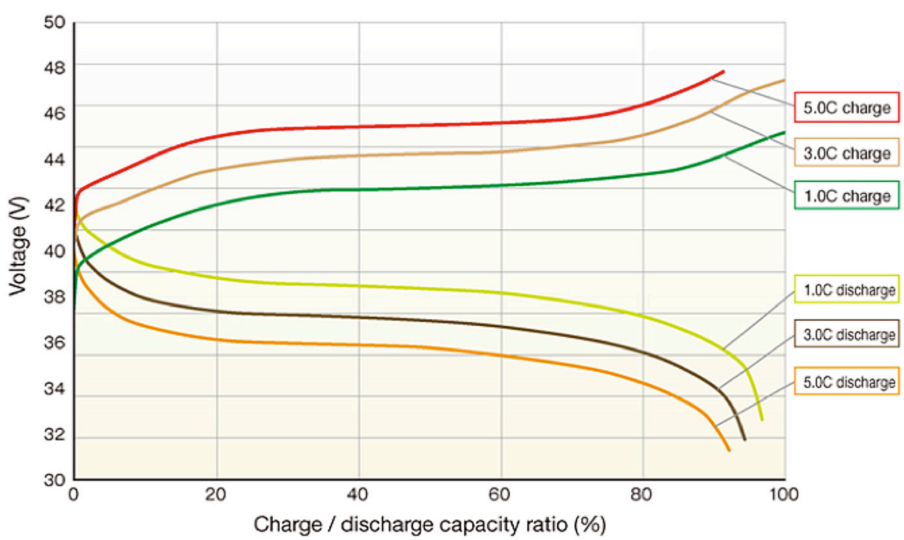
Battery Type	30-K5
Nominal voltage	36V
Rated capacity (1)	141Ah
Energy capacity	5.1kWh
Maximum output (2)	126kW
Outline dimensions L x W x H (3)	1287×218×350mm
Volume	98L
Weight	248kg
Energy density per unit volume	52Wh/L
Energy density per unit weight	21Wh/kg

(1) Discharge capacity when charged to 120% of rated capacity. As recommended capacity will depend on the operating conditions, please discuss your exact application need with our representative.
(2) Extrapolated from results of an I-V test (0.1 second discharge)
(3) Mounting hardware not included.
Specifications may change without notice.

Source: Kawasaki

Charging and discharging curves for type 30-K5 module are shown in Figure 2-2.

Figure 2-2
GIGACELL Charge and Discharge Curves (Type 30-K5)



Test conditions

Battery type	30-K5 GIGACELL
Environmental temperature	20 °C

Source: Kawasaki

The modules can be arranged in series to form a unit to provide higher voltage levels. The units can be arranged in parallel to provide desired current rating and energy capacity.

BPS Parameters

For each module:

- Number of cells in series: 30
- Nominal voltage: 36 V
- Ampere-hour capacity: 141 Ah
- Battery current at 1C charge/discharge rate: 142 * 1 = 141 A
- Battery current at 5C charge/discharge rate: 141 * 5 = 705 A
- Energy capacity: 141 * 36 / 1000=5.076 kWh

For each unit:

- Number of full modules in series: 18 (30 cells in series for each module)
- Number of partial module in series: 1 (19 cells in series for this module)
- Total number of cells in series per unit: 18 * 30 +1 * 19 = 559 cells
- Nominal voltage per unit: 559 * 1.2 V = 670.8 V
- Energy capacity per unit: 5.076 kWh * (18+19/30) = 94.58 kWh

For the full BPS:

- Number of units in parallel: 4
- Power rating for full system (at 5C charge/discharge rate): 670.8 * 705 * 4 / 1000 = 1,892 kW or 2 MW
- Energy capacity of the full system: 94.58 * 4 = 378.33 kWh

BPS System Installation

The BPS was installed in the West Falls Church substation located towards the west end of the Orange Line, as shown in Figure 2-3.

Figure 2-3

System Map for West End of Orange Line

The West Falls Church substation is near the West Falls Church station. It has four rectifier units; two feed the mainline tracks and two feed the yard tracks. The dc bus for the yard tracks is normally isolated from the dc bus for the mainline tracks. The BPS is connected to the dc bus for mainline tracks.

The two substations immediately adjacent to West Falls Church substation are Barbour Road substation (west of West Falls Church substation) and Fisher Street substation (east of West Falls Church substation), as shown in Figure 2-4.

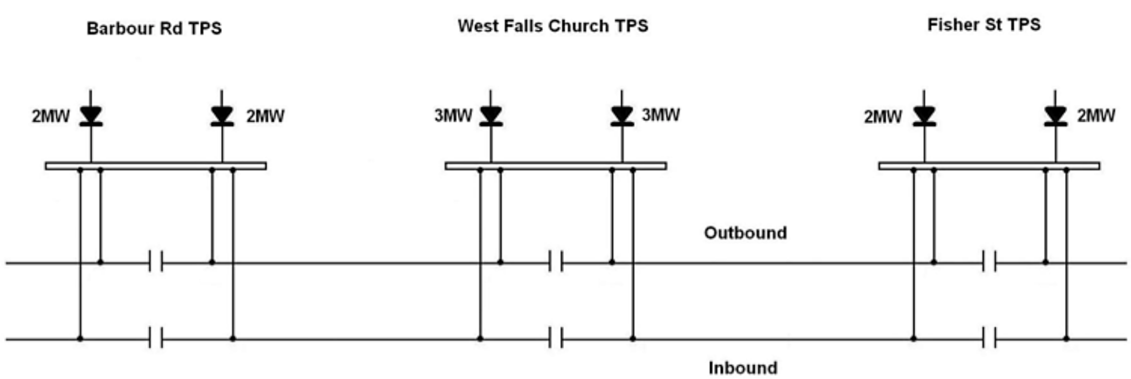


Figure 2-4

Simplified Electrical Single Line Diagram

The BPS was installed and put into service in June 2013. A photograph of the BPS installation is shown in Figure 2-5.

