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Liquid Metal Batteries as a Solution to Renewable Energy's Intermittency Issues

I. Introduction

Despite progress in cost reduction and efficiency, renewable energy sources only produced 13% of the US's total electricity production of 4.1 billion megawatt hours in 2014[1]. The sparse adoption of renewables can, partially, be attributed to intermittency issues associated with renewable sources since solar and wind naturally fluctuate. For example, strong winds at nighttime will generate electricity that goes unused due to low electricity demand, or solar panels on a home will produce wasted power during the day if nobody is home. The seemingly obvious solution to the intermittency issue is simply storing excess power from peak production hours—high wind speeds or midday sunlight—in a battery and using that power when demand surpasses production. While some current capacity for storing excess power exists, it is poorly suited for widespread application. A recent breakthrough in battery technology from MIT presents a potential solution for large scale storage by using high-temperature liquid metal batteries to store grid-level quantities of electricity. In this paper, I will aim to address the limitations of current storage technologies and the economic feasibility of liquid metal batteries for widespread use mediating the intermittency issues of renewable energy sources.

II. Current Storage Technology

There are two prominent options for storing large amounts of electric power. Hydroelectric pumped storage is by far the prevalent option. Hydroelectric pumped storage employs a pair of water reservoirs at different elevations connected by a pump and turbine, as shown on the right. When electricity demand is low, excess grid power pumps water up

[1] "What is U.S. electricity generation by energy source?" Energy Information Association. Last modified April 1, 2016. Accessed March 6, 2016. https://www.eia.gov/tools/faqs/faq.cfm?id=427&t=3.

from the lower reservoir to the higher reservoir. Then, to meet high demand, the water from the upper reservoir flows through the turbine to the lower reservoir to generate electricity[2]. Hydroelectric pumped storage benefits from extremely high capacity limited only by the size of the reservoirs and from the ability to rapidly switch from storage to production by switching pumps off and turbines on. Pumped hydro storage is also extremely efficient, typically converting about 80% of the energy used to pump water back into electricity[3]. Unfortunately, US pumped storage capacity is only around 20 GWh[4]. The obvious constraint around hydroelectric pumped storage is size and cost. The two-reservoir system is inherently large and must either be built into a hillside or have a hillside constructed around it, both of which are expensive—though some projects have been proposed that could utilize abandoned mines in place of the lower elevation reservoir[5]. As a consequence, hydroelectric pumped storage can only be implemented in areas accommodating the elevation requirements.

The second storage option is high-capacity lithium-ion storage batteries, which store energy in individual homes rather than for a full electrical grid. Tesla's Powerwall battery has a capacity of 6.4 kWh and is available for $3000[6]. The Powerwall is designed for in-home use, with one battery's full charge powering a typical American home for a day. The battery, shown to the left, is wall-mounted, about three feet wide, four feet tall, seven inches

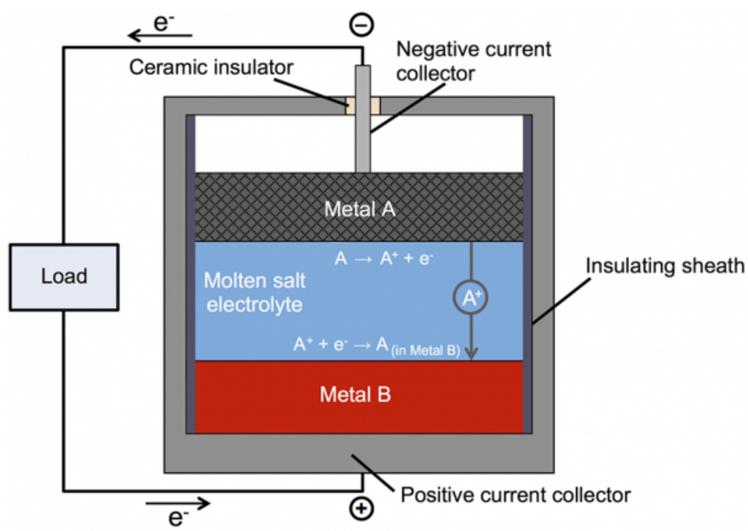
[2] "Pumped Storage Projects," Federal Energy Regulatory Commision. Last modified October 8, 2015. Accessed March 6, 2016. http://www.ferc.gov/industries/hydropower/gen-info/licensing/pump-storage.asp.
[3] "Challenges and Opportunities for New Pumped Storage Development," National Hydropower Association. Accessed March 6, 2016. http://www.hydro.org/wp-content/uploads/2014/01/NHA_PumpedStorage_071212b12.pdf.
[4] "Pumped Hydro," National Hydropower Association. Accested March 6, 2016. http://www.hydro.org/tech-and-policy/technology/pumped-storage/.
[5] "Sub-Surface Pumped Hydroelectric Storage," Energy Storage Association. Accessed March 6, 2016. http://energystorage.org/energy-storage/technologies/sub-surface-pumped-hydroelectric-storage.
[6] "Powerwall," Tesla Motors. Accessed March 6, 2016. https://www.teslamotors.com/powerwall.

