UNDERSTANDING RAIL WAYSIDE ENERGY STORAGE REQUIREMENTS AND RELATIVE COSTS FOR HIGH-POWER, HIGH-CYCLABLE TECHNOLOGIES

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ABSTRACT

Continuing urban growth is driving increased demands on metro rail systems. To meet this demand, rail authorities are increasing the number of vehicles per train, number of trains per hour and operating hours per day. These changes result in higher electric energy consumption and higher operating energy costs. Rail authorities are increasingly investigating how to increase energy efficiency and decrease operating energy costs with existing infrastructure. Modern metro trains have regenerative braking which helps reduce their electric energy consumption. The reduction in electric energy consumption depends on the instantaneous ability of the rail section near the braking train to use or store regenerative braking energy. This paper introduces rail wayside energy storage systems, presents specifications for a wayside energy storage system, and investigates metro rail wayside energy storage technologies best applied to projects seeking low replacement costs and high return on investment, while satisfying high-power density requirements and improving energy efficiency. This paper introduces the 3 leading energy storage options: flywheels, supercapacitors and batteries. It compares lifetime, cyclability, cost, energy characteristics, ease of installation and environment effects, such as temperature. It describes flywheel and supercapacitor energy storage system sizing for a high-power density energy storage application and compares the lifetimes, costs and return on investment. For a high power, high cyclable environment, such as a metro passenger station, the paper shows the flywheel wayside energy storage system has the lower cost of ownership and quickest return on investment.

Keywords (Energy, Storage, Efficiency, Rail, Footprint, Wayside, Flywheel, Braking, Regenerate, Supercapacitor)
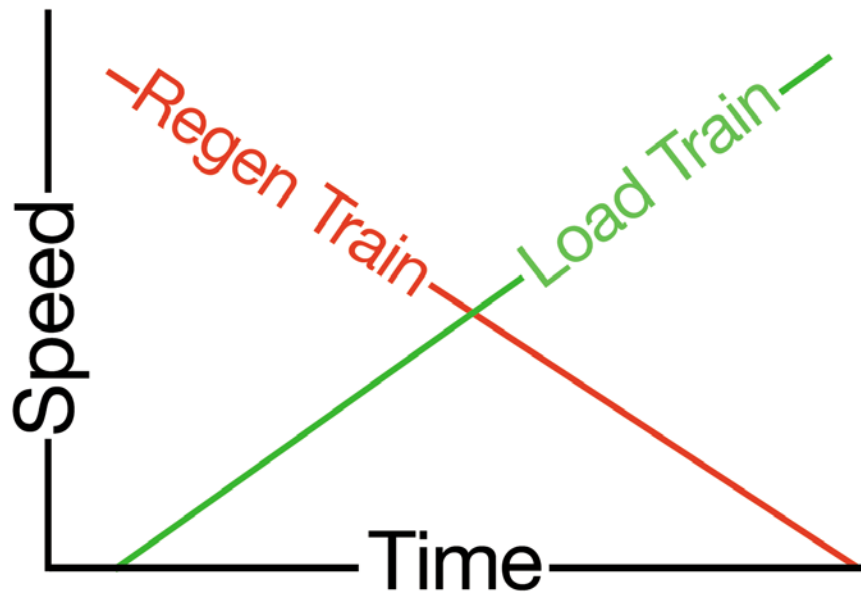
1 INTRODUCTION TO REGENERATIVE BRAKING TECHNOLOGY

1.1 Regenerative Braking

In the U.S. and around the world, new electrically propelled DC traction power subway trains and light rail vehicles use AC propulsion, with induction traction motors and variable voltage, variable frequency drives. One benefit to these AC propulsion trains over older trains is their regenerative braking capability. When one of these trains brake, its traction motors act as generators, providing power that can be fed back to the third rail or overhead contact system. This regenerated power from the braking train ("Regen Train") can power other trains ("Load Trains").

Traditionally, for regenerative braking to work, one or more Load Trains must accelerate at the same time as the Regen Train brakes, and the Load Train must be physically close to the Regen Train. Figure 1 illustrates this "Close Enough" scenario, where the Regen Train is braking and at the same time the Load Train is accelerating. If no Load Train is "Close Enough" to a Regen Train, the regenerative energy from the Regen Train is dissipated as heat through brake resistors which are typically mounted onboard each train.

