Large Diameter and Highly Homogenous Homopolar Active Magnetic Bearings for Energy Storage and Aerospace

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Abstract

High-speed Active Magnetic Bearing (AMB) technology can be used to construct a kinetic energy storage device that achieves significantly lower cost per kWh cycled than better-established technologies such as batteries, Pumped Storage Hydro (PSH), and Compressed Air Energy Storage (CAES). The key is to manufacture a large ring that orbits in a homogeneous magnetic field within a toroidally-shaped vacuum chamber. The supporting magnetic fields prevent hoop stresses within the ring from exceeding the tensile strength of the ring material. This allows a ring of sufficient diameter to store much more kinetic energy per unit of mass than is possible with a flywheel. The Levelized Cost of Energy Cycled is calculated and shown to be inversely proportional to the radius of the ring. Rings with a radius of 30m are cost-competitive with the best Li-Ion battery systems. At a radius of 50m, Ring Energy Storage (RES) is cost-competitive with PSH and CAES. At a radius of 120m, RES paired with scalable but intermittent renewable technologies, such as wind and solar, can supply most of the world's energy grids with reliable power at competitive rates.

If this technology is sufficiently matured and de-risked for commercial energy storage applications, there are more advanced applications of the technology that could be game-changing within the aerospace industry. For example, energy storage on the Moon or Mars where the energy storage capacity per unit of mass shipped between planets is a metric of paramount importance. Non-nuclear energy solutions for off-world use are also valuable for environmental and geopolitical reasons.

Keywords: *Homopolar, Active, Magnetic Bearing, Kinetic Energy Storage, Flywheel*

1. Introduction

High-speed Active Magnetic Bearings (AMBs) that can operate in a vacuum with very low magnetic friction have important applications in the aerospace and renewable energy industries. Areas of active interest include low-cost kinetic energy storage, electromagnetic launch, and hypersonic vehicle testing. Some useful performance metrics for defining application requirements are listed in Table 1.

A new sub-class of homopolar AMBs, called Highly Homogeneous Homopolar AMBs (H3AMBs), is a potential candidate technology for these applications. In a traditional homopolar AMB (an H1AMB) the electromagnets are arranged so that any given point on the rotor's surface will only travel past same-polarity magnetic poles (either all North or all South). An H3AMB is engineered so that, in the absence of field strength changes enacted by control circuits to compensate for perturbations, the nominal pole-to-pole variation in magnetic field strength is minimized. Low magnet friction, and thus a low rate of energy loss, becomes possible because unvarying magnetic fields do not induce eddy currents to flow, and they do suffer from magnetic hysteresis losses.

The technique of magnetic shimming used to achieve magnetic field homogeneities on the order of a few parts-per-million (ppm) in magnetic resonance imaging (MRI) machines, is considered for maximizing magnetic field homogeneity when designing, manufacturing, and tuning H3AMBs. Other techniques include high-tolerance manufacturing, strict process control, mechanical isolation, and the physical separation of electromagnetic motor/generator components from H3AMB components.

The use of a magnetically confined ring for kinetic energy storage has not been reported in recent articles that review the state of the art in Flywheel Energy Storage (Mongird *et al.*, 2020); however, the authors are aware of a relevant study that was published in 1984 (Hull and Iles, 1984). This early study concluded that the idea had promising commercial applications. At the time, potential investors may have disagreed with this assessment as wind and solar were still expensive technologies and climate change was a less pressing concern.

Performance Metrics

Highly disruptive technologies can emerge from heritage technologies that have found niche markets to survive in. A key growth strategy for companies and organizations in niche markets is to, when publishing product performance data, broadly consider all possible growth opportunities, as opposed to only trying to address the needs of existing customers. Those that publish the most comprehensive price and performance data on their products and technology will be offered the best opportunities to enter highly disruptive and potentially very profitable new industries.

Kinetic energy storage is an example of a potentially disruptive new industry for manufacturers of magnetic bearings or magnetically levitated trains. To understand why one must first consider some of the metrics used by the energy storage industry (see Table 1).