Figure 2-5

System Installation on Concrete Pad in West Falls Church Substation

Photo courtesy of Kawasaki

As shown in Figure 2-5, the BPS units are installed on a concrete pad outside of West Falls Church substation building. The concrete pad has an overall dimension of 24' x 50'. Of the three rows of cubicles shown in the photograph, the two outside rows have four BPS units and the center row has ancillary equipment, including high speed circuit breaker, cable terminations, etc.

A closer view of the two BPS units in the front row is shown in Figure 2-6.

Figure 2-6

Two BPS Units

Photo courtesy of Kawasaki

An air-conditioning unit is installed on top of the cubicle for each BPS unit. Each air-conditioning unit has a thermal capacity of 56,000 BTU (16.4 kWh).

Inside each BPS unit cubicle, four stacks of battery modules are housed together with air circulation fixtures for temperature control. The cubicle panels are insulated. A partial view of the internal arrangement is shown in Figure 2-7.

Figure 2-7

Battery Modules and Air Circulation Fixtures inside a Unit

As shown in Figure 2-7, each of the four stacks can house up to five battery modules. In this particular installation, a total of 19 modules was installed, 18 of which have 30 cells each. The 19th module has 19 cells, making it a partial module (19/30, or $^{2}/_{3}$). All battery modules within one unit are connected in series to yield the desired nominal voltage.

As part of the BPS installation, a battery monitoring system (BMS) also was installed inside the West Falls Church substation and is shown in Figure 2-8. A range of BPS parameters is monitored so that the BPS can be protected against fault conditions. These include battery temperature, pressure, cell voltage, etc.

Figure 2-8

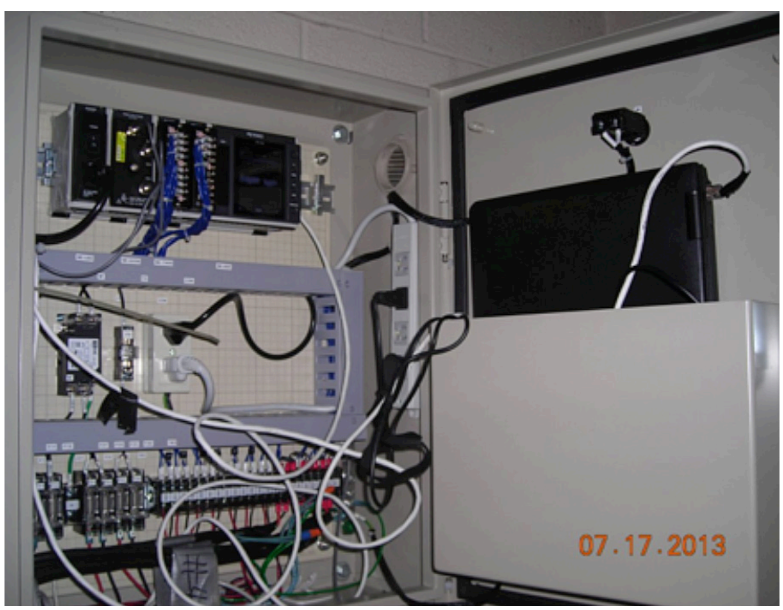
BMU inside West Falls Church Substation

Photo courtesy of Kawasaki

A data acquisition and communications unit was installed inside the West Falls Church substation. This was mounted on the wall of the building, as shown in Figure 2-9.

Figure 2-9

Data Acquisition and Communications Cubicle



A range of data was recorded, including rectifier currents, dc bus voltage, BPS charge and discharge currents, etc. The recorded data can be accessed remotely and was downloaded regularly for analysis.

Similar data acquisition units were installed in the Barbour Road substation and the Fisher Street substation to record the substation data at those sites.

SECTION

3

Test Results

BPS Test Scenarios

A number of tests were conducted to evaluate the performance of the BPS. The test scenarios are shown in Table 3-1.

Table 3-1

List of Scenarios and Test Durations

Scenarios	Tests	Rectifier Capacity kW	BPS Capacity kW	Start Date	End Date	No. of Days
A	A-1	6,000	0	Monday, 10/21/13	Sunday, 10/27/13	7
	A-2	6,000	2,000	Monday, 10/28/13	Sunday, 11/3/13	7
B	B-1	3,000	0	Monday, 8/9/13	Sunday, 8/25/13	7
	B-2	3,000	2,000	Monday, 8/26/13	Sunday, 9/1/13	7
C	C-1	0	0	Monday, 9/9/13	Sunday, 9/15/13	7
	C-2	0	2,000	Monday, 9/16/13	Sunday, 9/22/13	7

Note: For Scenario B, weekend data were not useable for energy saving calculation due to special single-track operation for engineering work unrelated to the BPS tests.

- Scenario A – West Falls Church substation with 6MW rectifiers
- Scenario B – West Falls Church substation with 3MW rectifiers
- Scenario C – West Falls Church substation without any rectifier, acting as a tie-breaker station

A summary of the collected data is listed in Table A-1 in Appendix A. This section summarizes the analysis results.

Energy Savings

For the three test scenarios, the effects of the BPS on energy saving are shown in Table 3-2.

Table 3-2

List of Scenarios and Test Durations

Test Designation	Scenario A	Scenario B	Scenario C
West Falls Church substation Rectifier Capacity (MW)	6	3	0
Energy Consumption –BPS Off (MWh)	8,897	N/A	8,731
Energy Consumption – BPS On (MWh)	8,255	N/A	7,383
Energy Saving (MWh)	642	N/A	1,347
Energy Saving (%)	7.2%	N/A	15.4%

Note 1: Energy consumption figures are after corrections based on daily car counts.
Note 2: Scenario B does not have complete data for annual energy consumption and energy saving calculations.

Peak Power Shaving

For the three test scenarios, the aggregated power from the three substations was calculated, and the peak power was derived. Peak power is defined as the maximum of 30-minute averages of power. (Each hour has 2 averages, making

48 averages in one day). The effects on peak power shaving are shown in Figures 3-1 and 3-2.