deep, and weighs 220 lbs. Tesla designed the battery for use with solar panels, produced by Tesla's sibling company Solarcity, as a solution to solar power's intermittency problems. After announced in April 2015, the Powerwall was enthusiastically received and sold out until mid-2016, totaling roughly $1 billion of sales[7]. Though Tesla's battery appears wonderfully suited for home-sized electricity storage, particularly solar-powered homes, it seems ambitious to use these batteries in every house-hold in a wind-powered region as an answer to wind's intermittency issues. Furthermore, the batteries are ill-suited for industrial applications, where electricity demand vastly exceeds the Powerwall's 6.4 kWh capacity. Tesla's batteries require cooling systems, which scale poorly to larger sizes.

The current storage options are either too large (hydroelectric pump storage) or too small (lithium ion batteries) for broad-reaching adoption. An effective solution to intermittency issues will have to be medium-sized: larger than lithium-ion packs so that one won't be necessary for each household, but smaller than hydroelectric pump storage plants to avoid large construction costs and geographical constraints.

III. Liquid Metal Batteries

The liquid metal battery project began at MIT with the objective of producing a cost-effective grid-scale form of electricity storage, resulting in a 2012 American Chemical Society publication that determined batteries comprised of molten magnesium and antimony could operate as efficient storage cells when operated at high temperatures (700 ºC)[8]. Magnesium and antimony (Metals A and B in the diagram



[7] "Elon Musk's Tesla Battery So Popular It Sold Out Through 2016," Ecowatch. Last modified August 6, 2015. Acessed March 6, 2016. http://ecowatch.com/2015/08/06/tesla-battery-sold-out/.

[8] David Bradwell, Hojong Kim, Aislinn Sirk, and Donald Sadoway. "Magnesium-Antimony Liquid Metal Battery for Stationary Energy Storage," Journal of the American Chemical Society, no. 134 (2012): 1895-1897. Accessed March 6, 2016. http://pubs.acs.org/doi/pdf/10.1021/ja209759s.

above) were chosen for their low melting points, low cost, and low and high electronegativites (an element's affinity for gaining electrons). Magnesium costs $5.15/kg and antimony costs $7/kg, and both are abundant, so there is little obstacle to their widespread use in storage cells. After the study, Dr. Donald Sadoway, the MIT professor who led the research project, started the Liquid Metal Battery Corporation—now called Ambri—to develop the batteries for potential market applications by exploring new battery chemistries for higher capacity and charging efficiency.

A battery, on the most basic level, consists of a cathode, an anode, and an electrolyte. In the anode, a metal is oxidized, releasing electrons, which travel through the electrolyte to the cathode, where another metal accepts the electrons. This transfer of electrons can either be spontaneous or non-spontaneous. If the transfer is spontaneous, it produces current; if the transfer is nonspontaneous, it requires the input of current to occur, and the electrons will then spontaneously flow back, releasing the current that was input. The spontaneous flow is the discharging of the battery, and the nonspontaneous flow represents charging. Liquid metal batteries are comprised very simply of a magnesium layer (the anode) and an antimony layer (the cathode) sandwiching a layer of molten salt electrolyte. To discharge, the magnesium layer donates electrons to antimony, and the magnesium ions flow through the electrolyte to bond with antimony and form an alloy. To charge the cell, current is applied to the cell, breaking apart the magnesium-antimony alloy into uncharged magnesium and antimony[9]. In a solid-state battery, ions moving from the anode to the cathode would cause shrinking and expanding in the electrodes, potentially causing cracking, a major source of decay in solid-state batteries. However, because the metals are liquid, the metal can flow from anode to cathode without complication since the liquid cell will always take the shape of its container. The lack of cracking grants the batteries a remarkable estimated 25- to 30-year lifetime—Ambri has yet to actually see a battery expire in the company's brief lifetime—significantly beyond most lithium-ion battery lifetimes[10]. Additionally, the liquid state eliminates the need for separation

[9] Martin Lamonica. "Ambri's Better Grid Battery", MIT Technology Review. Last modified Fecruary 18, 2013. Accessed March 6, 2016. https://www.technologyreview.com/s/511081/ambris-better-grid-battery/.

[10] Eric Wesoff. "Ambri Wins $35M in VC Funding for Liquid Metal Battery Grid Storage," Last modified April 30, 2014. Accessed April 6, 2016.

membranes since the magnesium, electrolyte, and antimony will naturally separate themselves by density.