Table 1: Energy Storage Performance Metrics

Acronym	***Performance Metric***	***Units***
LCoP	Levelized Cost of Power Input/Output	USD/Watt
LCoS	Levelized Cost of Energy Storage Capacity	USD/Joule
LCoC	Levelized Cost of Energy Cycled	USD/Joule
	Energy Density	W/m^3
	Specific Energy	W/kg
η_{RT}	Round Trip Efficiency	(none)
	Nominal Energy Consumption per Unit of Energy Storage Capacity	W/J
	Nominal Energy Consumption per Unit of Energy Stored	W/J

The term "Levelized" refers to the lifetime cost, including societal costs, which ideally should be comprehensive and include manufacturing, disposal, maintenance, financing, and externalities[1] such as waste disposal, disaster clean up, cost of polluting, etc. Levelized Cost of Energy Cycled is perhaps the most interesting metric in the field of energy storage. It considers how much total energy will be cycled through the device over its lifetime. For example, an energy storage device designed to be coupled with a tidal energy generation facility could cycle energy through storage once every 6 hours and 12 minutes. If the service life of the energy generation system is 50 years, then over its lifetime the system will cycle its storage system 70,694 times. A typical Li-Ion battery can handle only 1200 to 2000 80%-depth-of-discharge charge cycles, so if Li-Ion batteries were paired with tidal energy generation, over the system's lifetime they would need to be recycled and replaced 35 to 59 times. Kinetic energy storage can, in theory, handle an effectively infinite number of charge cycles; therefore, it is a potentially disruptive technology in the grid-scale energy storage market.

Table 2: Energy storage technologies and their performance metrics.

	Li-Ion LFP[2]	**Li-Ion NMC[3]**	**Lead-Acid**	**Vanadium RFB[4]**	**CAES[5]**	**Pumped Storage Hydro**	**Hydrogen Energy Storage**	**Ring Energy Storage**
Cycle Life	**2000**	**1200**	**599**	**5201**	**10403**	**13870**	**10403**	**13870**
Down Time	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**	**0.05**
Depth of Discharge	**0.8**	**0.8**	**0.8**	**0.9**	**0.8**	**0.8**	**0.8**	**0.8**
Cycles Per Year*	**346.75**	**346.75**	**346.75**	**346.75**	**346.75**	**346.75**	**346.75**	**346.75**
Round Trip Efficiency	**0.86**	**0.86**	**0.85**	**0.68**	**0.52**	**0.80**	**0.35**	
Years of Operation	**5.77**	**3.46**	**1.73**	**15**	**30**	**40**	**30**	**40**
Annualized Cost ($ per kWh-year)*	**93**	**140**	**310**	**65**	**29**	**36**	**56**	**(see below)**
Levelized Cost of Energy Cycled ($ per kWh-cycled)	**0.268**	**0.404**	**0.894**	**0.187**	**0.084**	**0.104**	**0.161**	**(see below)**

*Assumes daily cycling with 5% downtime

Table 2 lists some of the better-known grid-scale energy storage technologies along with their performance metrics obtained from a 2020 report from the Pacific Northwest National Laboratory (Mongird et al., 2020). The rightmost column of Table 2, "Ring Energy Storage" lists the assumptions that will be used here when analyzing the performance of energy storage based on H3AMB technology. It should be noted that the cheapest technologies in the table, such as CAES and Pumped Storage Hydro, need geographically suitable sites to exist close to the population centers that need

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[1] In practice, inaccurate estimates of levelized performance metrics are published, for example, when certain societal costs are excluded. Therefore, when publishing, a detailed statement of assumptions is important.

[2] Lithium-ion Iron Phosphate

[3] Lithium-ion Nickel Manganese Cobalt

[4] Redox Flow Battery

[5] Compressed Air Energy Storage

energy storage; therefore, there are many markets where these technologies cannot address the need. Because of the high cost of energy storage, at present intermittent renewable energy generation paired with energy storage does not compete well with fossil fuel energy generation. To transition to a carbon-neutral economy, we will need an energy storage technology that can both:

a) Achieve a 10-fold reduction in cost, and

b) Scale rapidly to meet the huge global demand for energy storage in 2050 (Jorgenson *et al.*, 2050).

