Liquid air energy storage

Cryogenic energy storage for the clean energy transition

By **Stephen B. Harrison**, Managing Director, **sbh4 consulting**

Variable and non-programmable renewable energy is making an increasing contribution to power generation. In parallel, the 'electrification of everything' is a fundamental mantra of decarbonisation. These aspects combine to mean that long-term, high-capacity energy storage will become essential to balance supply and demand on the power transmission grid. Liquid air energy storage (LAES) is emerging as a high potential clean energy storage technology for this purpose.

LAES relies on cryogenic engineering and expertise, which sits in the heart of the industrial gases sector. In LAES, liquefied air is produced on a liquefaction unit and stored as a cryogenic liquid in highly insulated tanks. The production of liquid air can coincide with periods when there is excess renewable power available in the grid, such as overnight when the wind is blowing hard and consumer demand is low or during peak sunlight hours in the middle of the day.

When the grid requires support, such as on days where there is little wind or solar power generation, the liquid air is pumped to a high pressure, vaporised, and released to an expansion turbine, which generates electricity for the grid.

The world's first LAES demonstration plant was built by Highview Power at the Pilsworth landfill waste management site close to Manchester in the UK and commenced operations in 2018. Highview Power has since announced two commercial scale units for Vermont in the US and Carrington in the UK. Each will have the capability to generate 50 MW of power and will have energy storage capacity exceeding 250 MWh equivalent to five hours of continuous discharge.

LAES demonstration plant built by Highview Power

> "The main turbine on a LAES facility expands pressurised air from around 150 bar to atmospheric pressure in four stages..."

Technology selection

The most suitable technology for power or energy storage depends on the required duration, release rate and storage capacity.

Ultra-capacitors and flywheels can release small amounts (kilowatt-hour, or kWh) of power within seconds. Batteries come in to play for storing moderate (megawatt-hour, or MWh) of power to be released over a few hours.

Compressed air energy storage (CAES) works in a similar way to LAES, but air is simply compressed into a very large storage chamber such as an underground cavern and then released through a turbine. In CAES, no liquefaction of the air takes place. CAES and pumped-hydro schemes can release several gigawatt-hour (GWh) of power over a period of hours.

Underground storage of hydrogen (UHS) in salt caverns is effective when terawatt-hour (TWh) of energy storage is required for release on a seasonal basis. Air Liquide and Linde operate UHS facilities in Texas to balance their hydrogen pipeline supply schemes to customers. The Linde cavern at Moss Bluff can store 6,000 tonnes of hydrogen, the equivalent of two weeks production from a large steam methane reformer (SMR).

Similarly, underground storage of natural gas (UGS) is used for seasonal energy demand balancing. The UGS facility operated by NAM – an exploration and production company – at Norg in the Netherlands stores seven billion cubic metres of natural gas in a depleted gas field and can release that gas at a rate of three million cubic metres per hour at periods of peak demand – such as during a cold winter's day when heating demand is at its highest.

LAES fits into this continuum of energy storage technologies close to the middle, with a similar profile to CAES or pumped hydro energy storage. The advantage that LAES has over these technologies is that it can be implemented in almost any geography. Pumped hydro requires suitable contours in the natural geography to enable water to be stored in two nearby lakes with a suitable height difference. CAES can only be implemented at large-scale where the underground geology allows cost-effective creation of a compressed air storage cavern.

As with the storage capacity continuum, LAES lies around the mid-point of these efficiency and CAPEX metrics. The round-trip efficiency can be as high as 70% if the heat energy required for vaporisation of the liquid air is available from a nearby 'waste-heat' source, such as a combined heat and power plant.

In addition to the available geology, storage capacity, release speed and storage duration, other performance metrics must be considered. Energy density might be important, and the round-trip efficiency is critical in the long-term. The CAPEX cost per MWh of energy storage is often a deciding factor when two energy storage systems have similar operational characteristics.

From a sustainability perspective, the materials of construction must also be considered. The construction of a LAES facility uses steel and avoids lithium and cobalt which are required to produce Li-ion batteries. The price of lithium climbed by 400% during 2021, so avoiding dependence on this commodity makes good economic sense also.