Figure 3-1

Effects on Peak Power

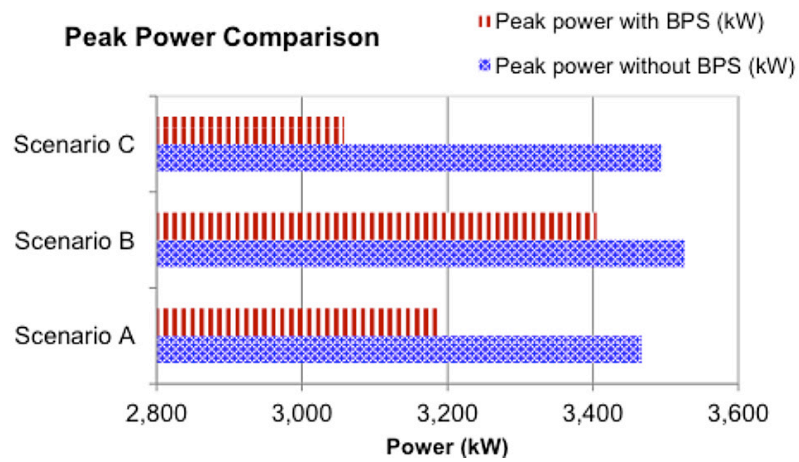
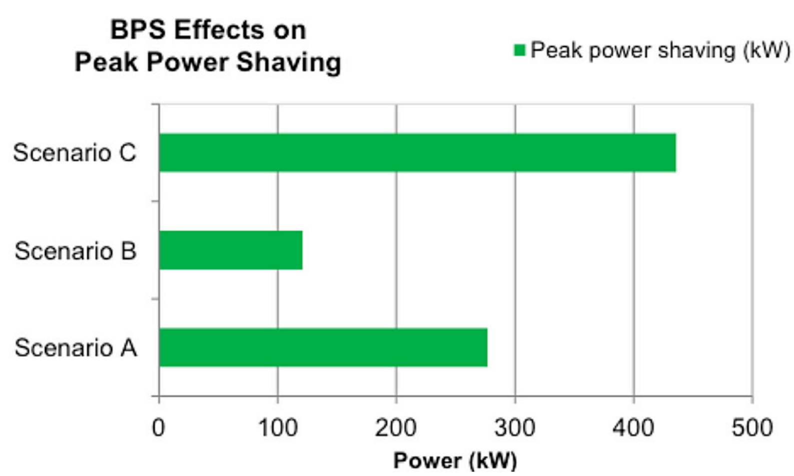


Figure 3-2

Effects on Peak Power Shaving



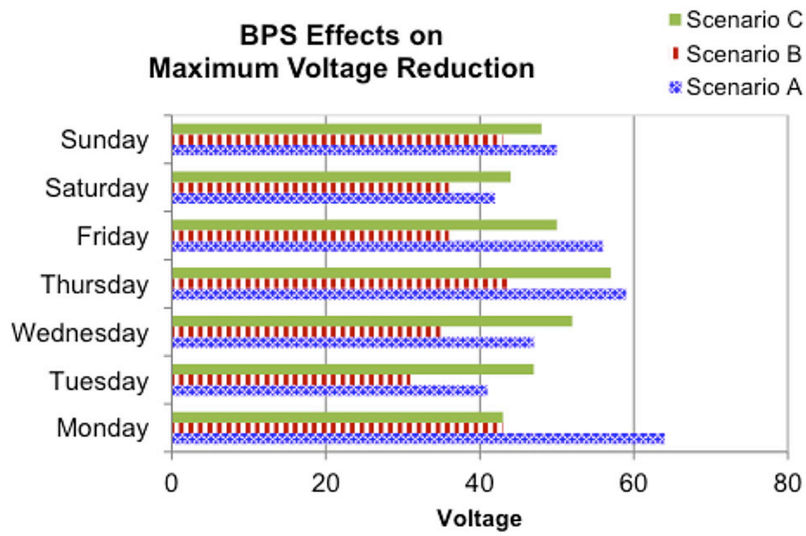
System Voltage Improvement

When there are one or more trains in regenerative braking mode, they feed power towards the traction power system when there are one or more trains nearby that demand power. The voltages at the regenerative trains are pushed higher as a result of the reverse power flow. If the voltage is too high, the regenerated power cannot be absorbed completely by other trains. The regenerative train will detect this excessive level of voltage and divert its excess power output to its onboard resistors. Therefore, the maximum voltage level is an indicator of how receptive the system is to absorbing the regenerated power. The higher the voltage above a certain threshold, the less receptive is the system.

When the BPS is in operation, it helps absorb the excessive power by charging the batteries, thus helping the system receptivity and reducing the maximum voltage. The voltages at West Falls Church substation were recorded and compared, and the effects are shown in Figure 3-3 for the three test scenarios.

Figure 3-3

Effects on Maximum Voltage Reduction at West Falls Church Substation

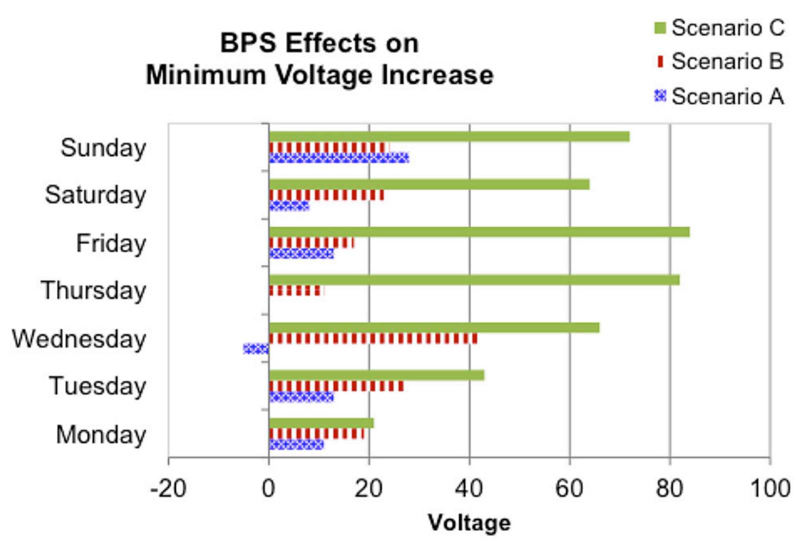


When there are one or more trains that demand power, the voltages at these trains are pushed lower. If the voltage is too low, the power demands cannot be fully met by the traction power system. As a result, some loads need to be shed. Therefore, the minimum voltage level is an indicator of how robust the system is in delivering power to meet demands. The lower the voltage, the weaker is the system.