3. Comparative Analysis Study

Flywheel energy storage systems so far have not been able to achieve a low enough energy storage cost to be a disruptive technology in the energy storage marketplace. While some of the most advanced flywheel energy storage systems do make use of H1AMBs, they rely entirely on the specific strength of the material in the flywheel's disk to manage the spinning disk's hoop stress. The maximum rim speed, and thus the energy stored per kg of flywheel material, is limited by the specific tensile strength of the material. Increasing the diameter of the disk does not enable the flywheel to store more energy per kilogram of disk material.

However, this limitation can be circumvented if the moving material (that is, the kinetic energy storage medium) is instead confined, and made to travel in a circle, by using magnetic fields. In this case, the amount of kinetic energy that can be stored per kg of material *will* increase with the radius, r, of the circular path. Such a system would not be a flywheel energy storage system (FESS) but rather an energy storge system based on magnetically confining a ring-shaped, hub-less, spoke-less, rotor, or "mass-stream". Technically, the path of the mass-stream does not need to be circular, although a circle is likely the optimal topology for most applications. If we assume a circular, continuous, unbroken, ring-shaped, mass-stream, the total specific energy of a Ring Energy Storage System (RESS), 'E_{Sp}', is given by…

$$E_{Sp} = \frac{1}{2}\frac{m_{rotor}}{m_{system}}\left(\frac{\sigma_t}{\rho} + ra_m\right) \qquad 1$$

Where:
'σ_t' is the maximum tensile stress that rotor material will be required to withstand,
'ρ' is the density of the rotor material,
'r' is the radius of the circular path of motion,
'a_m' is the inward acceleration applied to the rotor by the magnetic field,
'm_{rotor}' is the mass of the rotor, and
'm_{system}' is the mass of the entire energy storage system.

For grid-scale energy storage, it is not difficult in principle to engineer a system where $ra_m \gg \sigma_t/\rho$; therefore, the viability of such a system becomes dependent on engineering considerations (such as energy losses from magnetic friction) instead of physical limitations such as the specific strength of known materials or the fundamental limits of battery chemistry.

The way that the energy density, 'E', scales with 'r' depends on the assumed values for σ_t, ρ, and a_m. For example, if a ring were made from steel, σ_t would be roughly 200 MPa and ρ would be 7840 kg/m^3. However, the key to making a ring energy storage system economically viable is maximizing the 'ra_m' term.

From (Schweitzer G, 2002), in an electromagnet, the force exerted, 'F', is related to the energy, 'W_a', stored in the two airgaps between the electromagnet and the plate that is attracting (note: "airgap" is a term used in the art, but technically it would be a "vacuum gap" in this application).

$$W_a = \frac{1}{2}B_aH_a2A_as \qquad 2$$

Where:
'B_a' is the flux density in the airgaps,
'H_a' is the magnetic field in the airgaps,
'A_a' is the cross-sectional area of each airgap, and
's' is the distance across the airgaps.

If we assume that s is small in relation to A_a, then for small displacements, ds, the magnetic flux, $\mathrm{B_a A_a}$, remains constant. Then…

$$F = \frac{dW_a}{ds} = B_a H_a A_a \tag{3}$$

Because B_a and H_a are related by…

$$\boldsymbol{B} = \mu_0 \mu_{r,H} \boldsymbol{H} \tag{4}$$

…we can substitute for H_a to obtain…

$$F = \frac{B_a^2 A_a}{\mu_0 \mu_{r,H_a}} \tag{5}$$

Where:
‘μ_0’ is the vacuum magnetic permeability ($4\pi \times 10^{-7}\,\mathrm{H/m}$),
‘μ_{r,H_a}’ is the relative permeability of the vacuum in the airgap to μ_0, which in our case is just 1.