Figure 1: "Close Enough" scenario: Regenerative braking occurring between a Regen Train braking and at the same time the Load Train is accelerating. [1]
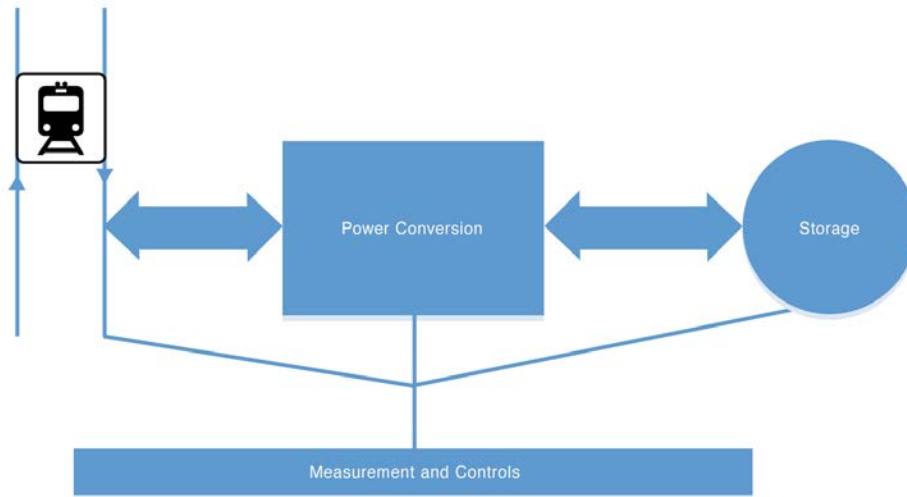

These regenerative events often occur at passenger stations where trains brake and accelerate in the same area. Even at passenger stations, "Close Enough" regenerative events depend on traffic level. Each year thousands of kWh are lost per passenger station. This lost regenerative braking energy is an opportunity for rail authorities to substantially reduce operating costs and improve energy efficiency.

1.2   Wayside Energy Storage System
Wayside Energy Storage System (WESS) saves otherwise lost regenerative braking energy by capturing and storing braking energy from a Regen Train. The WESS then delivers the captured energy to a Load Train without the Load Train being close in time or position to the Regen Train, and without the Load Train having matched acceleration and braking profiles.
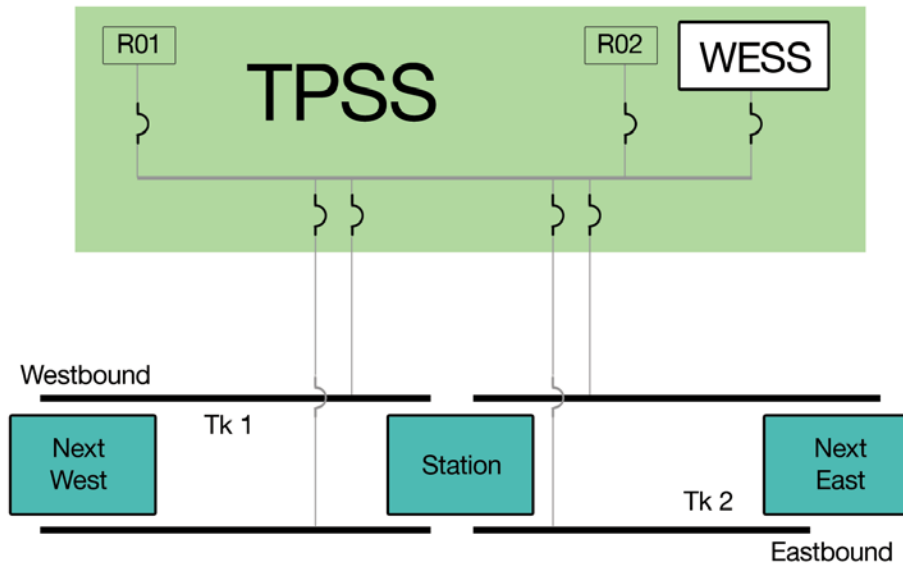
Figure 2: Elements of a rail WESS

A WESS consists of 3 elements, shown in Figure 2:

- Storage element – mechanism for storing regenerative energy, most commonly batteries, flywheels or capacitors
- Power conversion – usually a bidirectional DC-DC or DC-AC power electronic converter with switchgear – the power conversion components and switchgear are common across WESS applications
- Measurement and controls – hardware and software often integrated with the power conversion cabinet, critical to WESS maintenance and assurance of functionality

Figure 3 shows a block diagram of a WESS at a traction power substation (TPSS) near a passenger station. The WESS is connected to the third rail bus in the TPSS in parallel with two traction power rectifiers. When a train brakes to a stop at the passenger station, the regenerated energy is sent through the third rail from the Regen Train to the WESS. The WESS charges and stores the regenerated energy. When a Load Train accelerates from the station, the WESS discharges, acting like a traction power rectifier, sending energy through the third rail to the accelerating train.