When the BPS is in operation, it helps meeting the power demands by discharging the batteries, thus increasing the minimum voltage and improving the system robustness. The effects are shown in Figure 3 4 for the three test scenarios.

Figure 3-4

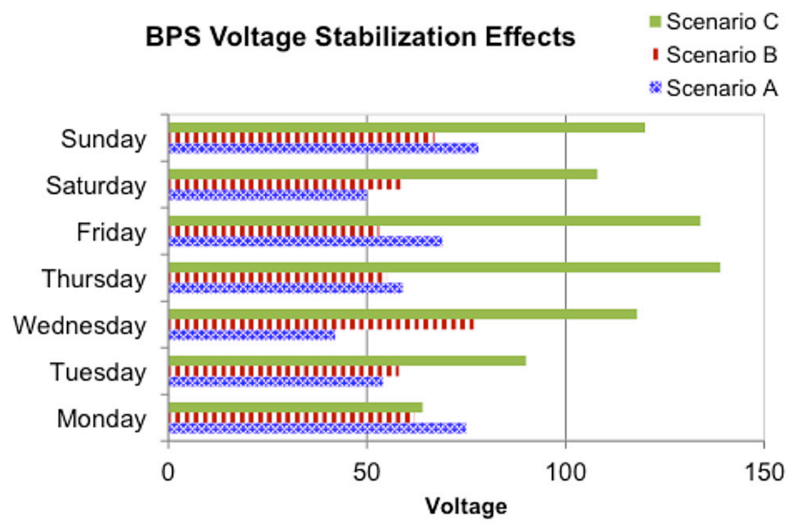
Effects on Minimum Voltage Increase at West Falls Church Substation



The above figures illustrate that the BPS has the effects of both maximum-voltage reduction and minimum-voltage increase. Combining these two, the overall effect is to stabilize the voltage levels more within a desired range. This overall effect is termed "voltage stabilization effect" in this report. For the three test scenarios, voltage stabilization is shown in Figure 3-5.

Figure 3-5

Effects on Voltage Stabilization at West Falls Church Substation



Using BPS for Emergency Power

To demonstrate the interaction between the BPS and trains under controlled conditions, a series of train tests was carried out between 11/5/13 and 11/7/13 in the track section between West Falls Church substation and Vienna Station. These included two tests that used the BPS as the sole source of power for train movements. These two tests and the results are summarized Table 3-3.

Table 3-3

Summary of Test Results – BPS as an Emergency Power Source

Test #	Test Description	Consumed BPS SOC (%)
E1	Train 1 accelerating to 10 mph and maintaining this speed; traveling a distance of 2,800'; Train 2 outside of feeding section	4.0%
E2	Train 2 accelerating to 10 mph and maintaining this speed; traveling a distance of 2,800'; Train 1 remaining stationary and drawing auxiliary power only	6.4%

All trains are of 6-car trains at AW0 load, with mixed car types.

As shown in Table 3-3, Test E1 indicates that to move one 6-car train with empty cars (82,500 lb per car) from standstill by 2,800 feet at a maximum speed of 10 mph, 4% of the BPS full-charge energy is consumed. If the same train is on crush load (AW2 load with 175 passengers in each car), the energy consumption is as shown in Table 3-4.

Table 3-4

Adjustment of Energy Consumption for Train Movements from Empty Train Load (AW0) to Crush Train Load (AW2)

Parameters	AW0 Load (0 passengers)	AW2 Load (175 passengers per car)	Ratio AW2/AW0
AW0 load (lb/car)	82,500	82,500	
Rotational allowance (% of AW0)	5%	5%	
Rotational weight (lb/car)	4,125	4,125	
Number of passengers per car	0	175	
Passenger weight (lb/person)	154	154	
Total passenger weight (lb/car)	0	26,950	
Effective total weight (lb/car)	86,625	113,575	131.1%
BPS energy consumption (% of SOC) for moving a 6-car train by 2800’	4.00%	5.24%	Scaling based on effective weight ratio
Number of trains that can be moved by 2800’ by using BPS at 100% SOC	25.0	19.1	
Number of trains that can be moved by 4000’ by using BPS at 100% SOC	17.5	13.3	

From this test and the calculations above, it can be seen that a fully-charged BPS can move 19 crush-loaded (AW2) 6-car trains by 2,800 feet in succession until the BPS energy is depleted, assuming that no other train draws power from the BPS at the same time.

If the required distance to move the train is different from 2,800 feet, the number of trains that can be moved can be calculated according to the proportion of 2,800 feet over the required distance. For example, to move the trains by 4,000 feet under the same condition, the number of AW2 loaded 6-car trains that can be moved by 4,000 feet is 13.

As illustrated in Test E2 results, stationary trains that draw auxiliary load from the BPS will impact the state of charge (SOC) of the BPS. The impact on the SOC of the BPS depends on how much power is being drawn and for how long. Consequently, the number of trains that can be moved by the BPS power will vary.

Summary of Train Test Results

In addition to the emergency power test described above, other tests were performed to prove the BPS effects on voltage stabilization BPS reception of regenerative power or current. Table 3 5 presents a summary of the voltage stabilization effects of the BPS.

