# Hydrogen and ammonia: Technical assumptions

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# Context for cost assumptions

- This presentation only covers hydrogen for energy storage
- Study optimisation modelling is based on costs disclosed in the literature, rather than actual completed project costs
- We are aware that the current cost environment for equipment is very volatile due, amongst other things, to :
  - Supply chain disruptions
  - Inflation
  - High demand for some equipment types, especially electrolysers
- The costs in the study are forecasts for 2050, and pre-date recent changes in the market. We quote costs in £ of 2021.
- Some of the changes in costs compared to today are significant, especially the costs of electrolysers and fuel cells
  - Electrolyser long term cost forecasts show a broad consensus, but all are based on extrapolation from a fairly small deployment base today
  - Cost is shown as a function of time, but is really a function of deployment
- There is therefore considerable uncertainty in some elements of the cost modelling which we have addressed by sensitivity analysis, and we believe our conclusions to be robust to these sensitivities
  - We also recommend more detailed engineering studies as one of our follow up actions
- Optimisation modelling does not include modification of the power transmission system
  - Grid will most likely need significant change in the future in any case because of increasing demand and changes in sources of power from power stations to renewables
  - Very difficult to quantify grid upgrade costs in a modelling study of this nature

FIGURE 7

Bulk storage of hydrogen.

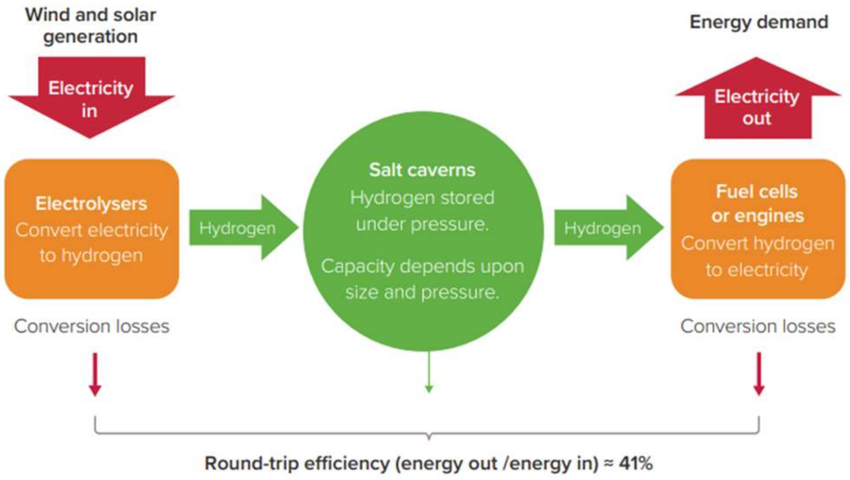
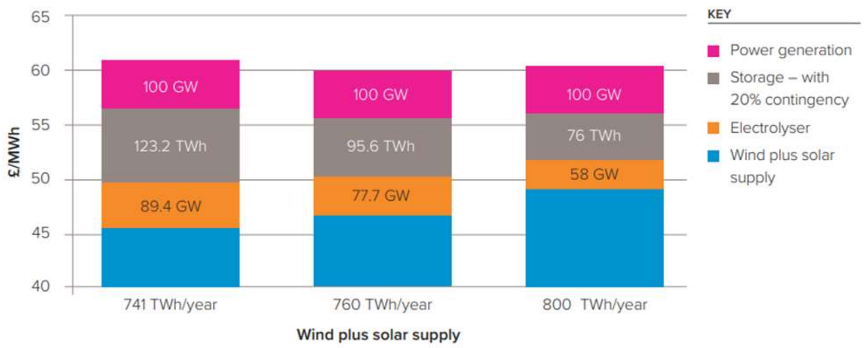