Figure 3: WESS Instillation at TPSS

1.3 Applications and Benefits of WESS

The Institute of Electrical and Electronic Engineers (IEEE) Vehicular Technology Society Rail Transportation Standards Committee is creating a "Guide for Wayside Energy Storage for DC Traction Applications [2]." The IEEE draft Guide is the product of more than three years of work of 31 participants from 20 Transit Operators and rail engineering and equipment companies.

The IEEE draft guide identifies WESS applications. A WESS may focus on a few applications and have secondary benefits.

Energy Recovery. The WESS can reduce traction power system energy consumption and reduce the amount of energy dissipated through the brake resistors. It also permits for the same train to be the Regen Train and Load Train.

Voltage Regulation. The WESS can stabilize the traction power system voltage. When there is a voltage sag, on the third rail, caused by an accelerating train, the WESS discharges and boosts the traction voltage. When there is a voltage peak, on the third rail, caused by a decelerating train, the WESS charges and brings down the traction voltage. This keeps the traction power system voltage within normal operating range, preventing equipment damage from over voltages or delays caused by voltage sags. The WESS can potentially replace a TPSS and the utility connection costs associated with a TPSS.

Emergency Backup WESS. The WESS can store energy at full capacity during normal conditions and in case of a power outage, or if the utility is unstable, the WESS provides energy to run trains to the next passenger station where passengers can safely exit the train.

Peak-Shaving. The WESS can reduce short-term fluctuations in traction power system power demand caused by trains accelerating. The WESS discharges when there is a large power demand on the traction power system, usually when a train is accelerating, reducing

the peak power demand and power demand costs. This would allow the size of power delivery equipment to be minimized.

Load Shifting. The WESS charges when electricity is inexpensive, during off-peak times. The WESS then discharges the energy when electricity is expensive, during peak times. This saves money on energy costs and helps the utility manage the duck curve.

Frequency Regulation. The WESS acts as an on-demand utility load. When transmission frequency increases, the WESS charges acting as a load and restores the transmission frequency. When transmission frequency decreases, the WESS supplies energy to the traction power system, reducing the utility load. Some utilities pay for frequency regulation and frequency regulation can generate revenue for the Transit Operator.
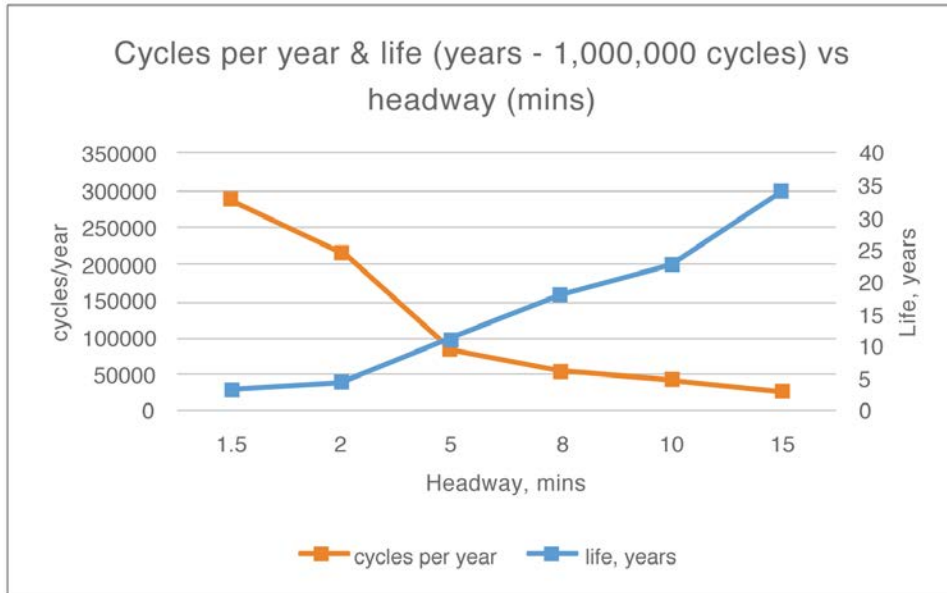
2 RAIL REQUIREMENTS FOR WESS

The WESS' benefits depend on its match to the requirements of its rail system application. This section discusses the rail system requirements that affect WESS design specifications.