Table 3-5

Summary of Train Test Results – Voltage Stabilization by BPS

Test #	Test Details	Test Descriptions	Observed Parameters	Without BPS	With BPS	BPS Voltage Stabilization (V)
V1	Day 1 Test 1-1; Day 2 Test 1-2	1 train accelerating at full power	Voltage drop (V)	60	56	4
V2	Day 1 Test 2-1; Day 2 Test 2-2	1 train braking at full-service braking	Voltage rise (V)	65	37	28
V3	Day 1 Test 3-2; Day 2 Test 3-1	1 train accelerating and 1 train braking	Voltage variation (minimum to maximum)	120	82	38
V4	Day 3 Test 1-2; Day 3 Test 2-1	2 trains accelerating at full power	Voltage variation (minimum to maximum)	218	143	75
V5	Day 3 Test 1A-1; Day 3 Test 2A-2	2 trains braking at full-service braking; WFC rectifiers offline	Voltage rise (V)	59	28	31

Note: Track section between Barbour Rd substation and Fisher St substation was fed by West Falls Church substation only. Voltages were recorded in West Falls Church substation.

Table 3-6 presents a summary of the captured energy by the BPS from the regenerative train and the maximum charging currents.

Table 3-6

Summary of Train Test Results – Reception of Regenerated Energy and Maximum Charging Current

Test #	Test Details	Test Descriptions	Observed Parameters	BPS Reception
R1	Day 1 Test 2-1; Day 2 Test 2-2	1 train braking at full service braking	captured energy (kWh)	3.94
R2	Day 1 Test 3-2; Day 2 Test 3-1	1 train accelerating and 1 train braking	captured energy (kWh)	1.40
R3	Day 3 Test 2A-2	2 trains braking at B5 mode	captured energy (kWh)	7.74
R4	Day 3 Test 2B	2 trains braking at B3 mode	captured energy (kWh)	8.91
R5	Day 2 Test 4	1 train braking at full-service braking in Dunn Loring Station (11,618' from WFC)	maximum charging current (A)	820
R6	Day 2 Test 4	1 train braking at full service braking in Vienna Station (24,187' from WFC)	maximum charging current (A)	304

Note: Track section between Barbour Rd substation and Fisher St substation was fed by West Falls Church substation only for tests R1 to R4. For tests R5 and R6, normal feeding arrangement was used.

Tests R5 and R6 demonstrate how far the BPS can reach to capture regenerative power in the traction power system. When the braking train was 11,618 feet (2.2 miles) away from the BPS, the BPS absorbed 820 Amps from the train (or 574kW at 700V). When the braking train was 24,187 feet (4.6 miles) away from the BPS, the BPS absorbed 304 Amps from the train (or 213 kW at 700V).

SECTION

4

Return-on-Investment (ROI) Calculations

Potential Energy Cost Savings

Based on the annual energy savings listed in Table 3 2, the potential cost savings due to reduced energy consumption and reduced peak power demand were calculated for scenarios A and C.

Scenario A

For Scenario A, the potential cost savings due to reduced energy consumption under a range of electricity prices are listed in Table 4-1.

Table 4-1

Potential Energy Cost Savings – Scenario A

Cost ($/kWh)	Year 1	Year 5	Year 10	Year 15	Year 20
$0.070	$44,965	$235,878	$501,454	$800,465	$1,137,122
$0.080	$51,388	$269,575	$573,090	$914,817	$1,299,568
$0.090	$57,812	$303,272	$644,726	$1,029,169	$1,462,014
$0.100	$64,236	$336,969	$716,362	$1,143,521	$1,624,460
$0.110	$70,659	$370,666	$787,999	$1,257,873	$1,786,906
$0.120	$77,083	$404,363	$859,635	$1,372,226	$1,949,351
$0.124	**$79,652**	**$417,842**	**$888,289**	**$1,417,966**	**$2,014,330**
$0.130	$83,506	$438,060	$931,271	$1,486,578	$2,111,797
$0.140	$89,930	$471,757	$1,002,907	$1,600,930	$2,274,243
$0.150	$96,353	$505,454	$1,074,544	$1,715,282	$2,436,689
$0.160	$102,777	$539,150	$1,146,180	$1,829,634	$2,599,135

Note: Electricity cost escalated 2.4% per year; kWh savings per week = 12,353

Electricity cost varies widely according to geographical area. As of May 2015, the average electricity cost in the Washington, DC area was $0.124/kWh, according to a publication of U.S. Bureau of Labor Statistics [4]. This is shown in Figure 4-10.