The acceleration that can be generated by the magnets is given by $a = F/m$. The mass, ‘m’, is the rotor material density times its volume. The area of the airgap is…

$$A_a = w_a l = w_a 2\pi r_i \tag{6}$$

Where:
‘w_a’ is the width of the magnet at the airgap,
‘l’ is the circumference of the rotor, and
‘r_i’ is the inner radius of the rotor.

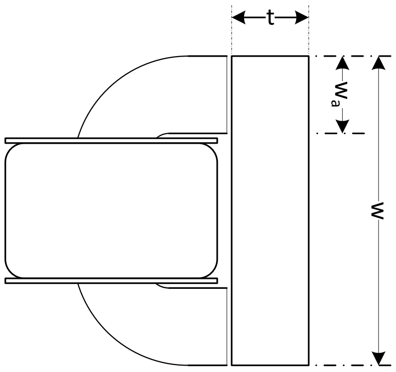


Figure 1: Cross-section of the rotor (right) and primary electromagnets (left)

If the rotor is a circular band with inner radius ‘r_i’, outer radius ‘r_o’, and a rectangular cross-section of ‘t’ by ‘w’ (as shown in Figure 1) the volume of the rotor is …

$$V = \pi(r_o^2 - r_i^2)w \tag{7}$$

(Note: Figure 1 only illustrates the generation of the primary magnetic field in support of the derivation of equations. Additional magnets that generate levitation and control fields and permanent magnet biasing are not shown.)

The mass of the rotor is…

$$m = \rho V = \rho\pi(r_o^2 - r_i^2)w \tag{8}$$

The inward acceleration of the rotor is thus…

$$a = \frac{F}{m} = \frac{B_a^2 A_a}{\mu_0 \mu_{r,H_a}} \cdot \left(\frac{1}{\rho\pi(r_o^2 - r_i^2)w}\right) = \frac{B_a^2 w_a 2\pi r_i}{\mu_0 \mu_{r,H_a} \rho\pi(r_o^2 - r_i^2)w} = \frac{B_a^2}{\mu_0 \rho} \cdot \left(\frac{w_a 2\pi r_i}{\pi(r_o^2 - r_i^2)w}\right) \tag{9}$$

The storage capacity of the system is…

$$E_{Capacity} = \frac{1}{2} m_{rotor} \left(\frac{\sigma_t}{\rho} + r\,\frac{B_a^2}{\mu_0 \rho} \cdot \left(\frac{w_a 2\pi r_i}{\pi(r_o^2 - r_i^2)w}\right)\right) \tag{10}$$

This system must be anchored to a foundation. If the mass of this foundation were included in the mass of the system, then the specific energy of the system would be no better than the specific energy of a flywheel. However, in most grid-energy storage applications, the cost of the storage system’s foundation is a negligible small portion of the total cost.

In some applications, the mass of the system (not including the mass of the foundations) per unit of energy stored is of critical importance. For example, if we were designing an energy storage system that was to be built on earth and then shipped to the moon to supply power to a lunar base (see Figure 4b), the mass per unit of energy cycled would be extremely important because of the high cost of delivering mass to the surface of the moon.

A figure of merit more appropriate for earthly grid energy storage applications is the aforementioned Levelized Cost of

Energy Cycled (LCoEC). LCoEC is…

$$LCoEC = \frac{LevelizedCost}{n_{Cycles}E_{Capacity}} \quad 11$$

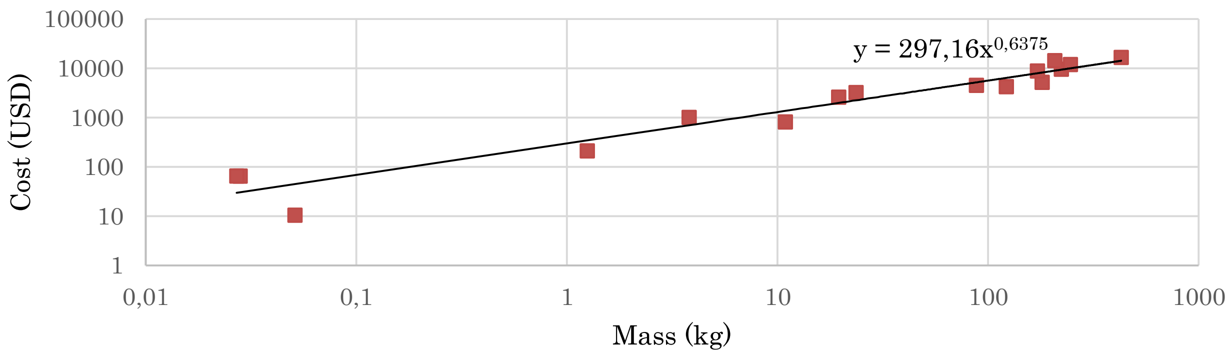
We can estimate the levelized cost from the mass of the system by using cost-over-mass data from similar systems, such as electric motors.