Whilst UHS in salt caverns offers low-cost, low-carbon, seasonal energy storage at utility scale, it has a low round-trip efficiency (MW power required for electrolysis compared to MW power generated on a turbine or fuel cell) in the order of 40%. On the other hand, ultra-capacitors have a very high round-trip efficiency at about 95% but discharge their entire stored energy within minutes, leak around 10% of their stored energy per day, and their CAPEX cost is around 100,000 times more than underground hydrogen storage, per unit of energy stored.

LAES – Leveraging ASU technology

LAES operates in a very similar way to a cryogenic air separation unit (ASU). A typical ASU configuration involves an air compressor with cooling towers to remove the heat energy of compression. The warm air is cooled by counter-current heat exchange with cold gases leaving the ASU. Inside the ASU, the cold air is further cooled by expansion on a high-speed expansion turbine. The turbine produces electrical power which improves the energy efficiency of the ASU.

Cryogenic gases such as liquid oxygen and liquid nitrogen flow from the ASU and are stored in large, insulated tanks. Additionally, nitrogen gas from the ASU can be liquefied in a separate nitrogen liquefaction unit (NLU). If large quantities of liquid nitrogen are required, the thermodynamic efficiency of the NLU can exceed that of the air separation unit and justify the additional ▶

"The machines used by Baker Hughes for LAES applications are integrally geared with tilting pad, oil-lubricated bearings"

capital expenditure of this separate process unit.

The liquid oxygen and liquid nitrogen from the ASU and NLU may be distributed to customers in road tankers. Alternatively, they are pumped to around 30 bar by a cryogenic pump then vaporised in a bath of heated water and introduced into the high-pressure pipeline network for supply to industrial gases tonnage customers. The equipment is referred to as a TPV, or tank, pump and vaporiser system. It is deployed only at times when it is necessary to supplement gaseous production from the ASU.

Vaporisation is also a critical part of the LAES cycle, and like the TPV system in ASU operations, it is only activated when the electrical grid needs a boost. However, in LAES, expansion of the vaporised gas across a turbine is essential to generate the electrical power for which the system has been implemented – and the liquid is pumped to around 150 bar to maximise the energy recovery across the expansion turbine.

High speed rotating machinery

Within the LAES cycle, there are four requirements for high-speed rotating machinery. The first step is to compress air to around 15 bar.

A four-stage centrifugal compressor would be ideal, as might be used as the main air compressor on an air separation unit. Drying of the air and CO_2 removal is the next step to avoid solids and blockages in the subsequent process stages.

A second two or three-stage centrifugal air compressor then boosts the main inlet air, plus some boil-off air from the cold box, to around 60 bar. Liquefaction of the air is then achieved using an expansion turbine inside the cold box.

Andrea Burrato, Energy Storage Platform Manager at Baker Hughes in Italy, says that, "We offer all of the gas compression and expansion turbomachinery required for a LAES facility. We also offer similar equipment for CAES applications. They are based on radial machines that we have used for many years for energy recovery in natural gas pipeline let-down stations and non-condensing axial steam turbines."

In addition to the compressors and turboexpanders that are required to produce liquid air, the heart of the LAES plant is the power generation turbine. "The main turbine on a LAES facility expands pressurised air from around 150 bar to atmospheric pressure in four stages," adds Burrato. "There are three interstage air reheaters between each turbine stage, to maximise power recovery and efficiency."

The selection of the expansion turbine depends on the size of the LAES facility. Up to around 20 MW calls for a multi-stage radial expansion turbine rotating at speeds of up to 10,000 RPM. "The machines used by Baker Hughes for LAES applications are integrally geared with tilting pad, oil-lubricated bearings," says Burrato.

For larger sizes, an axial turboexpander would be more appropriate. These machines are direct coupled to the synchronous generator and run at synchronous speed (3,000 or 3,600 RPM), without the need for a gearbox.

The start-up time of an LAES system cannot compete with ultra-capacitors or batteries, which react within milliseconds or seconds but can ramp up to be fully operational within less than 10 minutes from a 'cold-start' or only a few minutes from a 'warm-start'. Burrato adds that, "The rate-limiting factor at start-up is the need to limit the thermal stress of the turbine and of the other equipment. Think of a diesel engine in your car: turn the key and the electrical engine heater is activated. Then wait until the 'engine warming' lamp is off and hit the ignition and the gas pedal. Sophisticated machinery lasts longer if we treat it with respect." gw

LAES demonstration plant built by Highview Power