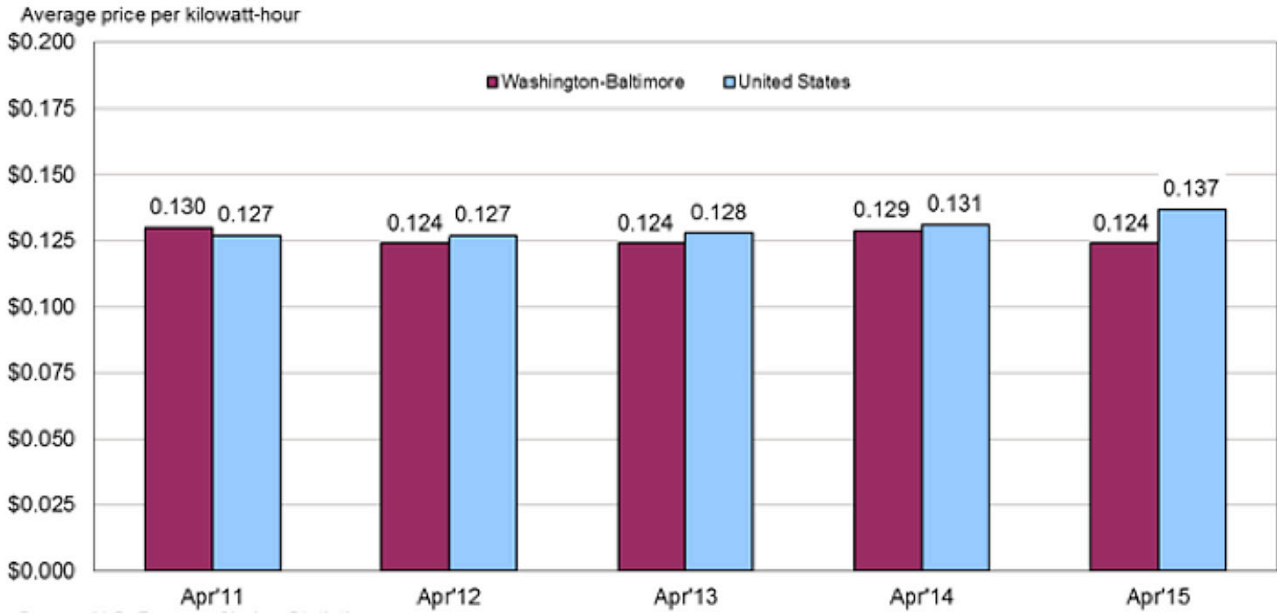


Figure 4-1

Average Prices for Electricity for Washington-Baltimore Area

Potential cost savings under the price of $0.124/kWh for the Washington/ Baltimore are highlighted in bold in Table 4 -1.

The electricity cost increase of 2.4% per yer is the national average that is projected in a publication by the U.S. Energy Information Administration [3]. No projected data were found for regional cost increases.

The potential cost savings due to reduced peak power demand under different demand charges are illustrated in Table 4-2.

Table 4-2

Potential Peak Power Cost Savings – Scenario A

Cost ($/kW)	Year 1	Year 5	Year 10	Year 15	Year 20
$5.00	$16,620	$87,186	$185,348	$295,869	$420,305
$10.00	$33,240	$174,371	$370,696	$591,738	$840,609
$15.00	$49,860	$261,557	$556,044	$887,607	$1,260,914
$20.00	$66,480	$348,743	$741,392	$1,183,476	$1,681,218
$25.00	$83,100	$435,928	$926,740	$1,479,345	$2,101,523

Note: Electricity cost escalated 2.4% per year; peak power kW reduction = 277.

Peak power demand charges vary widely according to geographical area. As there are no peak power charges in the Washington, DC / Baltimore area, no cost savings from peak power reduction were counted in the ROI calculations in this report.

Scenario C

For Scenario C, the cost savings due to reduced energy consumption are listed in Table 4-3.

Table 4-3

Potential Energy Cost Savings – Scenario C

Cost ($/kW)	Year 1	Year 5	Year 10	Year 15	Year 20
$0.070	$94,316	$494,766	$1,051,823	$1,679,013	$2,385,166
$0.080	$107,790	$565,447	$1,202,083	$1,918,872	$2,725,904
$0.090	$121,263	$636,128	$1,352,343	$2,158,731	$3,066,642
$0.100	$134,737	$706,808	$1,502,604	$2,398,590	$3,407,381
$0.110	$148,211	$777,489	$1,652,864	$2,638,449	$3,748,119
$0.120	$161,685	$848,170	$1,803,125	$2,878,308	$4,088,857
$0.124	**$167,074**	**$876,442**	**$1,863,229**	**$2,974,251**	**$4,225,152**
$0.130	$175,158	$918,851	$1,953,385	$3,118,167	$4,429,595
$0.140	$188,632	$989,532	$2,103,645	$3,358,026	$4,770,333
$0.150	$202,106	$1,060,213	$2,253,906	$3,597,885	$5,111,071
$0.160	$215,580	$1,130,893	$2,404,166	$3,837,744	$5,451,809

Notes: Electricity cost escalated 2.4% per year; kWh savings per week = 25,911

Potential cost savings for Scenario C at $0.124/kWh are highlighted in bold in the above table.

The potential cost savings due to reduced peak power demand under different demand charges are illustrated in Table 4-4.

Table 4-4

Potential Peak Power Cost Savings – Scenario C

Cost ($/kW)	Year 1	Year 5	Year 10	Year 15	Year 20
$5.00	$26,160	$137,231	$291,739	$465,700	$661,562
$10.00	$52,320	$274,462	$583,478	$931,400	$1,323,125
$15.00	$78,480	$411,693	$875,217	$1,397,100	$1,984,687
$20.00	$104,640	$548,924	$1,166,957	$1,862,800	$2,646,250
$25.00	$130,800	$686,154	$1,458,696	$2,328,500	$3,307,812

Note: Electricity cost escalated 2.4% per year; peak power kW reduction = 436.

Similar to Scenario A, no cost savings from peak power reduction were counted in the ROI calculations for Scenario C in this report.

Return-on-Investment

Calculations for ROI were conducted according to the following equations.

On the cost side, the components are:

Total Cost = (Equipment Cost + Maintenance Cost) – (Cost for Displaced Investment)

Where the "Cost for Displaced Investment" represents the cost that may be needed for an alternative installation (such as a traditional rectifier) to achieve the same effects as the BPS installation. This cost is used as an offset item for the total cost that is needed for a BPS installation.

On the saving side, the components are:

Total Saving = (Energy Cost Saving)
+ (Peak Demand Power Cost Saving)

The ROI is obtained as:

ROI = (Total Saving – Total Cost) / (Total Cost) × 100%

The equipment cost includes cost of installation. The cost for displaced investment includes equipment cost (including cost of installation) and maintenance cost.

ROI at 10 Years

The calculations for ROI at 10 years for Scenario A are listed in Table 4-5.

Table 4-5

ROI at 10 Years – Scenario A

Equipment Cost	$500,000	$625,000	$730,000	$875,000	$1,000,000	$1,500,000	$2,000,000
Maintenance Cost	$157,274	$157,274	$157,274	$157,274	$157,274	$157,274	$157,274
Total Cost	$657,274	$782,274	$887,274	$1,032,274	$1,157,274	$1,657,274	$2,157,274
Savings							
$0	-100%	-100%	-100%	-100%	-100%	-100%	-100%
$250,000	-62%	-68%	-72%	-76%	-78%	-85%	-88%
$500,000	-24%	-36%	-44%	-52%	-57%	-70%	-77%
$888,289	**35%**	**14%**	**0%**	**-14%**	**-23%**	**-46%**	**-59%**
$1,000,000	52%	28%	13%	-3%	-14%	-40%	-54%
$1,250,000	90%	60%	41%	21%	8%	-25%	-42%
$1,500,000	128%	92%	69%	45%	30%	-9%	-30%

Note: Maintenance cost escalated at 2.0% per year.