FIGURE 23

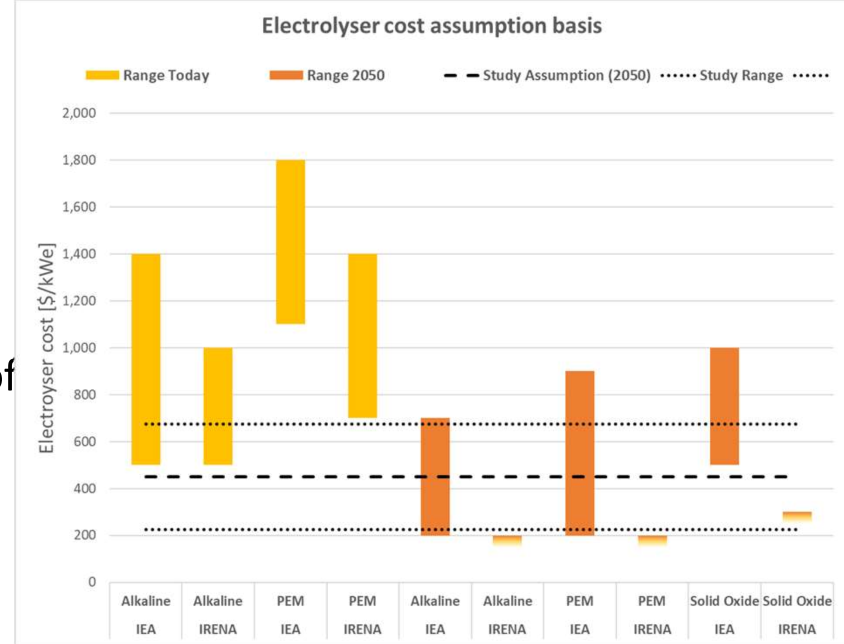
Breakdown of average cost of electricity.

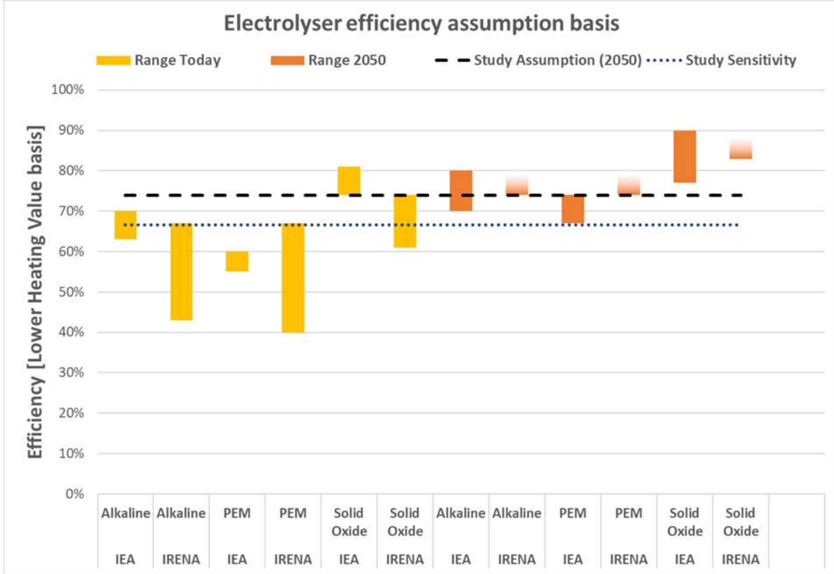
Breakdown of the average cost of electricity for different levels of wind and solar supply, with the base costs for hydrogen storage and a 5% discount rate. The cost of wind and solar supply dominates the total (note the suppressed zero).



# Green hydrogen assumptions

- Key data sources are IEA Future of Hydrogen* and IRENA Green Hydrogen Cost reduction**
- Costs are intended to represent installed project costs per kW of power into the electrolysers
- Most if not all published studies forecast significant falls in electrolyser costs due to :
    - Manufacturing at multi-GW scale
    - Larger projects (going from 10’s of MW to 10’s of GW), leading to economies of scale
    - Technological advances

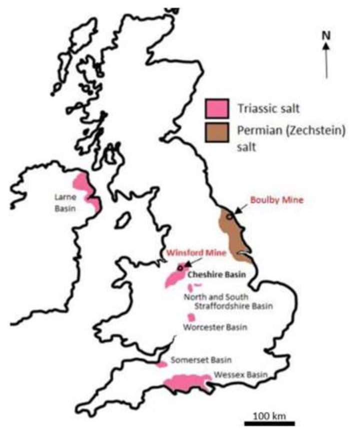



- Efficiency is also predicted to improve over time, as the technology continues to develop
- Our study is agnostic to electrolyser technology
    - Electrolyser response time is not a critical issue for this application, so choice is purely economic

