Supplemental

Performance Comparison of Rechargeable Batteries for Stationary Applications (Ni/MH vs. Ni–Cd and VRLA)

S1. Ni/MH Battery in Telecom Market

When a major telecom power systems supplier began developing an innovative solution for powering outdoor small cells, it conceptualized a low-cost system with a small battery reserve, 15 to 20 minutes, enough to power through almost 90 percent of grid power interruptions. Traditional telecom backup systems are designed to provide 4 to 8h of runtime, but these large systems are not feasible here since outdoor small cells are normally deployed on utility poles, streetlights or sides of buildings. In addition to physical size, other key requirements must also be considered, including aesthetics, weight, operating temperature range, environment, safety, mounting flexibility, and maintenance. Utilizing the high power-density of Ni/MH cells, a low profile, compact battery system with integrated battery management electronics was developed. Shown in Figure S1, the system weighs less than 12 kg and occupies less than 0.013 m^3 in volume. It can be used to power loads up to 600W at ambient temperatures ranging from –40 to +55 °C [S1].

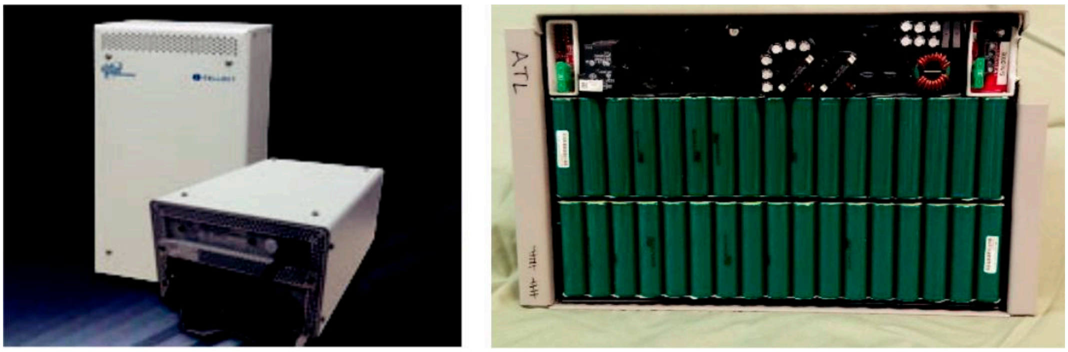


Figure S1. A 600 W Small Cell Power System (left) and its integrated battery module with Ni/MH cells and batter management system (right). Photos are courtesy from Alpha Technologies Ltd. (Burnaby, British Columbia, Canada) and FDK Corp. (Tokyo, Japan).

S2. Large Format Ni/MH Battery in Power System

In contrast to this small cylindrical cell-based battery, Kawasaki Heavy Industries (KHI, Tokyo, Japan) has introduced a large-format prismatic Ni/MH cell product [S2,S3]. Their GigaCell uses a Co-free $RE_{0.9}Mg_{0.1}Ni_{3.9}Al_{0.2}$ (RE: rare earth) metal hydride alloy and a carbon-coated $Ni(OH)_2$ as the active materials in negative and positive electrodes, respectively, and a 4.8 M KOH + 1.2 M NaOH electrolyte [S4]. The negative-to-positive ratio was set to 2.5 to guarantee superior high-rate discharge performance [S5]. At a total stored energy of 5400 Wh (36 V, 150 Ah) this product dwarfs all other commercially available Ni/MH batteries. The specific energy and power of these high-power KHI-Ni/MH batteries are compared to commonly-used stationary battery modules of other chemistries in Table S1. From the information, it is obvious that KHI trades energy density in favor of power density targeting high-power applications. A unique bi-polar battery construction designed for efficient cooling and higher delivered power (Figure S2) is employed for rapid charge/discharge applications (Figure S3). More details about the cell structures can be found in related Japanese Patent Applications reviewed before [S6].