2.1 Headway and duration of operation

WESS operating conditions continuously change throughout the day and throughout the season. Track headways can be as low as 2 minutes during rush hour and 20 minutes or longer during off-peak hours. Trains accelerate for 15 - 60 seconds, and may brake to a stop in as little as 15 seconds. Typical operating headways are 3 minutes during peak hours and 5 to 8 minutes in semi-peak and off-peak hours, with an average headway of about 5 minutes. Rail authorities are decreasing headway to accommodate more passengers into the existing rail infrastructure and more rail authorities are working toward 2.5 minute headway. As the headway decreases, the number of start-stops increases in a given period of time. Additionally, a typical metro operates 20 hours a day, but many large metros are moving to 24-hour operation. The increased operating times result in increased WESS usage. A successful WESS must operate at a high-duty cycle and high number of cycles.

Figure 4 graphs the WESS cycles per year versus headway time. Figure 4 also shows the expected WESS life in years versus headway time. The WESS life is based on the energy storage industries goal of 1,000,000 usable cycles for cycling storage elements.

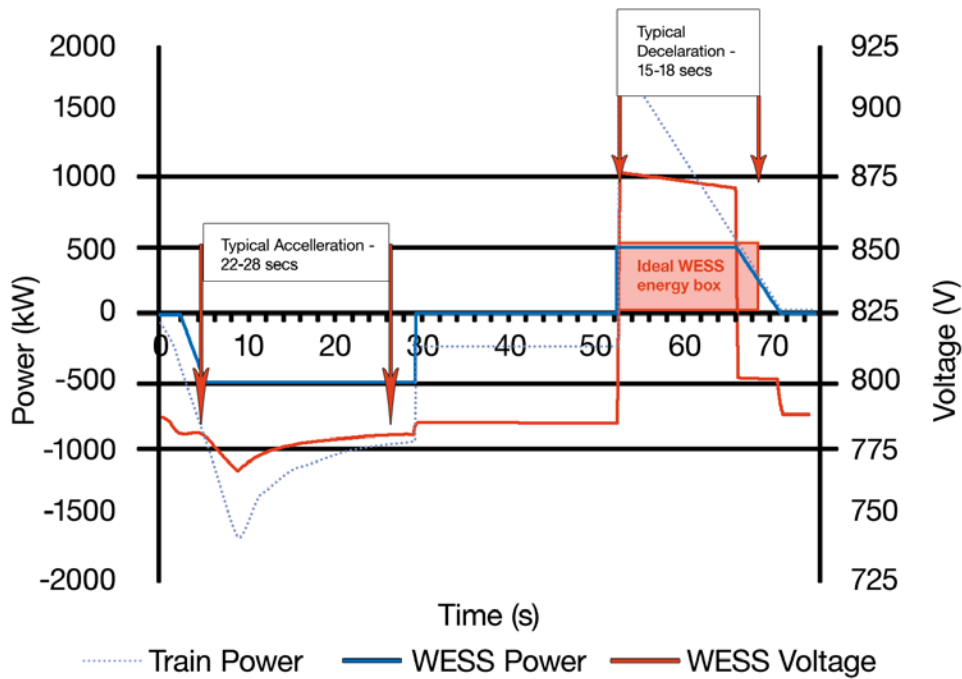Figure 4: Cycles per year and WESS life vs. Headway

The WESS sizing must consider the headway, the expected life of the system and return on investment (ROI). An undersized WESS will have poor performance and decreased life. An oversized WESS will have a longer ROI.

2.2   Voltage, Power and Energy Capacity

The goal of a WESS is to capture and supply the captured energy to trains in a cost-effective manner. WESS power and energy sizing are key considerations for optimized performance and ROI. Figure 5 shows the energy profile of a typical metro train with a WESS installation from Bombardier [3]. At 0 to 30 seconds a train is accelerating and a WESS is discharging. At 30 to 50 seconds the train is maintaining its speed. At 50 to 70 seconds the train is regen braking and the WESS is charging.

Figure 5: Energy profile of a metro train with WESS

Train braking events are typically short, 20 seconds in this example. Most braking energy that WESS can capture is available during the first 15 to 18 seconds of the braking event. For this example, the red box shows ideal WESS sizing, 500 kW at 15 to 18 seconds.

The red dotted line shows the third rail voltage and how much the voltage changes when a train accelerates and decelerates. A typical 750 V DC rail bus can swing from 650 V to 900 V. The WESS must safely operate within the full third rail voltage range.

Every WESS installation size may differ and should be evaluated on a case-by-case basis.

2.3   Controls, Energy Management and Diagnostics

Regenerated energy is most efficient when directly transferring energy from a Regen Train to a Load Train. The WESS measurement and control system must acquire data from the TPSS to promote and not prevent direct Regen Train to Load Train energy transfer. The WESS controls should allow operators to tune and adjust charge-discharge thresholds to optimize direct energy transfer.