Ambri has since reduced the battery's cost and operating temperature by adding lead and other inexpensive metals to the batteries, bringing the operating temperature down to 500 ºC. Using a lead-antimony alloy for the cathode produces a lower melting point without reducing cell potential because positively charged ions will preferentially bond with antimony ions. 500 ºC is far from ambient conditions, but the high operating temperature actually presents a pricing advantage. Though ambient-temperature devices are conventionally thought of as more cost-efficient, high-capacity batteries tend to heat up from large flows of power, so high temperature occurs incidentally. As a result, the temperature control used in liquid metal batteries is an insulating layer of ceramic rather than a cooling system, which is substantially cheaper and simpler to produce.

Ambri's base storage unit is called the Ambri core (size depicted to the left), an aggregate of 768 8-inch liquid metal cells. The cores each have a capacity of 200 kWh and are designed to be further aggregated into systems of up to 1 MWh[11]. This 1 MWh system has an equivalent capacity to 156 Tesla Powerwalls. To be cost effective, the 1 MWh system should be roughly as expensive as 156 Tesla Powerwalls, which were successful enough to sell out for a year in advance when announced. At $3000 per unit, 156 Powerwalls cost $468,000, so this is a reasonable target cost for a 1MWh system, and a price lower or approximately equal to this figure will indicate market viability.

The battery's design is remarkably simple, consisting only of metal disks and salt sealed inside an insulator, which means that the cost of assembly should be very low, and can be minimized with scale. The more widely adopted the batteries, the cheaper and more efficiently the batteries can be produced. The bulk of the cost of the batteries will be tied up in the raw

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http://www.greentechmedia.com/articles/read/Ambri-Wins-35M-in-Venture-Funding-For-Liquid-Metal-Battery-Grid-Storage.

[11] "Project Imua," Analysis Group, Ambri. Last modified November 2015. Accessed March 6, 2016. http://static1.1.sqspcdn.com/static/f/1497163/26724787/1449674657127/Project+Imua+-+Storage+and+Renewables+in+Hawaii.pdf?token=%2BC%2Bfo7yS7SqPcldf4LHGwHBUE6Q%3D

materials. Ambri is constantly testing new chemistries for greater efficiency and lower cost, and the company doesn't release the exact chemistry of their batteries to protect the startup. Because of this, we will (crudely) estimate the price of the materials using the original cell composed of magnesium, antimony, and a magnesium chloride electrolyte. As stated earlier, magnesium costs $5.15/kg and antimony costs $7/kg, or $5150/metric ton and $7000/metric ton, and magnesium chloride can be purchased for $13.78/metric ton; magnesium chloride is virtually worthless and widely used to salt roads during the winter[12]. Because magnesium has a +2 oxidation state and antimony has a -3 oxidation state, the battery will likely use 3/2 as many moles of magnesium as antimony. Using their respective molar masses of 24.305 and 121.76 g/mol, we get that there will be 3.34 times as many tons of antimony as magnesium. It is difficult to predict how much magnesium chloride electrolyte is used, but its cost is so much lower than the cost of the metals that it can probably be ignored, especially since Ambri's current battery chemistry has likely reduced cost in some way that offsets this minor cost. The 1 MWh system is reported to weigh 50 tons[13]. Using the 1:3.34 magnesium to antimony weight ratio, we get that the 1 MWh system has around 11.5 tons of magnesium and 38.5 tons of antimony, which translates to 10.4 metric tons of magnesium and 34.9 metric tons of antimony. Using the cost per metric ton of magnesium and antimony, the cost of the system comes to just under $300,000, or $300/kWh. This figure falls significantly below $468,000, the cost of equivalent storage in lithium ion batteries. Better still, this cost estimate leaves significant room for the cost of assembly and other parts, such as the insulator and electrolyte, while still falling within a competitive price range.

However, this price hinges on magnesium and antimony prices remaining at or around current levels. Fortunately, this appears reasonable based on US Geological Survey data on world reserves of magnesium and antimony. Magnesium reserves are effectively limitless

[12] "Magnesium Chloride Price," Alibaba.com. Last modified March 6, 2016. Accessed March 6, 2016. http://www.alibaba.com/showroom/magnesium-chloride-price.html.