Table 3: Electric motor mass, power, and cost data.

Electric Motor	Model	Mass (kg)	Power (W)	Cost (USD)	Source of Information
RS PRO	238-9715	0.051	5.75	10.42	nz.rs-online.com/
Faulhaber	1727U012CXR	0.028	5.3	64.7	shop.faulhaber.com/1727u012cxr.html
Portescap	Athlonix 17DCT	0.027	4.5	65	portescap.com
Anaheim Automation	23D306S	1.25	1.2	210	anaheimautomation.com
Baldor-Reliance	CEL11303	11	373	812	baldor.com
Oriental Motor	ARM98AK-N5	3.8		1003	orientalmotor.com
Baldor-Reliance	CEBM3546T	20	746	2587	baldor.com
Baldor-Reliance	CEBM3558T	24	2237	3203	baldor.com
Baldor-Reliance	CEM2333T	122	11185	4222	baldor.com
Baldor-Reliance	CEM2514T	88	14914	4490	baldor.com
Baldor-Reliance	EM4102T-G	181	14914	5170	baldor.com
Baldor-Reliance	CEM2539T	171	29828	8769	baldor.com
Baldor-Reliance	CEM2543T	223	37285	9537	baldor.com
Baldor-Reliance	CEM2547T	246	44742	11868	baldor.com
Baldor-Reliance	CEM2551T	207	55927	14217	baldor.com
Baldor-Reliance	CEM2555T	429	74570	16526	baldor.com

Plotting cost versus mass for the data in Table 3 produces Figure 2, which gives us a rough indication of how the cost of an electromagnetic machine is related to its mass.

Figure 2: Electric motor cost versus mass.



If we use the cost-over-mass relationship of Figure 2, the cycle life and depth of discharge values from Table 2, density and tensile strength values for steel, an engineering factor of 2, and assume $B_a = 1.5T$, $\frac{w}{w_a} = 4$, $t = w_a$, $\frac{m_{system}}{m_{rotor}} = 4$ then we can plot and observe the relationship between LCoEC and the radius of the ring (see Figure 3) for a flywheel and for a magnetically confined ring system.

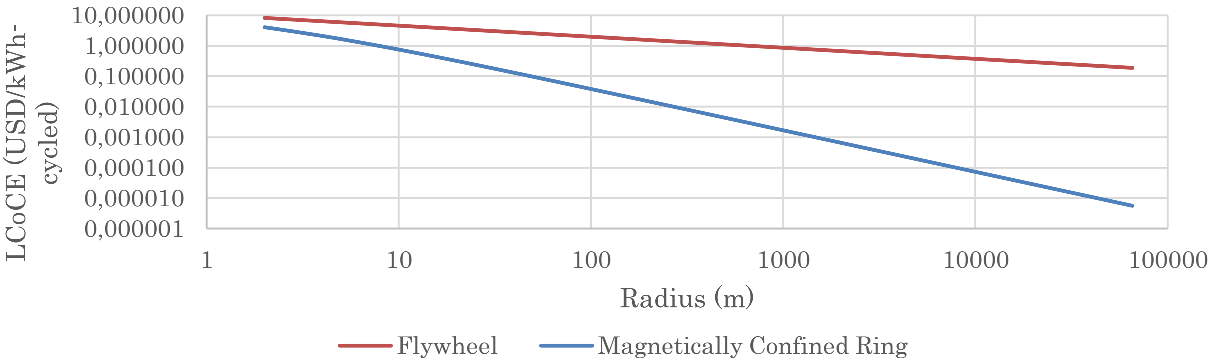


Figure 3: Relationship between Levelized Cost of Energy Cycled (LCoEC) and ring radius.