A WESS must not charge by consuming power from the TPSS rectifiers. In addition, the WESS should discharge to a Load Train as soon as possible to minimize leakage losses.

A WESS should perform remote diagnostics and take remote corrective actions. In addition, it should be possible to switch the WESS offline or online, without metro staff on-site action or interruption to the rail services.

The WESS must maintain electromagnetic compatibility (EMC) with the train control and communication system.

2.4   Location, Ambient Conditions and Auxiliaries

WESS can be typically installed in an existing TPSS and integrated with existing traction power equipment, installed in a new TPSS as part of a line extension, or installed in a new or existing structure near a passenger station. Existing TPSS typically have limited space for new equipment or may be underground. The WESS needs to be modular to fit into the existing space and leave room for maintenance. The WESS may require new conduit and cable ducts.

WESS design must consider the operating environment where it will be installed. TPSS are typically dusty. The dust can infiltrate electrical equipment shortening their operational life. TPSS are typically not temperature controlled and the temperature varies widely depending on the season and location. The WESS should be designed for indefinite operation between temperature ranges specified in EN 50155-2 Railway applications - Environmental conditions for equipment - Part 2: Fixed electrical installations. Temperature control must be considered for WESS technologies whose lifetime is affected by temperature. TPSS may experience water ingress due to flooding or rain.

2.5   Reliability and Maintenance

Transit Operators principal mission is moving people on trains. WESS are tools to help Transit Operators save operating costs, and so they are not directly coupled to the Transit Operator principal mission. The WESS must be reliable so it does not interfere with daily rail operations, rail reliability or safety. Transit Operators may permanently shut down a WESS if it delays or disrupts transit operations.

WESS must be reliable and require little maintenance, because they are non-mission-critical systems. Transit Operators operations and maintenance (O&M) staff are typically busy maintaining service-critical rail equipment, which is a higher priority than WESS. Transit Operators may permanently shut down a WESS if it becomes a nuisance for O&M, or if maintenance costs outweigh the benefits.

Transit Operators typically expect a minimum design life of 20 years for new equipment, including a WESS.

2.6   Return on Investment (ROI)

Transit Operators call for a 5 to 8 year ROI for WESS installations using proven products and technologies. High Power, high cyclable WESS payback comes primarily from reducing total energy consumption and reducing peak power demand. Every utility has different rates for energy usage and peak power demand. The more energy usage and peak power demand by the rail authority, the faster the WESS payback.

3   WESS ENERGY STORAGE TECHNOLOGIES

The power conversion and controls portion of all WESS and their associated costs are generally similar. The WESS storage technology typically determines the capital investment, maintenance cost, efficiency, lifespan and replacement cost of the WESS. The common energy storage technologies in use for various applications and environments are:
-    Batteries (Li-Ion, NimH, Li-polymer)
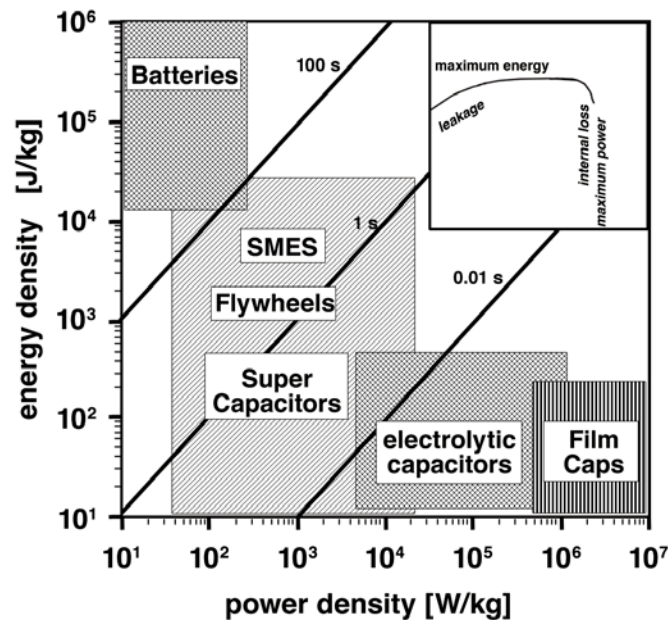-   Capacitors (supercaps)

- Flywheels

This section introduces these energy storage technologies and discusses their applications and abilities to meet the rail system specifications described in section 2.

3.1 Batteries

Batteries can contain a large amount of energy in a compact space, but batteries charge and discharge that energy relatively slowly when compared to other technologies. Figure 6 shows the Ragone Plot, a graph of the amount of storable energy per unit weight (the energy density) versus the rate at which that energy is delivered per unit weight (the power density). Batteries generally occupy the top left corner, with high-energy densities and low-power densities.

