Hydrogen for energy storage

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Hydrogen storage has been used in the UK for a very long time (town gas, Teesside)

Town gas was first deployed widely around 200 years ago. It contained around 50% hydrogen. The first gas holder was invented in 1824, and many were constructed in Victorian times to storage town gas, and more recently natural gas.

Numerous salt caverns have been constructed in the UK as short-term natural gas stores. On Teesside, three hydrogen salt caverns were created to store hydrogen used in industrial processes. They have now been decommissioned.

Gasometer image from: https://commons.wikimedia.org/wiki/File:Gas_Holder_from_Kimberley_Road, _London_N18_ - geograph.org.uk - 315911.jpg
Bulk electricity storage is expensive, particularly for storage over long periods.

<table>
<thead>
<tr>
<th>Type</th>
<th>£/kW</th>
<th>£/kWh</th>
<th>Eff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Li-Ion</td>
<td>1000</td>
<td>200</td>
<td>90%</td>
</tr>
<tr>
<td>Pumped Hydro</td>
<td>1000</td>
<td>33</td>
<td>78%</td>
</tr>
<tr>
<td>Molten salt</td>
<td>300</td>
<td>2</td>
<td>67%</td>
</tr>
<tr>
<td>CAES</td>
<td>550</td>
<td>30</td>
<td>56%</td>
</tr>
<tr>
<td>Hydrogen salt cavern</td>
<td>150</td>
<td>3</td>
<td>35%</td>
</tr>
</tbody>
</table>

Bulk electricity storage is expensive, so we currently tend to store precursors to electricity instead (e.g. coal; gas). That might not be possible in the future if renewables have a large share of total generation and there is substantial excess generation at times of high generation and low demand. Given the reduction in renewable costs, this is becoming increasingly likely.

All types of storage vary in costs and performance, for both power output and energy storage capacity. We need to consider how hydrogen compares to alternatives such as Li-ion batteries. Hydrogen systems have much lower energy storage costs, but relatively low round-trip efficiency, so are considered particularly promising for interseasonal energy storage if demands in some seasons are much higher than in others (e.g. heat pumps in winter).

While batteries are seen as having a key potential role, they are very expensive for storing electricity over long periods. Hydrogen is a potential alternative, despite the low roundtrip energy efficiency.

Table source: UCL comparison of the literature.
We know that hydrogen storage works – and can be designed flexibly to meet the system needs.

Electricity can be used to produce high-quality hydrogen from electrolysis. The hydrogen can then be stored, and at a later date used to generate electricity through a fuel cell or turbine. Each part of the system is independent and can be sized according to the requirements of the system.

We need to understand how hydrogen energy storage might best fit into the energy system in the future.

Hydrogen has competition from other storage technologies.

It would also be possible to use hydrogen as a fuel, rather than for pure power-to-power storage – for example, we already use large amounts of hydrogen in ammonia manufacturing.

Finally, hydrogen could be a precursor to synthetic fuels.

Let’s analyse options using models working at different temporal scales

1. Types of hydrogen storage

2. Can hydrogen storage help to integrate renewable electricity generation?

3. How might hydrogen storage feature when we consider the wider energy system?

First, we will review some types of *large-scale* hydrogen storage. We are not going to talk about smaller-scale storage, for example at refuelling stations or in vehicles.

Next, we will consider whether hydrogen storage is a cost-effective approach to integrating high levels of renewable generation, and what it’s role might be, using a high-resolution electricity investment model.

Finally, we’ll consider whether hydrogen storage is still cost-effective when we consider the wider energy system rather than just the electricity system.
1 Types of hydrogen storage

Hydrogen is a very small and buoyant molecule. There’s very little in the atmosphere as it tends to escape the Earth’s gravity.

It escapes easily from porous materials, and only a few impermeable storage materials are suitable. We need to choose these materials carefully. Hydrogen gas has a low energy density so is often compressed to high pressures in order to maximise storage capacity.
Salt caverns are used to store natural gas, and were used to store hydrogen in the past. They are produced by dissolving underground salt deposits using water and pumping out the brine. They operate at high pressures of 50–250 bar.