Without magnetic confinement (that is, operating entirely within the range of speeds that the tensile strength of the rotor's material allows) a flywheel-style kinetic energy storage system does not become cost-competitive with the incumbent technologies on an LCoEC basis - even at the largest scales shown on the chart. However, with magnetic confinement (that is, designing the system so that the energy storing ring orbits within a confining magnetic field), the system becomes cost competitive with incumbent technologies when the radius reaches 30m. A ring with a radius of 120m achieves an LCoEC low enough to make renewable energy generation and storage more economical than fossil-fuel-based energy generation for reliably powering the grid.

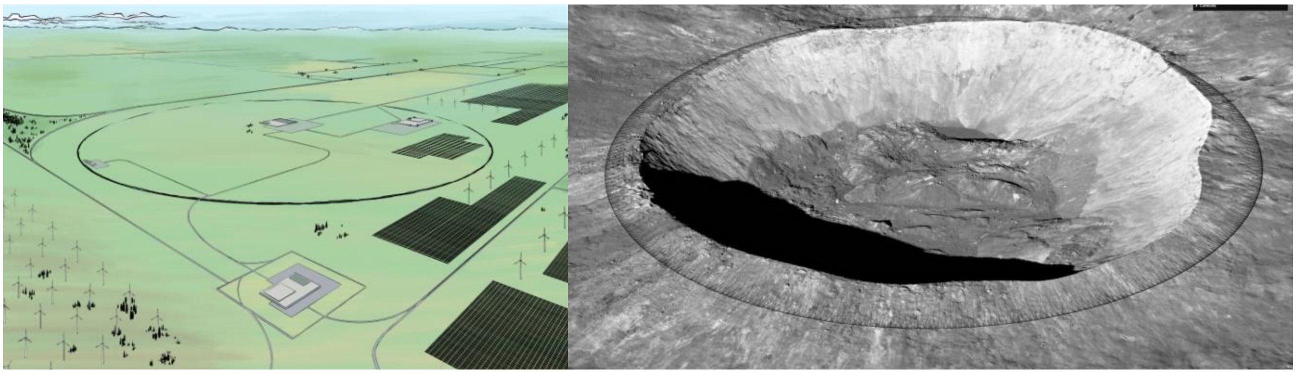


Figure 4: Grid-scale energy storage on the Earth and the Moon. Because of high launch costs, high specific energy, operating temperature range, and the potential for in-situ resource utilization are critically important for lunar storage.

While it still may be challenging for energy storage technologies to gain an economic foothold in our fossil-fuel-powered economy, it is generally possible to find microgrid applications where the economics are favorable. These include, for example, remote communities and bases where electric power is generated by using diesel generators, and diesel fuel must be either shipped in or flown in.

Other potential applications include actively supported systems for terrestrial transportation and the development of low-cost space launch infrastructure (Swan, 2023).

The development of this technology from a concept to a minimally viable product may face some engineering challenges. Low levels of magnetic and aerodynamic friction are needed to achieve high round-trip efficiency and to make sure that the self-discharge rate is low. Converting from electric energy to kinetic energy and back must be efficient when the ring is travelling at higher speeds than other types of electric machines will typically operate at.

4. Conclusions

H3AMBs are highly energy efficient because they are engineered to minimize the degree to which metal parts are exposed to time-varying magnetic fields. They may also minimize magnetic friction by laminating magnet iron and employing ferrites. Energy consumption can further be improved by using PM-bias magnets. Significant future applications for such bearings exist beyond the niche markets in the shaft-supporting bearing industry that AMBs currently serve. Some of the more interesting applications are for grid-scale energy storage. If the technology is sufficiently matured and de-risked, additional aerospace applications may emerge.

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