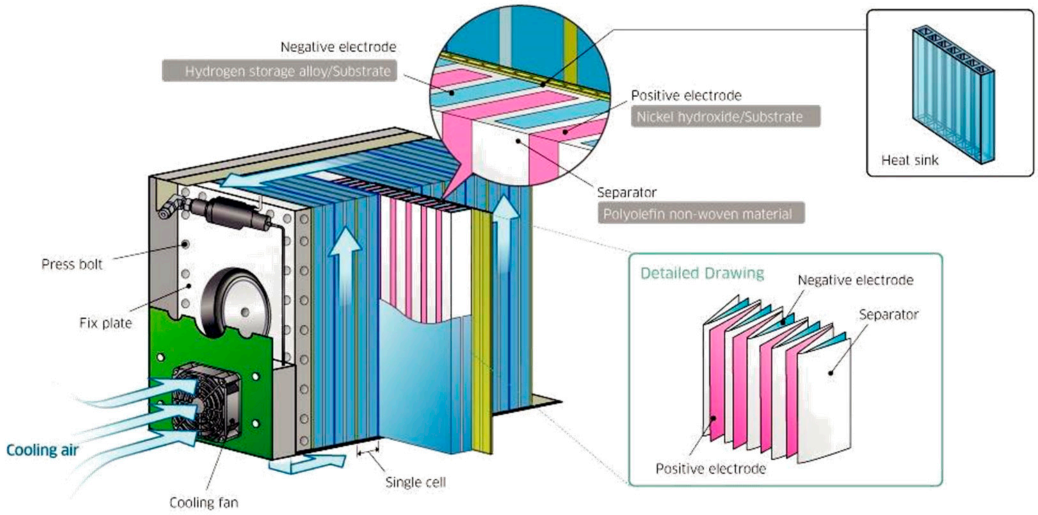


Figure S2. Bi-polar cell design/construction in KHI GigaCell [S7].

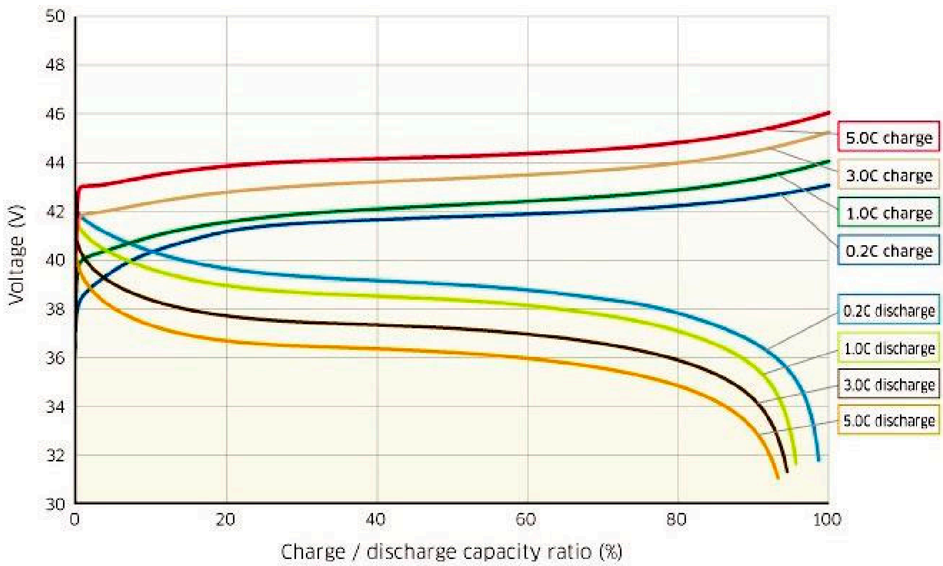


Figure S3. High-rate charge and discharge capability of KHI GigaCell. 5.0C equals 750 amps [S7].

Table S1. Specific energy and power for commercial large format battery modules of four different chemistries. (Ni/MH and Li-ion include integrated electronic components).

Chemistry	Specific Energy (in Wh·kg^{-1})	Specific Energy (in Wh·l^{-1})	Power Density (in W·kg^{-1})	Power Density (in W·l^{-1})
KHI-Ni/MH	21	52	508	1286
Ni-Cd	37	98	123	328
VRLA	45	88	111	219
Li-ion	123	163	182	215

Since 2010, numerous Ni/MH Battery Power Systems (BPS) using the KHI GigaCell product have been installed throughout Japan. The primarily use is in way-side railway storage to capture and reuse a train's regenerative braking energy (Figure S4). Reduced energy usage, lower peak power consumption, improved line voltage stabilization, and overall energy cost savings are commonly observed where these batteries are installed in subways, monorails and regional rail lines in Japan.