Figure 6: Ragone Plot: Relationship between energy density and power density for various storage technologies. The top right corner shows the maximum energy curve for an energy storage device, factoring in the energy leakage and internal losses. The maximum energy decreases with higher and lower power [4].

The ratio of energy density to power density corresponds to the time it takes to charge or discharge the storage technology. The diagonal lines are the charge and discharge times. Storage technologies on the same line have the charge and discharge times. For example, batteries charge and discharge times are mostly above the 100 s line.

For rail applications, Lithium Ion batteries are the closest application-capable chemistry. However, even the state-of-the-art Lithium Titanate Oxide (LTO) batteries cannot meet a charge or discharge duration of 15 to 18 seconds repetitively on a 2-minute duty cycle, as established by the rail requirements discussed in section 2.2, without being significantly oversized for the power and current rating of the application.
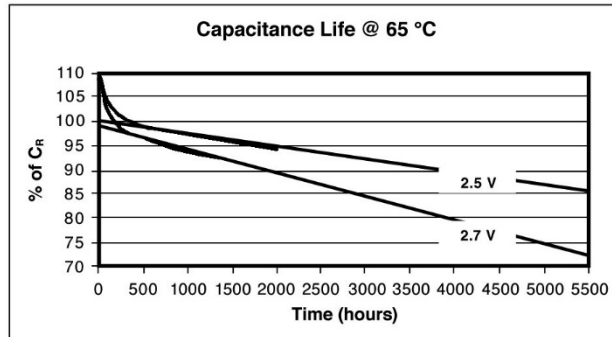
Batteries are better suited to applications, such as load shifting and emergency backup that do not require high-power density and high-cycle operation. Therefore, this paper does not consider batteries for the WESS size analysis.

3.2   Supercapacitors

Electrolytic Double layer Capacitors (EDLCS), or Supercaps, can operate in the 10s of seconds for a repetitive charge-discharge cycle. Therefore, supercaps are better suited for the demands of a WESS to meet a charge or discharge duration of 15 to18 seconds repetitively on a 2-minute duty cycle.

Like all typical capacitors, Supercaps are restricted by the level of discharge allowed to maintain life, and they have an internal resistance that can limit their power transfer. A typical capacitor is deemed to have reached the end-of-life if the capacitance drops to 80% of the initial value, or if the internal resistance (or Equivalent Series Resistance (ESR)) doubles from the initial value. Manufacturers' data on the capacitors' life is presented in Figures 7 and 8 [5, 6].

Figure 7: Capacitance Life of Supercaps

BCAP2600 Capacitance degradation at 2.7 V and 2.5 V at 65 °C

30% reduction in rated capacitance may occur for an ultracapacitor held at 2.7 V after

5,500 hrs	@ 65 °C
11,000 hrs	@ 55 °C
22,000 hrs	@ 45 °C
44,000 hrs	@ 35 °C
88,000 hrs	@ 25 °C

15% reduction in rated capacitance may occur for an ultracapacitor held at 2.5 V after

5,500 hrs	@ 65 °C
11,000 hrs	@ 55 °C
22,000 hrs	@ 45 °C
44,000 hrs	@ 35 °C
88,000 hrs	@ 25 °C

Figure 8: ESR Life of Supercaps

ESR Life @ 65 °C

[Graph: % ESR_R (y-axis, 90 to 240) vs Time (hours) (x-axis, 0 to 5500). Two curves labeled 2.7 V (rising steeply) and 2.5 V (nearly flat).]

BCAP2600 Resistance degradation at 2.7 V and 2.5 V at 65 °C

140% increase in rated resistance may occur for an ultracapacitor held at 2.7 V after

5,500 hrs	@ 65 °C
11,000 hrs	@ 55 °C
22,000 hrs	@ 45 °C
44,000 hrs	@ 35 °C
88,000 hrs	@ 25 °C

40% increase in rated resistance may occur for an ultracapacitor held at 2.5 V after

5,500 hrs	@ 65 °C
11,000 hrs	@ 55 °C
22,000 hrs	@ 45 °C
44,000 hrs	@ 35 °C
88,000 hrs	@ 25 °C

3.3   Flywheels

A flywheel WESS stores energy in the rotational energy of a spinning mass. A flywheel with a fully sealed vacuum housing and a rotor levitated on magnetic bearings reduces friction losses to a low level. Such flywheels have been in operation for over 2 decades and can be considered a mature technology for high duty-cycle storage. Being mechanical systems, flywheels are well studied and analyzed for mechanical, performance and life characteristics.