[13] Eric Wesoff. "Slideshow: Update on Ambri's Liquid Metal Grid-Scale Battery," Greentech Media. Last modified February 19, 2014. Accessed March 6, 2016. http://www.greentechmedia.com/articles/read/Slideshow-Update-on-Ambris-Liquid-Metal-Grid-Scale-Battery.

because it is prevalent in seawater, and we can remove it from the water with relative ease[14]. USGS data on antimony reports an estimated 1.8 billion metric tons of antimony in existing mines[15]. Is this enough antimony to meet potentially worldwide demand for storage cells? The world currently consumes around 55 TWh of electricity per day, which will serve as a decent estimate of the storage required[16]. From our earlier calculation, we know that a 1 MWh system needs 35 metic tons of antimony, so current known resources are enough for only 51.4 TWh of storage; however, as stated earlier, Ambri has found successful, unpublished chemistries that do not use solely antimony as the anode, which would significantly reduce the demand on antimony. Ambri has reported cells with no decrease in voltage using as much as 80% lead in the lead-antimony anode, which would mean current antimony resources could supply 257 TWh of storage, meaning worldwide grid adoption would take up only about a fifth of world antimony reserves[17]. Of course, the whole world is not going to rapidly decide to build storage cells overnight, so the demand is more likely to slowly, steadily increase, which could encourage the development of more antimony mines, keeping up with demand growth and alleviating some of the strain on antimony resources.

Additionally, when considering the batteries for grid-scale use, the competitive price range actually increases. The current electricity grid is formatted such that power plants have to constantly assume demand is slightlyhigher than it actually is because if demand spikes above production at any point, someone will end up without power. As a result, electricity plants produce significantly more electricity than consumers actually used. For example, in January 2016, total US generation was 350,863 GWh, but consumption was only 318,075 GWh[18]. While some of these losses can be attributed to transmission systems, a great deal is simply unused

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[14] "Magnesium Compounds," US Geological Survey. Last modified January 2016. Accessed April 4, 2016. http://minerals.usgs.gov/minerals/pubs/commodity/magnesium/mcs-2016-mgcom.pdf.

[15] "Antimony," US Geological Survey. Last modified January 2015. Accessed April 4, 2016. http://minerals.usgs.gov/minerals/pubs/commodity/antimony/mcs-2015-antim.pdf.

[16] "Global Energy Statistical Yearbook 2015," Enerdata. Accessed April 5, 2016. https://yearbook.enerdata.net/electricity-domestic-consumption-data-by-region.html.

[17] Nancey Stauffer. "New battery made of molten metals may offer low-cost, long-lasting storage for the grid," Phys.org. Last modified January 13, 2016. Accessed April 4, 2016. http://phys.org/news/2016-01-battery-molten-metals-low-cost-long-lasting.html.

[18] "Electricity," US Energy Information Administration. Last modified April 26, 2016. Accessed April 26, 2016. http://www.eia.gov/electricity/.

excess generation. If the electric utilities companies install batteries, they can actually cut back generation and save on fuel because their excess generation is now stored rather than lost, so the cost of the batteries are, in a sense, subsidized by the savings from fuel. The batteries actually become a cost-saving measure if you consider the construction of new plants, where companies can replace a few kW of generation capacity with liquid metal batteries. Looking at the EIA's overnight cost estimate for various types of power plant, we see that the plant type with the lowest overnight cost, natural gas advanced combustion turbine, had an overnight cost of $676/kW, above our earlier estimate of $300/kWh for liquid metal batteries[19]. Liquid metal batteries compare even more favorably to the overnight costs of renewables, which are all estimated to be over $2000/kW. Importantly, the reduction of electrical losses means that rather than serve as an additional cost to using renewable energy, liquid metal batteries actually reduce cost by reducing the generation capacity needed to fulfill an area's power needs.

The main drawback to liquid metals is their general lack of testing. So far, only Ambri has put significant research into batteries at high temperatures. Most scientific data on the behavior of materials is at or near room temperature, so Ambri constantly came across unusual findings because the materials they tested would behave differently under very high temperatures. The lack of knowledge surrounding materials at high temperatures has already caused Ambri some developmental complications. In September 2015, the company announced that it would cut a quarter of its staff and delay their commercial deployment scheduled for early 2016 because the batteries' seals were failing under the high temperatures and they needed more time to produce a functional seal[20]. This complication is indicative of the sort of unexpected problems that plague emerging technologies. Liquid metal batteries, despite all their promise, are likely to face many more unexpected complications, any of which could ultimately prove the technology inoperable or ineffectual. However, the same limited knowledge of liquid metal batteries that impedes their

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[19] "Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants," US Energy Information Administration. Last modified April 2013. Accessed April 26, 2016. http://www.eia.gov/forecasts/capitalcost/pdf/updated_capcost.pdf.

[20] Eric Wesoff. "Ambri to Cut Staff, Postpone Commercial Shipments to Hone Battery Design," Last modified September 10, 2015. Accessed April 6, 2016. http://www.greentechmedia.com/articles/read/Ambri-To-Cut-Staff-Postpone-Commercial-Shipments-to-Hone-Battery-Design.

development means that there is likely significant room for making the technology more efficient and affordable.