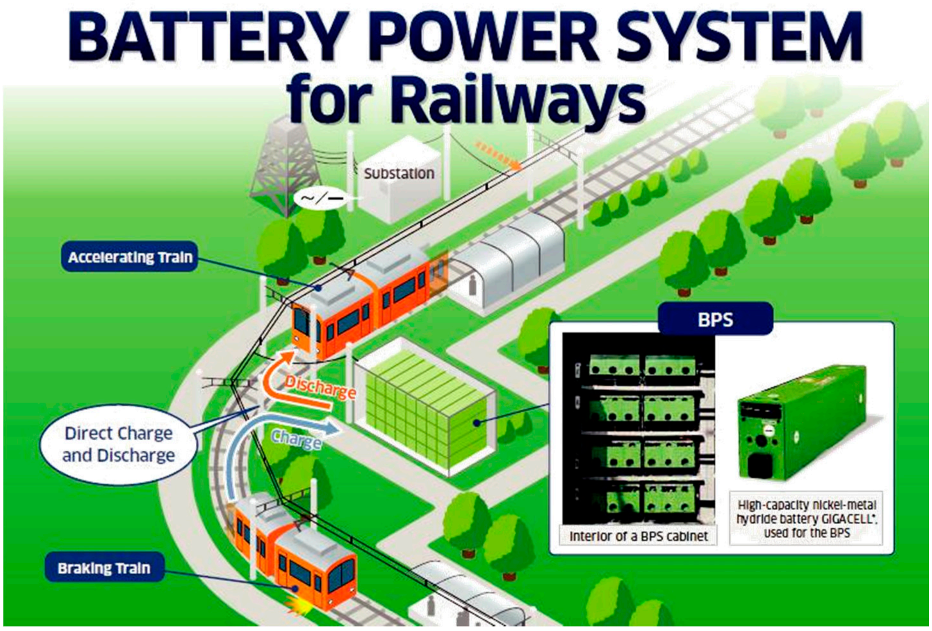


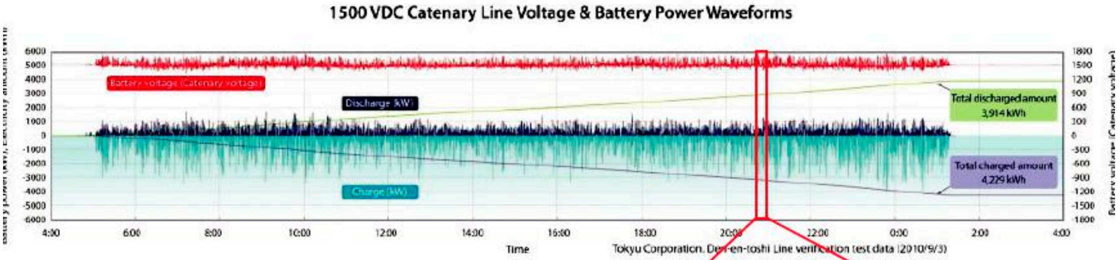
Figure S4. Illustration of a wayside railroad BPS installation [S7].

S3. WMATA Energy Storage Demonstration Project

A Ni/MH BPS was utilized for the Washington Metropolitan Area Transit Authority (WMATA) Energy Storage Demonstration Project installation of a 2 MW / 400 kWh Ni/MH BPS in 2013. The Washington-DC Metrorail system carries 720,000 passengers daily with 91 stations on six lines covering more than 117 miles of track. Trains are powered by 100 substations through a 700 Vdc third-rail distribution system. The BPS installed at the West Falls Church substation consists of four parallel units. Each of them is composed of 19 battery modules (5 kWh each). The outcomes of the two-year study, as reported by the US Department of Transportation Federal Transit Administration last year [S2], were overwhelmingly favorable with up to 15.4% energy savings, up to 12.5% peak power reduction, and a 75.5V average line stabilization.

S4. Ni/MH in Other Fields

A typical railway storage battery experiences around 4000 charge/discharge cycles daily (similar to the output of a large solar or wind farm) as shown in Figure S5. Use of Ni/MH BPS technology in grid-tied renewable energy installations is also being evaluated in Japan. An example is the 102 kWh Ni/MH BPS used to balance the electricity output of a 10 MW solar plant near Osaka as shown in Figure S6.



BPS capacity	400kWh
Cycles per day (1 charge & 1 discharge= 1 cycle)	Approximately 4,000 cycles
Maximum charge power	Over 3,200kW (8C)

Figure S5. Single day charge/discharge profile for a wayside railroad BPS installation [S7].

Figure S6. Solar farm and Ni/MH BPS near Osaka, Japan [S7].

References

S1. Alpha Technologies Ltd. Cellect™ 600 product data sheet. Available online: https://atl.app.box.com/v/cellect-600-48v-dc (accessed on 31 July 20017)

S2. WMATA Energy Storage Demonstration Project, Federal Transit Administration Final Report, June 2015. Available online: https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/FTA_Report_No._0086.pdf (accessed on 31 July 20017).

S3. Nishimura, K.; Takasaki, T.; Sakai, T. Introduction of large-sized nickel-metal hydride battery GIGACELL for industrial applications. *J. Alloy. Compd.* **2013**, *580*, S353–S358.

S4. Takasaki, T.; Nishimura K.; Saito, M.; Fukunaga, H.; Iwaki, T.; Sakai, T. Cobalt-free nickel-metal hydride battery for industrial applications. *J. Alloys Compd.* **2013**, *580*, S378–S381.

S5. Young, K.; Wu, A.; Qiu, Z.; Tan, J.; Mays, W. Effects of H_2O_2 addition on the cell balance and self-discharge of Ni/MH batteries with AB_5 and A_2B_7 alloys. *Int. J. Hydrogen Energy* **2012**, *37*, 9882–9891.

S6. Ouchi, T.; Young, K.; Moghe, D. Reviews on the Japanese Patent Applications regarding nickel/metal hydride batteries. *Batteries* **2016**, 2, 21; doi:10.3390/batteries2030021

S7. About GIGACELL. Available online: http://global.kawasaki.com/en/energy/solutions/battery_energy/about_gigacell/index.html (accessed on 31 July 20017).