system would also be harvesting energy in addition to storing it, but since solar heat is free, from an economic perspective the result is the same as a higher storage efficiency.

DISCUSSION AND FUTURE WORK

We have given a complete and precise description of a thermally closed AE-CAES system that makes use of regenerative thermal energy storage and thermo-chemical refrigeration techniques. There are many open questions regarding the performance and costs of such a system, but some significant advantages over other many other forms of energy storage are already clear.

First, the system will be environmentally benign, in that it contains no toxic, caustic or otherwise dangerous materials that could not safely be disposed of in a land-fill. If charged with electricity from renewable sources and provided with a biofuel backup in place of propane, it could also be operated in a entirely carbon-neutral fashion. Second, it will be at least as safe as any form of energy storage available today, since the cold zeolite will only release its air slowly as it warms, so that a simple pressure relief valve ensures that it discharges safely even if everything else fails. The fact that the system is largely underground adds to its safety and makes sabotage difficult, in addition to freeing up the land above it for other uses. These features makes it highly suitable for use in populated areas near to the load centers, where energy storage is generally most valuable.

Third, zeolites do not degrade under pressurized air unless heated to temperatures above 400°C when wet or 500°C when dry. Since we do not need to go above 100°C in normal operation and the modules will be fed dry air, the zeolite will last essentially forever under the intended operating conditions. The modules also contain no moving parts that could wear out, and nothing that could corrode unless the membrane fails and moisture reaches the steel components. Such membranes are very durable, being used to waterproof basements and other subterranean structures that would be difficult to service. Therefore it seems safe to say our modules will need no maintenance and have a mean time to failure on the order a century – considerably longer than any energy storage technology of which we are aware that does not rely on geological formations and hence may be deployed freely. This should result in a low life-cycle cost per unit of energy stored and released over the system's lifetime, as well as with respect to the Barnhart and Benson metric [9].

The upfront and operating costs per unit power will also be quite favorable, since it will be dominated by the cost of the twin-screw compressors that are also used for electricity generation. At 50 kW these run about $500 / kW (lower at larger scales), which is considerably less than electrochemical technologies such as flow batteries. Well designed and maintained compressors with the modest compression ratios required for AE-CAES will also be better than 95% efficient in both compression and expansion. Of course they will need to be maintained and replaced every decade or two, but as a rule the cost of ownership of such compressors is 75% electricity and only 25% maintenance and capital costs.

Given the efficiency of compression and expansion, the main sources of efficiency losses that remain to be quantified are (1) the mechanical energy lost due to friction as the air passes through the packed beds, and (2) the thermal energy lost from the modules and other regenerators over the storage cycle. The first of these can be estimated by numerical simulations for any given regenerator and particulate geometry, but finding the geometries that minimize frictional losses while still obtaining the desired performance characteristics is a nontrivial problem. Chemical engineering software like that available from Aspen Technologies™ can solve such optimization problems, but their cost has precluded our doing up to this time. Even so, the results of such simulations must always be confirmed by building and analyzing actual prototypes.

Because of the large number of potential sources of thermal energy losses, it will probably not be possible to give a meaningful estimate of their magnitudes until the resources needed to build full-scale prototypes have been summoned. What we can say at this time is that the work by Isentropic Ltd. [2] and nearly two centuries of engineering experience with regenerators indicates that these losses can be managed. By this we mean that they can be reduced to a level at which they can be compensated for by a reasonably small solar thermal or other low-cost sources of low-grade heat, together with a reasonably small refrigeration system driven, at least in part, by such low-grade heat. Until this has been demonstrated in practice, however, thermally open AE-CAES systems may be a more saleable value proposition, albeit one with a smaller market potential.

In summary, we have given a detailed design for a thermally closed AE-CAES system, and described some of its advantages over batteries. AE-CAES is not, of course, a perfect substitute for batteries, which can respond much faster and are considerably more compact. AE-CAES is nevertheless very suitable for diurnal load shifting in a distributed setting, because it is very safe, capable of long durations, and its thermal losses are minimized by daily cycling. Thermally open AE-CAES systems also promise to be useful in matching thermal and mechanical loads in microgrids powered by some subset of gas-fired turbines, internal combustion engines, wind turbines, photovoltaics or solar water heaters. Perhaps the most important difference between AE-CAES and batteries, however, is the following. Rather than being a device which is assembled in a factory and then shipped ready-for-use to its destination, AE-CAES facilities are expected to be construction projects that are built to-order onsite out of standardized components, and then become part of the locality's basic infrastructure. This is of course much closer to how electric utilities have traditionally thought about their investment strategy.

In order to realize the promise of AE-CAES, Energy Compression is currently seeking to partner with a well-established engineering firm that focuses on energy and other infrastructure projects. This partnership may include an exclusive license to AE-CAES, restricted to a selected geographic region and/or energy storage application, in exchange for developing and marketing a corresponding product tailored to that region or application. Interested companies are invited to contact the author for further discussion.

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