Images from BGS: https://www.bgs.ac.uk/downloads/start.cfm?id=1370
Used gas fields *probably* could be used in the future

<table>
<thead>
<tr>
<th></th>
<th>Salt cavern</th>
<th>Used gas field (Rough)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy density</td>
<td>Up to 2 MJ/litre</td>
<td>0.2 MJ/litre</td>
</tr>
<tr>
<td>Usable storage</td>
<td>70 GWh</td>
<td>12,000 GWh</td>
</tr>
<tr>
<td>Hydrogen power output</td>
<td>1.3 GW</td>
<td>6.3 GW</td>
</tr>
<tr>
<td>Duration</td>
<td>2 days</td>
<td>80 days</td>
</tr>
<tr>
<td>Cost</td>
<td>£3/kWh</td>
<td>£0.1/kWh</td>
</tr>
</tbody>
</table>

The Rough undersea used gas field provided long-term storage for the UK gas system for many years. It was capable of storing 3.3 bn cubic metres of natural gas, which is 3% of the UK’s gas demand in 2018, but the rate of charging and discharging was much more limited than for salt caverns. The hydrogen capacity of Rough would only be 42% of the natural gas capacity, due to the lower energy density of hydrogen.

The principal advantage of used gas field storage, compared to salt cavern storage, is a much lower capital cost and very high capacity, which could make it ideal for seasonal hydrogen storage.

There has been some debate about whether used gas fields could be used to store hydrogen, or whether there would be leakage or issues with hydrogen-eating bacteria. A paper from Amid et al (2016) concluded that while the biological reduction of sulphur minerals to \( \text{H}_2\text{S} \) remains a potential problem, there should not be substantive technical impediments. The jury will be out until used gas field storage is tested.

Salt cavern data is from the ETI.
Liquid hydrogen storage is also an option

-240 °C
10 MJ/litre

Liquid hydrogen has five times the energy density of 700 bar hydrogen gas, so in theory could be cheaper to store. In practice, the hydrogen needs to be cooled to -240 °C (33 K), and required an active cooling system to avoid boil-off. Electricity consumption for liquefaction is expensive. Liquid hydrogen is therefore mostly used for applications where high energy density or very pure hydrogen is required, and the higher bulk cost can be justified.

The Brayton cycle, with helium as a refrigerant, is generally used for small liquefaction plants. The Claude cycle, which has higher capital costs but lower operating costs, and economies of scale, is used for larger plants. Liquid hydrogen would likely be stored in tanks rather than geological formations, to maximise control and minimise losses. The need for active cooling would reduce its viability for seasonal storage.

Image from: https://www.nasa.gov/content/liquid-hydrogen-the-fuel-of-choice-for-space-exploration
2 Can hydrogen storage help to integrate renewable electricity generation?
We use the highRES electricity systems model to identify energy storage investments to support the electricity system.

The *high* spatial and temporal *resolution* electricity system model (highRES) covers GB, runs for one snapshot year (here, 2050) at full hourly resolution (8760 hours per year). It simultaneously makes capacity investment (where and how much for generation and storage) and dispatch (operational) decisions so supply $\geq$ demand in every hour of the year at least cost. So rather than using a rolling dispatch, in the way that some electricity models attempt to mimic markets, it makes all dispatch decisions at the same time with perfect foresight.

This version of highRES includes load shape changes for heat pumps and EVs.
Hydrogen storage is consistently deployed across the weather years. The amount of hydrogen energy storage needed varies quite a bit from year to year -> 15-25 TWh.

In these simulations, highRES only considers existing caverns and depleted fields, for which we have data, and assumes conversion of these to hydrogen. The maximum hydrogen storage capacity the model can deploy is 25 TWh in these runs, so 1996, 1998, and 2010 could have had higher investment if that had been available. It only considers power-to-power storage (i.e. power-to-gas and then back to power).
Hydrogen is used primarily for interseasonal storage, alongside short-term battery storage.