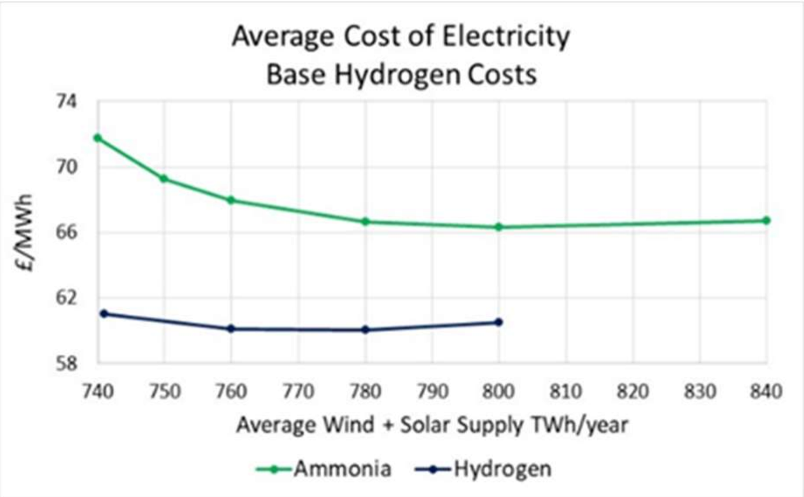
*IEA. 2019 The Future of Hydrogen. See https://www.iea.org/reports/the-future-of-hydrogen
**IRENA. 2020. Green Hydrogen Cost Reduction: Scaling up Electrolysers to Meet the 1.5ºC Climate Goal https://irena.org/-/media/Files/IRENA/Agency/Publication/2020/Dec/IRENA_Green_hydrogen_cost_2020.pd

# Hydrogen storage




- Hydrogen storage would be in salt caverns, formed by solution mining in one of three GB regions
  - East Yorkshire, Cheshire, Wessex
- Hydrogen storage caverns have been operated successfully for decades in the following locations in Teesside (1970's) and Texas (1983 and 2007) :
- It is believed that sufficient capacity exists in the UK, but suitable sites are quite localized
- Costs have been based on literature data, with a scaling factor for cavern size. The central case is based on H21 NoE study + 50% following literature review
  - Range of costs = £267/400/534 /MWh usable hydrogen stored (LHV basis)