The 2% cost escalation per year for maintenance is based on the best estimation for the general trend of labor cost inflation. This is because no official project data were available.

This table indicates that for Scenario A to be financially viable at 10 years (the break-event point), the equipment cost (offset by additional benefits and cost for displaced investment that are not yet quantified) needs be at or less than $730,000.

The calculations for ROI at 10 years for Scenario C are listed in Table 4-6.

Table 4-6

Return on Investment at 10 Years – Scenario C

Equipment Cost	$1,000,000	$1,500,000	$1,750,000	$1,870,000	$2,000,000	$2,250,000	$2,750,000
Maintenance Cost	$157,274	$157,274	$157,274	$157,274	$157,274	$157,274	$157,274
Total Cost	$1,157,274	$1,657,274	$1,907,274	$2,157,274	$2,157,274	$2,407,274	$2,907,274
Savings							
$0	-100%	-100%	-100%	-100%	-100%	-100%	-100%
$1,000,000	0%	-33%	-43%	-47%	-50%	-56%	-64%
$1,500,000	50%	0%	-14%	-20%	-25%	-33%	-45%
$1,750,000	75%	17%	0%	-6%	-13%	-22%	-36%
$1,863,229	**86%**	**24%**	**6%**	**0%**	**-7%**	**-17%**	**-32%**
$2,000,000	100%	33%	14%	7%	0%	-11%	-27%
$2,500,000	150%	67%	43%	34%	25%	11%	-9%

This table indicates that, for Scenario C to be financially viable at 10 years (i.e., the break-even point), the equipment cost (offset by additional benefits and cost for displaced investment that are not yet quantified) needs to at or less than $1,870,000.

ROI at 20 Years

The calculations for ROI at 20 years for Scenario A are listed in Table 4-7.

Table 4-7

Return on Investment at 20 Years – Scenario A

Equipment Cost	$250,000	$410,000	$500,000	$750,000	$1,000,000	$1,500,000	$2,000,000
Maintenance Cost	$1,594,403	$1,594,403	$1,594,403	$1,594,403	$1,594,403	$1,594,403	$1,594,403
Total Cost	$1,844,403	$2,004,403	$2,094,403	$2,344,403	$2,594,403	$3,094,403	$3,594,403
Savings							
$0	-100%	-100%	-100%	-100%	-100%	-100%	-100%
$1,000,000	-46%	-50%	-52%	-57%	-61%	-68%	-72%
$1,500,000	-19%	-25%	-28%	-36%	-42%	-52%	-58%
$2,014,330	9%	0%	-4%	-14%	-22%	-35%	-44%
$2,250,000	22%	12%	7%	-4%	-13%	-27%	-37%
$2,500,000	36%	25%	19%	7%	-4%	-19%	-30%
$2,750,000	49%	37%	31%	17%	6%	-11%	-23%

Note: Maintenance cost escalated at 2.0% per year; maintenance cost includes battery change at year 10

This table indicates that for Scenario A to be financially viable at 20 years (the break-event point), the equipment cost (offset by additional benefits and cost for displaced investment that are not yet quantified) needs be at or less than $410,000.

The calculations for ROI at 20 years for Scenario C are listed in Table 4-8

Table 4-8

Return on Investment at 20 Years – Scenario C

Equipment Cost	$1,000,000	$1,500,000	$2,000,000	$2,500,000	$2,650,000	$2,750,000	$3,000,000
Maintenance Cost	$1,594,403	$1,594,403	$1,594,403	$1,594,403	$1,594,403	$1,594,403	$1,594,403
Total Cost	$2,594,403	$3,094,403	$3,594,403	$4,094,403	$4,244,403	$4,344,403	$4,594,403
Savings							
$0	-100%	-100%	-100%	-100%	-100%	-100%	-100%
$1,000,000	-61%	-68%	-72%	-76%	-76%	-77%	-78%
$2,000,000	-23%	-35%	-44%	-51%	-53%	-54%	-56%
$3,000,000	16%	-3%	-17%	-27%	-29%	-31%	-35%
$4,000,000	54%	29%	11%	-2%	-6%	-8%	-13%
$4,225,152	**63%**	**37%**	**18%**	**3%**	**0%**	**-3%**	**-8%**
$5,000,000	93%	62%	39%	22%	18%	15%	9%
$6,000,000	131%	94%	67%	47%	41%	38%	31%
$7,000,000	170%	126%	95%	71%	65%	61%	52%

Note: Maintenance cost escalated at 2.0% per year; Maintenance cost includes battery change at year 10.

This table indicates that for Scenario C to be financially viable at 20 years (the break-event point), the equipment cost (offset by additional benefits and cost for displaced investment that are not yet quantified) needs be at or less than $2,650,000.

Other Benefits

In addition to energy cost savings, the BPS also will bring other benefits to the system owner, as follows:

- Voltage support for trains so that the traction power system can effectively support the desired train service levels.
- Emergency power to trains in traction power blackout situations—this is particularly valuable in tunnel environments where the requirements for safety evacuation of passengers are more demanding than open track environment.
- Significant capital cost savings if a BPS can be installed in place of one or more traditional rectifier units.
- Where the site conditions do not permit installations of traditional rectifier units.

Quantification of these additional benefits is dependent on the actual situation. The realization of these benefits may significantly improve the ROI calculation results. This is consistent with the findings from a previously-published study by the Transit Cooperative Research Program [5]: an energy storage installation in a rail transit environment is most practical when it realizes more than one benefit simultaneously rather than focusing the application primarily on solving any one problem alone.