Flywheels can accelerate and decelerate at very high rates, and therefore can charge and discharge energy in seconds. A typical flywheel can work a million cycles of deep discharge without any effect on performance or life of the storage element. Compared to supercaps, they have a higher energy density (see Figure 5). The low losses, high-power density, and high reliability make them ideal for demanding duty cycle applications.

Flywheel systems can operate in a broad range of environments.

4   WESS SIZING: CAPACITOR VS. FLYWHEEL

Due to the different nature, composition, and characteristics of the storage element in the WESS, it is not possible to make a direct comparison of the different technologies. For example, while manufacturers' claim capacitors life could be 10 years at 25° C and 2.7 V, independent lab tests often do not reach that value for a variety of reasons – degradation characteristics, temperatures. Table 1 shows the differences in Maxwell Boostcap lifetime expectancy from various laboratories.

Table 1: Life estimations of Maxwell Boostcap by different tests [7]

TABLE I
COMPARISONS OF LIFETIME EXPECTANCY ACCORDING TO MANUFACTURER AND LABORATORY MODELS FOR MAXWELL TECHNOLOGY CELLS (RATED CAPACITANCE: 350 F, 2600 F OR 3000 F)

	θ_0	V_0	$T_{life}^{ref} = T_{life}$ (2.7 V, 65°C)	T_{life} (2.7 V, 25°C)	T_{life} (0 V, 70°C)
Maxwell data-sheets [4]	-	-	1500 h	10 years	4 years
LUSAC [5]	8.7 K	-	1550 h	4.3 years*	-
IMS [6]	-	100 mV	1910 h	-	-
RWTH [7]	10 K	100 mV	1500 h	2.7 years*	16 x 10⁶ years*
PSI [8]	10K	95 mV	1450 h	2.6 years*	42 x 10⁶ years*
Ampére [9]	8.6 K	87 mV	1500 h	4.4 years*	260 x 10⁶ years*

*These values correspond to extrapolations.

To compare WESS storage technologies, a WESS is sized according to the same requirements and specifications. This allows the WESS storage technologies to be compared side-by-side in the same conditions of design and operation.

Table 2 presents the specifications of a WESS based on the requirements discussed in Section 2.

Table 2: Required Specification of Rail WESS

Requirement Category	Specification
Power Rating	500 kW
Energy Rating	2.5 kWh typical; 2 – 8 kWh range
Cycling	18 seconds full charge or discharge with max pause of 54 seconds
Cycling period	90 s
Daily operation period	20 hours minimum
Ambient Conditions	40 deg F, 95% RH non-condensing
Cooling Configuration	Minimal auxiliary cooling requirement. Self cooled preferred
Footprint & Weight	Minimal, configurable in modules to meet different space topologies
Location	Preferred location at electrical substations
Product Life	20 years min.
Other desirables	Payback of 5 – 6 years Self diagnosis and fault reporting Maintenance interval 3 months min.

4.1   Supercap Based WESS Sizing

Table 3 shows the calculations for sizing a Supercap WESS that meets the specification in Table 2. The calculated Supercap life is 2.84 years or 235,789 cycles before replacement.

Table 3: System Life Calculations – Capacitors

Parameter	Value	Note/ calculation
Standard life @ 25 C (Cycles)	1,000,000	When capacitor value decreases by 20% and/or ESR reaches 200%
Standard life @ 25 C (Hours)	88,000	
Temperature (°C)	40	
Life due to temperature and capacitance reduction		
V flt (Volts DC)	2.7	Operating Voltage of Capacitor
Temperature derate multiplier	0.35	Exponential derating for temperature from standard life
Rated Capacitance reduction %	20	End-of-life reduction in capacitance
Voltage derate multiplier	0.67	Reduction in capacitance when held at temperature is 15% at 2.5 V and 30% at 2.7 V
Life (Hours)	20,749	Equals life in hours at 25 C x temperature derate x voltage derate
Cycle life (cycles)	235,789	Equals life in cycles at 25 C x temperature derate x voltage derate
Life due to temperature and ESR reduction		
V flt (Volts DC)	2.7	Operating Voltage of Capacitor
Derate multiplier	0.35	Exponential derating for temperature
ESR increase %	200%	End-of-life increase in ESR
Life (Hours)	31,124	Equals life in hours at 25 C x derate multiplier
Cycle life (cycles)	353,684	Equals life in cycles at 25 C x derate multiplier
Combined ESR and Capacitance decrease life (Hours)	20,749	Lowest of the two (for hours) this is the maximum allowed hours
Combined ESR and Capacitance decrease cycle (cycle)	235,789	Lowest of the two (for cycles) this is the maximum allowed cycles
Allowed cycles/hour	11	Ratio of the max allowed values in cycles/hours
Charge discharge duration for rail system (s)	18	To be calculated based on rated current, Capacitance and charge discharge from rated to half rated voltage
Rest period between charge discharge cycle (s)	50	
Total cycle time (s)	118	
# Cycles/hr	31	
System Upsizing factor required by cycle/ hr	3	=31/11
System life in years with upsized factor	**2.84**	**=235,789/(11*20*365)** **End of Life – replacement due**

