The Oil Drum: Canada
DISCUSSIONS ABOUT ENERGY AND OUR FUTURE

# Compressed Air Energy Storage - How viable is it?

Posted by Libelle on July 27, 2008 - 10:00am in The Oil Drum: Canada
Topic: Alternative energy
Tags: compressed air, energy storage, thermodynamics [list all tags]

One of the most critical aspects of the implementation of renewable electricity is the ability to store electricity. If a good solution existed right now, our situation would be a good deal easier. On the face of it, compressed air seems a likely candidate: relatively easy to make, store and use - so what is the problem? Why isn't it used routinely?

## More Thermodynamics than You Ever Wanted to Know?

We usually speak of storing and using energy without being very precise about what we mean. That ends forever if you take a few chemistry or engineering courses. Thermodynamics rules everything.

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Let's start with the usual definition of work - using a force to push something a given distance (in the direction of the force). The amount of work is the force multiplied by the distance, and has units of energy. If we lift a 1 kg mass by 1 metre in the earth's gravitational field on the surface of the earth, then the work done on it is the force required: 1kg x 9.8 $m/s^2$ (9.8 Newtons), times 1 metre, or 9.8 Joules. Since a Watt is 1 Joule per second, then in principle (no friction), this lift could be carried out in 9.8 seconds by a 1 Watt electric motor. At the end of the process, the weight has acquired 9.8 Joules of gravitational potential energy.

We just constructed an energy storage device. The weight we lifted could now be allowed to descend, giving its potential energy back to an electrical generator and making electricity in the process. This is in fact the basis of possibly the most effective existing way of storing electricity. Water is pumped from a low reservoir to a high one at times when there is a surplus of electricity, and then allowed to flow back when there is a shortage. For useful amounts of energy storage using reservoirs that are not too large, one generally requires reservoir height differences of a hundred metres or more, which limits this to suitable terrain.

So what about compressed air? Surely a cylinder of compressed air contains energy that could be used to drive something?

This is where it all becomes a little strange. The energy content of compressed gas isn't very different from that of uncompressed gas at the same temperature. For an ideal gas, the energy contents are identical. How come we can get work from the compressed gas?

The answer is that compressed gas has a lower entropy than the uncompressed gas, and that the amount of useful work you can get out of something when it changes depends both on the change in energy content and the change in entropy. We usually focus so much on the energy side of things that we ignore the entropy side.

If the compressed gas has no more energy than the uncompressed gas, where did the energy used to compress it go? The answer can be found in the old bicycle pump experiment. When you compress a gas it becomes hot. In fact all the work put into an ideal gas to compress it is turned into heat. If that heat is thrown away, the same amount of energy as was in that work is thrown away with it.

To look at a definite example, if we take 1 cubic metre of air at 1 atmosphere pressure and 20C and compress it to 10 atmospheres pressure, its temperature will increase very considerably - to 293C. If we want to store this compressed air at 10 atmospheres pressure and 20C, then more compression will be needed as we cool the gas, or its pressure will drop as its temperature does. The total work done on the gas, and the total heat lost are both about 91.7 Watt-hours (Wh). (This assumes that the air is an ideal diatomic gas.)

This gas would now have a lower entropy than the same amount of uncompressed air. The entropy change is 796 J/K (Joules per degree Kelvin). Note the units are energy per degree. This gives a hint of how the entropy change is related to the work that can in principle be extracted from the compressed air. That work can be calculated by multiplying the entropy change by the temperature of the environment in degrees Kelvin. 20C is 293K, so the amount of work that can in principle be extracted is 233 kJ, or 64.8 Wh. If we compare this with the work done compressing the gas, we see that the efficiency of the process is about 71%, even if the compressor is perfectly efficient.

Looking at the expansion of the same air back to 1 atmosphere, using a motor to do work in the process, we can work out that the temperature will fall to -121C, and that the work that is done would be 47.5Wh. The efficiency of ths process is thus 47.5/64.8 = 73%, even with a perfect motor. The round-trip efficiency for energy storage and use would then be just 52%. With real compressors and motors it would clearly be considerably worse. These numbers above are for a compression ratio of 10. If we instead use a compression ratio of 100, things get worse still, with a round-trip efficiency of 27%.

This actually gives a clue as to how to improve the situation. The maximum efficiency of the cycle depends on the pressure ratio, and rises to 100% as that ratio approaches 1. The answer is to use staged compression, with cooling back to ambient temperature between the stages, and staged expansion, with reheat back to ambient temperature between stages. If we get the 100 times compression by two stages of times 10 each, then half the work goes into the first stage and half into the second, with efficiencies as for 10 times compression - a huge improvement. If we use four stages (ratio 3.17), then the maximum effficiency would be 72%. If we take into account that real compressors and engines are not perfect, and neither are coolers and reheaters, we can see that real overall efficiencies achieved are never likely to be very good, even with very complicated equipment.

Whether technology is useful depends, though, on comparison with the alternatives. The overall efficicency of a compessor train and a compressed air car may not look all that high, but an internal combustion vehicle engine can look pretty inefficient, even with North American fuel prices. This means that an air-powered car may make some sense. For more details on the MDI air car, see some MDI engine tests. Notice that in a conventional car you get free heating, but in a compressed air car you get free cooling.

Bulk power storage is another matter. Large reservoirs of compressed air can be and have been constructed, but they are not used simply to drive engines to regenerate power. Building large heat exchangers to warm the air in a power generating unit would be very costly and not very efficient, so the air is instead heated to a much higher temperature before the expansion turbine by burning natural gas in it. The whole installation is thus a sort of gas turbine, with the difference that the compressor and power turbines are run at different times instead of together. This is no longer a straightforward energy storage device.