APPENDIX

A

Summary of Recorded Data

Table A-1

Summary of Recorded Data

Scenarios			Date	Substation Energy (kWh)			BPS Discharge Energy (kWh)	BPS Charge Energy (kWh)	Number of Cars per Day	Avg Temperature (Deg. F)
Test #	WFC TPS Status	BPS Status		Barbour Rd TPS	WFC TPS	Fisher St TPS				
B1	3MW	OFF	8/19/2013	8,589	9,726	10,106	n/a		1,962	70
			8/20/2013	9,187	9,693	10,504			1,990	79
			8/21/2013	8,975	10,279	10,983			1,916	81
			8/22/2013	9,368	10,453	11,658			1,976	83
			8/23/2013	9,755	10,135	10,809			1,996	73
			8/24/2013	6,891	6,834	7,860			1,380	75
			8/25/2013	6,242	6,517	7,349			1,230	74
B2	3MW	ON	8/26/2013	8,564	9,505	11,153	2,642	2,851	1,958	77
			8/27/2013	Unscheduled Outage – East Falls Church Substation Offline			2,699	2,881	1,944	84
			8/28/2013	9,102	9,822	11,201	2,925	3,083	2,066	79
			8/29/2013	8,855	8,933	11,826	2,792	3,013	1,970	81
			8/30/2013	8,705	9,115	11,120	2,820	3,005	1,978	80
			8/31/2013	Unscheduled Work - Single Tracking			2,098	2,235	454	83
			9/1/2013	Unscheduled Work – Single Tracking			2,135	2,187	458	83
C1	0	OFF	9/9/2013	12,850	0	14,269	n/a		1,982	73
			9/10/2013	13,711	0	14,410			2,010	83
			9/11/2013	12,695	0	15,139			1,990	85
			9/12/2013	12,913	0	14,175			1,956	83
			9/13/2013	12,955	0	14,323			2,002	72
			9/14/2013	7,811	0	8,064			1,074	65
			9/15/2013	7,397	0	7,188			956	66
C2	0	ON	9/16/2013	11,867	0	11,517	4,112	4,337	2,010	70
			9/17/2013	11,710	0	11,830	4,227	4,506	2,024	63
			9/18/2013	11,933	0	11,066	4,192	4,582	1,994	63
			9/19/2013	12,071	0	11,360	4,210	4,580	1,944	67
			9/20/2013	11,772	0	11,797	4,178	4,576	2,030	72
			9/21/2013	4,645	0	5,336	2,826	3,173	750	72
			9/22/2013	5,326	0	5,706	2,971	3,191	918	67
A1	6MW	OFF	10/21/2013	6,738	11,526	9,010	n/a		1,908	57
			10/22/2013	7,319	12,650	8,919			1,974	60
			10/23/2013	7,344	11,090	9,080			1,982	54
			10/24/2013	7,671	13,139	9,451			2,048	48
			10/25/2013	7,379	11,524	9,982			2,028	48
			10/26/2013	3,691	5,636	5,183			1,042	46
			10/27/2013	3,339	5,565	4,860			966	53
A2	6MW	ON	10/28/2013	6,160	10,053	8,704	2,555	2,685	1,942	55
			10/29/2013	6,772	10,640	9,022	2,669	2,787	2,012	55
			10/30/2013	6,763	10,720	8,899	2,791	2,925	1,980	59
			10/31/2013	6,898	10,812	8,737	2,835	2,965	1,966	62
			11/1/2013	6,398	11,616	8,567	2,696	2,840	1,956	67
			11/2/2013	4,011	5,983	5,307	2,615	2,730	1,146	62
			11/3/2013	4,360	6,340	5,642	2,619	2,746	1,224	52

Note: More data were collected in the summary months of 2014. However, the collected data showed significant inconsistency for the days covered. The inconsistency was caused by train service irregularities due to the introduction of test and service trains that run on the new Silver Line, which pass through the test section. It was, therefore, decided that these data were not usable.

CONTACTS

FTA

Office of Technology, Room E43-440
1200 New Jersey Ave SE
Washington, DC 20590

Roy Chen, Transportation Engineer
Phone: (202) 366-0462
E-mail: RoyWeiShun.Chen@dot.gov

WMATA

CENI-Office of Chief Engineer, Infrastructure
4C-01
600 5th St NW
Washington, DC 20001

Moustapha Ouattara, Assistant Chief Engineer
Phone: (202) 962-1023
E-mail: mouattara@wmata.com

Gannett Fleming Transit & Rail Systems

85 Mechanic St, Suite E2-2
Lebanon, NH 03766

J. Gordon Yu, Manager of Traction Power Analysis
Phone: (603) 448-4458
E-mail: JYu@gfnet.com

Kawasaki Rail Car, Inc.

29 Wells Ave, Building #4
Yonkers, NY 10701

John Calvello, Marketing Sales Manager
Phone: (914) 376-4700 ext. 4743
E-mail: calvello@kawasakirailcar.com

REFERENCES

[1] Information about GIGACELL, available at http://www.khi.co.jp/english/gigacell/intro/index.html.

[2] Energy Information Administration, Information about Average U.S. Home Electricity Consumption, available at http://www.eia.gov/tools/faqs/faq.cfm?id=97&t=3.

[3] U.S. Energy Information Administration, Annual Energy Outlook 2015, Energy Prices, Electricity section (containing projection for price increases from 2013 to 2040 –reference case), available at http://www.eia.gov/forecasts/aeo/section_prices.cfm#elec.

[4] U.S. Bureau of Labor Statistics, Average Energy Cost in Washington/Baltimore Area, available at http://www.bls.gov/regions/mid-atlantic/news-release/averageenergyprices_washingtondc.htm.

[5] Transit Cooperative Research Program, "Guiding the Selection and Application of Wayside Energy Storage Technologies for Rail Transit and Electric Utilities," TCRP Web-only document 51, November 2010), available at http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_webdoc_51.pdf.

U.S. Department of Transportation
Federal Transit Administration

U.S. Department of Transportation
Federal Transit Administration
East Building
1200 New Jersey Avenue, SE
Washington, DC 20590
http://www.fta.dot.gov/research