The Supercap sizing calculations use the manufacturer's datasheets, established industry testing, and life norms from published literature. Figures 7 and 8 show that the supercap's base life is 88,000 hours or 1,000,000 cycles at 25° C. The base life is reduced with increasing temperature and ESR. The decrease in capacitance becomes the first limiting factor as the ESR takes longer to reach the 100% increased value.

Table 4 shows the published system datasheet from a supercap manufacturer [7]. Table 4 validates the Supercap system sizing calculated in Table 3. The installed nominal capacity from table 4 is 0.5* 94*750*750 = 7.3kWh. This is roughly three times the required 2.5 kWh size useable energy application. A 7.3 kWh WESS can optimally use 34% of its capacity.

Table 4: Data Sheet Detail from Manufacturer [8]

Supercap based Storage System	Value
Technical data*	
Input voltage	[V DC] 600 / 750
(tolerance range according to EN 50163)	
Total number of double-layer capacitors	1,152
Total capacity [F]	94
Usable energy content [kWh]	2.5
Maximum energy saving possible per hour [kWh/h]	80
Peak power [MW]	0.7
Auxiliaries supply [V]	3 AC 400 / 50 Hz
[V]	3 AC 220 / 60 Hz
Permissible ambient temperature [°C]	-20...+40

4.2   Flywheel based WESS Sizing

Table 5 shows the calculations for sizing a flywheel WESS that meets the specifications in Table 2. The calculated flywheel life is 4.49 years before recertification.

Table 5: Flywheel based WESS sizing

Parameter	Value	Note/ calculation
FW module technical data		
Power (kW)	125	at 90% DoD (depth of discharge)
Energy Capacity (kWh)	0.5	
Charge/ Discharge duration at rated power (s)	18	
Rated ambient temperature (^{o}C)	40	
Depth of discharge (DoD) permissible (%)	90	
Design Cycle life @ 40 C (Cycles)	1,000,000	Limited by physical stress cyclic capability of the flywheel design. Life is extendable by re-inspection and certification, every 1MM cycles
Total modules in a 2.5 kWh system	5	
Life and Performance in Rail System		
Charge discharge duration for rail system (s)	18	
Rest period between charge discharge cycle (s)	50	
Total cycle time (s)	118	
# Cycles/hr	31	
Cycle per year	222,712	
Life of FW based WESS in years	**4.49**	**Re-certification of life due**

The flywheel sizing is based on the published literature for a 0.5 kWh flywheel [9]. The calculation applies industry standards for extrapolations and derating.

5   COMMERCIAL CONSIDERATIONS: CAPACITOR VS. FLYWHEEL

Table 6 compares the basic ownership costs for a 0.5 MW, 2.5 kWh flywheel WESS and a 0.5 MW, 2.5 kWh supercap WESS using the lifetime system sizing values from section 4.

Table 6: Cost of Ownership Comparison for Supercap vs. Flywheel based WESS with 2.5 kWh useable capacity sizing

	Supercap WESS	Flywheel WESS
Initial cost of storage element	$240,000	$216,000
Replacement Cost	$240,000	NA
Replacement Period	2.84 yrs	NA
Replacement costs in 10 years (=$240,000*(10/2.84))	$845,070	NA
Re-certification Cost	NA	$50,000
Recertification Period	NA	4.49 yrs
Re-certification costs in 10 year (=$50,000*(10/4.49))	NA	$111,359
Total Cost of ownership over 10 years	**$1,085,070**	**$327,359**

The 2 WESS have similar initial storage element cost. Over 10 years a flywheel WESS recertification cost is $111,359 compared to the Supercap WESS replacement cost of $845,000. During the 10-year lifetime of equally sized flywheel and Supercap WESS, the flywheel WESS will cost roughly $757,000 less than a Supercap WESS.

The cost analysis highlights pros and cons to apply in choosing the storage technology for a high-power, high-cyclability WESS.

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II.   SUPPLEMENTARY SOURCES

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