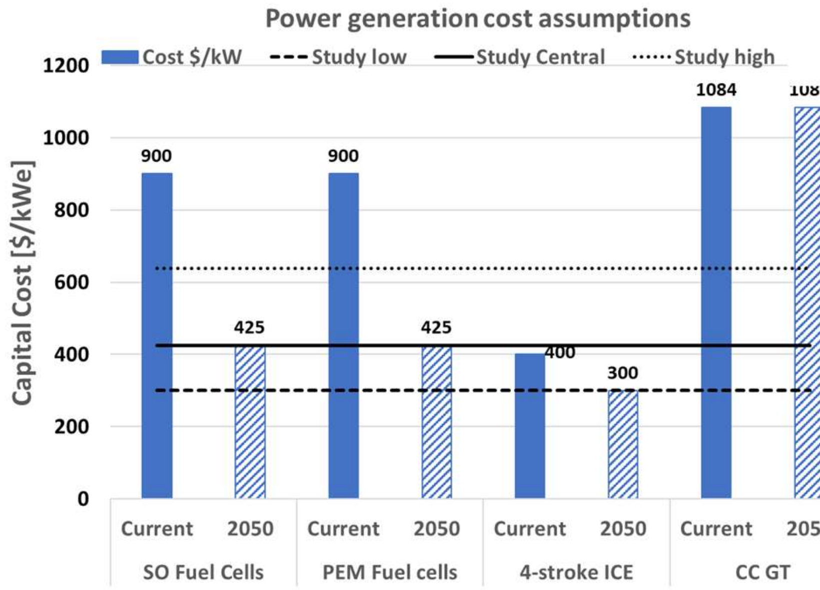
# Ammonia

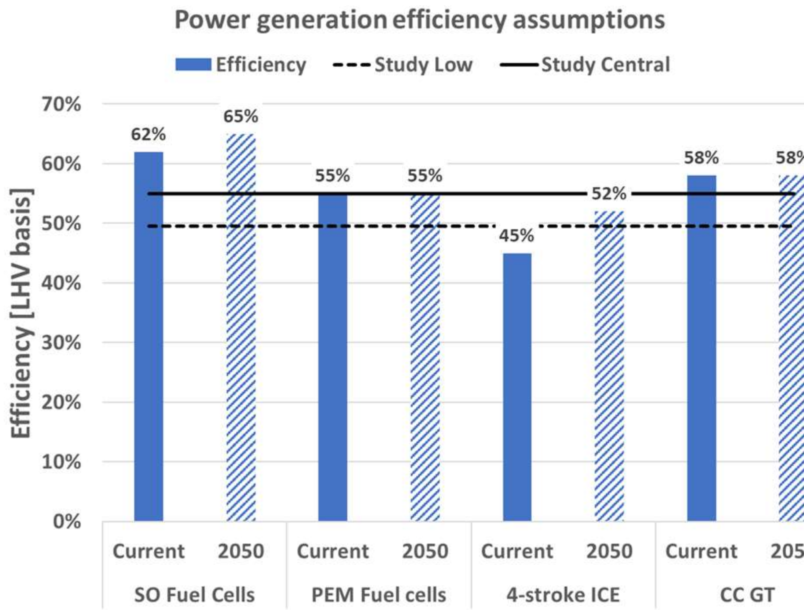



- Ammonia has been assessed as an alternative storage medium to green hydrogen, because it is easier and cheaper to ship and store than hydrogen
- There is a synthesis step following green hydrogen production, and nitrogen is supplied from an air separation unit
  - Assumed cost of ammonia synthesis and ASU = $900/annual te of ammonia today, and $760/annual te in 2050 at a scale of ~1 million tepa ammonia
  - Assumed cost of ammonia storage is £197/$MWh_{LHV}$
- Ammonia production / storage / power generation is not tied to geological storage locations
  - Hence ammonia may have a role mitigating infrastructure constraints, e.g. in areas remote from hydrogen storage regions
  - Ammonia also offers an option to import green energy into the UK
- Ammonia conversion to power is technically less well developed than hydrogen to power
  - We have assumed power generation costs from ammonia are the same as power generation costs from hydrogen
- We find that LCOE is higher when ammonia is used as the storage medium by ~£5/MWh

# Power generation from hydrogen

- Study modelling assumes that all power delivered from stored hydrogen has to be generated by new investment
  - Generation capacity assumed to be equal to peak grid demand of 100 GW
  - Average utilization is 9-10%, but in peak years will be significantly higher
- The central assumption is that generation will be by grid-scale hydrogen fuel cells, installed at a cost of $425/kWe (2021 $) in 2050, with an efficiency of 55%*
  - Current FC costs are much higher, but are for small systems (kW-scale) and often include steam reforming of natural gas
  - Manufacturing scale-up will also reduce unit cost of fuel cells
  - Expect continued optimization of the technology
- Technology development and/or demonstration is needed for all hydrogen to power options – full scale demonstrations have yet to be established




* Lower Heating Value basis

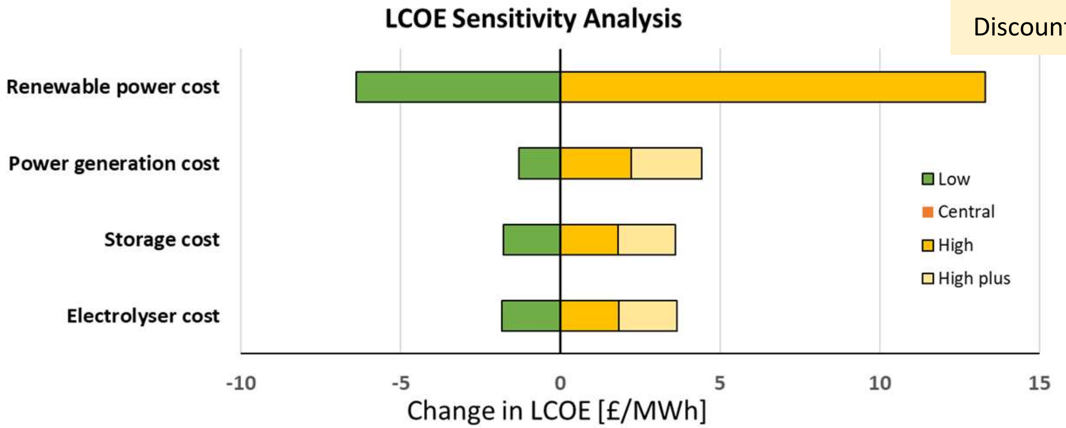
# Impact of uncertainties in assumptions

**Cost**

- Impact of changes from base line assumptions shown below with high plus cases added
- Baseline LCOE = £60/MWh
- About 14% of the total power supplied to the system comes from storage – moderating the impact of differences from the assumed costs on LCOE
- These costs are at constant renewable power generation
- Impact will be moderated somewhat if system is optimized, except for power generation sensitivity