This graph shows the quantity of hydrogen in storage in each hour of the year for the year 2010.

Hydrogen primarily provides interseasonal storage to meet winter peak electricity demands from heat pumps. The stores are steadily charged from summer (low demand) to winter (high supply and demand), and then discharged more quickly over winter. During spring, stores are mostly empty.
Long-term hydrogen storage reduces the cost of electricity and enables a greater renewable generation share.

SHORT shows scenarios with short-term storage – batteries – as the only available option.

ALL shows the same scenarios with hydrogen storage made available.

The left graph shows that the levelized cost of electricity (LCOE) is about £10/MWh lower on average when hydrogen seasonal storage is available.

The right graph shows that these lower system costs occur despite the optimal share of renewables increasing by 10% on average to almost 80% of all UK electricity generation.
3 How might hydrogen storage feature when we consider the wider energy system?
We use the UK TIMES energy system model to understand the role of hydrogen storage in the wider energy system.

The UK TIMES energy system model represents all energy demands and greenhouse gas emissions across the UK economy, and a wide range of options to meet those demands.

The hydrogen supply chain in UK TIMES includes a range of renewable and non-renewable hydrogen production technologies, delivery and storage technologies, and numerous potential end-use demands from transport, buildings and industry. It considers both power-to-power technologies, with flexible sizing, and hydrogen being used as a fuel. It doesn’t (yet) consider hydrogen as a feedstock for producing synthetic fuels.
Will there be demand for hydrogen in the future energy system that offers an alternative to power-to-power storage?

This graph shows hydrogen consumption by sector in 2050, for three scenarios:

- The first scenario shows hydrogen demand in a “least cost” scenario, in which UK TIMES calculates the cheapest set of technologies to meet an 80% reduction in emissions. This shows that hydrogen is likely to have a prominent role in the future.

- The second and third scenarios examine scenarios in which hydrogen comes to dominate in transport and building heat, and is also used for some electricity storage. These examine targets of 80% and net zero, respectively. They show that hydrogen can have a substantive role even with a net zero target.

The conclusion from this graph is that there is a demand for hydrogen from the wider economy that is independent of the availability of hydrogen from energy storage.
UK TIMES has only 16 timeslices, so does not identify the need for energy storage that exists in reality. It’s representation of intermittent renewable generation is particularly poor – it does not identify substantive generation shortfalls and excesses.

We can use a high-resolution electricity system model to identify excess renewable generation. If we force UK TIMES to put an appropriate proportion of renewable generation into storage, based on the results of the electricity system model, then we can understand how that hydrogen might be used.

We find that virtually no hydrogen is used as power-to-power storage. There is a role for hydrogen turbines to provide flexible electricity generation, but these consume little hydrogen. It is cheaper to use hydrogen as a fuel, and to build alternative electricity generation to meet electricity demands. This is because hydrogen can be produced with an efficiency of 85%, but the efficiency to generate electricity from hydrogen can only reach 60%.
All existing models of the role of hydrogen storage have shortcomings that we are trying to address.

There are trade-offs between high and low temporal resolution models, investment and operational models, short and long time horizons, and whole system and electricity models. The arrows point in the direction of increasing complexity. With greater complexity, models become larger and potentially less tractable.
We are confident that hydrogen storage has a role in the future, but we still don’t fully understand that role.

The holy grail is to examine whole energy system investment at high temporal resolution.

Load curves are important. Will there be a winter peak from electric heating in the future, as shown in the load curve above? How large would it be? Using hydrogen in fuel cells in some homes, and heat pumps in others, could greatly reduce seasonal variations. Work is needed in this area.

Another option that is currently being built into the model is the production of synthetic fuels from hydrogen, for example jet fuel or ammonia. We don’t consider currently ammonia in our model as an energy vector, although this is under development at the moment. I think Bill David is going to tell you why we should.
Thank you for listening

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