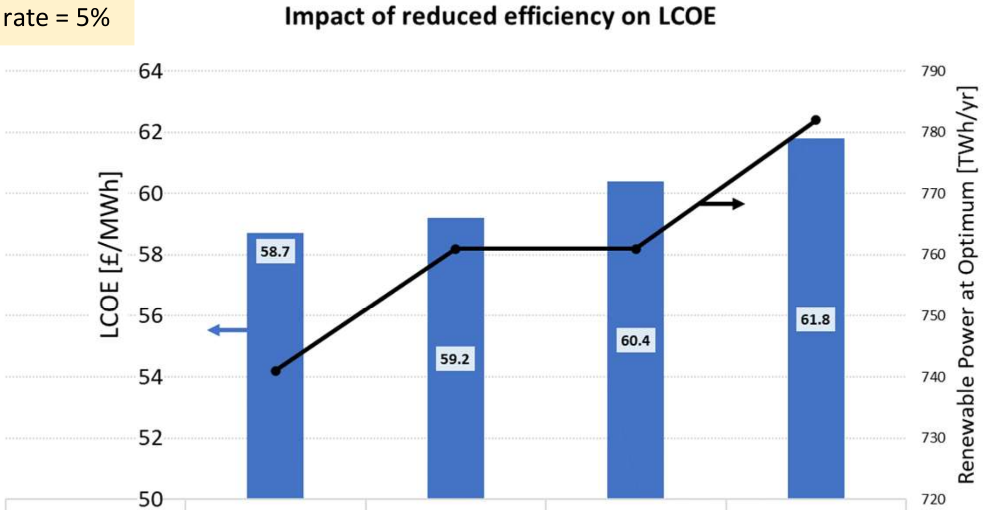
**Efficiency**

- Base line costs assumed in chart below, except for hydrogen store costs assumed to be low
- System has been optimised for each level of efficiency
- Effect of reducing round trip efficiency from 40.7% to 33% is ~5% of LCOE




| | | Low | Central | High | High plus |
|---|---|---|---|---|---|
| Electrolyser cost | $/kW | 225 | 450 | 675 | 900 |
| Storage cost | £/MWh H2 | 267 | 400 | 534 | 668 |
| Power generation cost | $/kW | 300 | 425 | 637.5 | 850 |
| Renewable power cost | £/MWh e | 30.2 | 35 | 45 | 45 |

Discount rate = 5%




| | | | | |
|---|---|---|---|---|
| Power generation eff. | 55.0% | 55.0% | 49.5% | 49.2% |
| Electrolyer efficiency | 74.0% | 66.6% | 74.0% | 66.6% |
| Round Trip Efficiency | 40.7% | 36.6% | 36.6% | 33.0% |

# Opportunities and challenges

- Further optimisation options include :
  - Demand side management to reduce peak load
  - Retrofit of existing CCGT power stations to hydrogen (depending on geography, especially costs of $H_2$ pipelines)
  - Internal combustion engines for power generation (promising results lately on efficiency, and potentially lower cost and flexible)
  - Reversible fuel cells/ electrolysers
  - Mixed technology solutions for power generation, deploying fuel cells for more frequent use and combustion engines for occasional use
- Technology readiness
  - Power generation from hydrogen at grid scale by fuel cells is relatively low TRL today
  - **Development and demonstration at scale is needed**
- Understanding infrastructure requirements
  - Future grid design will impact on optimum deployment of storage, for example determining the role of ammonia
  - Need to assess retrofit options to existing assets, such as possible re-use of natural gas pipelines for hydrogen in future
- Supply chain development
  - If the storage system is built over (say) 20 years, then ~5 GW/yr of fuel cells and ~4 GW/yr of electroylsers would be needed
  - Fuel cell sales in 2021 were 2.3 GW – increasing 70% over 2020, most growth in mobile applications
  - Electrolyser sales were 1.2 GW/yr in 2022 – double the sales in 2021
  - **Need to see significant scale up in these supply chains globally**
- Cavern construction
  - Thousands of caverns have been constructed globally, including 5 for hydrogen
  - Water source : large volumes required – sourcing strategy needed
  - Brine disposal : will most likely be at sea, which is already practiced, but must be done with care
  - Project duration ~5 years, with ~3 years of solution mining
  - Need to build 80 clusters of 10 caverns
  - **"…Building this many clusters by 2050 would be challenging, but the technical capabilities needed to execute such projects already exist in the UK"**