Hydrogen Power Generation – Challenges and Prospects for 100% Hydrogen Gas Turbines

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Thought Exercise – What is the scale of the challenge?
Let’s convert 2.2 GWe RWE Pembroke Power CCGT from natural gas to 100% hydrogen operation...

Opened: 2012
Rated Electrical Output: 2.2 GW
Thermal Efficiency: 60%
# of GTs: 5 x Alstom GT26Bs
Let’s convert RWE Pembroke Power CCGT from natural gas to 100% hydrogen operation...

1. How much hydrogen will we need? \(2.2 \text{ GW}_e / 60\% = 3.7 \text{ GW}_{\text{th,Fuel}}\)

<table>
<thead>
<tr>
<th>@15°C, 1 bar, approx. values</th>
<th>Methane</th>
<th>Hydrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHV (MJ/kg)</td>
<td>50</td>
<td>120</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>0.67</td>
<td>0.084</td>
</tr>
<tr>
<td>Mass Flow for Pembroke (kg/s)</td>
<td>73.3</td>
<td>30.6</td>
</tr>
<tr>
<td>Volume Flow for Pembroke (m³/s)</td>
<td>109</td>
<td>363</td>
</tr>
<tr>
<td>Volume Flow for Pembroke (m³/d)</td>
<td>9.4M</td>
<td>31M</td>
</tr>
</tbody>
</table>

Note: Current UK Annual Hydrogen Production = 0.74 Mt/yr = 24M m³/d [3]
Let’s convert RWE Pembroke Power CCGT from natural gas to 100% hydrogen operation...

2. How do we generate 31M m$^3$/d of “blue” or “green” hydrogen?

Reforming (SMR/ATR) + CCS
- Air Products SMR: 5M m$^3$/d H$_2$ [4]
- So we’ll need 7!
- Requires 12M m$^3$/d natural gas
  - Based on Table 12 of [5]
  - 15% of Dragon LNG + South Hook LNG Capacity
- Produces ~7 Mt CO$_2$/yr
  - Based on 7.05 kg CO$_2$/kg H$_2$ [6]
  - +~60% on CCGT (~4.3 Mt/yr [7])
  - Larger than 5 Mt CO$_2$/yr capacity of Northern Lights

Electrolysis
- ITM Power 10MW Electrolyser (REFHYNE): 0.042M m$^3$/d H$_2$ [8]
- So we’ll need 742!
- Requires 7.4 GW of electricity
  - >3x Pembroke CCGT Output
  - 65 TWh/yr (>90% of UK Wind + Solar Generation)
  - 4.8x World’s Largest Solar Park (Tengger Desert)
  - 1.2x Hornsea Offshore Wind Farms

While 100% H$_2$ at Pembroke is unlikely, H$_2$ blending is a real possibility.
Why Hydrogen GTs?

1) Requires H₂ production at large-scale, lowering cost and supports decarbonization of industry, transport, and heat on path to net-zero

2) Lower LCOE than CCGTs in flexible operation and nuclear plants in baseload operation under future BEIS carbon price projections [9]
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Source: www.gridwatch.templar.co.uk
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Current State-of-the-Art

High H₂ (up to 100%) gas turbines are a reality today...

- Often requires diffusion flames with steam dilution to control emissions (e.g. NOₓ) with efficiency penalty
- Dry low emissions (DLE) and dry low NOₓ (DLN) lean premixed burners limited to ~60% H₂
- Sequential and micromix burners show promise

In 2019, CTOs of Siemens, General Electric, Solar, Mitsubishi, Ansaldo, and MAN Energy Solutions committed to 100% H₂ GTs by 2030 [11]
H₂ Combustion – GT OEMs Hydrogen Combustors

Ansaldo Energia GT26/GT36 Sequential Combustor

Current Allowable H₂ [1]

- Up to 30% H₂
- Up to 45% H₂ derated
- Up to 50% H₂

Ansaldo Energia and Equinor collaborating on validation of 100% H₂ gas turbine combustor [1]
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H$_2$ Combustion – GT OEMs Hydrogen Combustors

Current Allowable H$_2$ [1]
Up to 50% H$_2$

General Electric DLN 2.6e Micromix Combustion System for 9HA Gas Turbine

General Electric developing 100% H$_2$ gas turbine combustor technology pathway [1]
H₂ Combustion – The fun part!

We compared H₂ and CH₄ earlier, but how do they burn?

Methane + Air (21% O₂): \[ CH_4 + 2(O_2 + 3.76N_2) \rightarrow CO_2 + 2H_2O + 7.52N_2 \] (9.50 %vol CO₂)

Hydrogen + Air (21% O₂): \[ 2H_2 + (O_2 + 3.76N_2) \rightarrow 2H_2O + 3.76N_2 \] (0.04 %vol CO₂)

[13]
**H₂ Combustion – The fun part!**

Let’s compare some key flame properties:

<table>
<thead>
<tr>
<th>@15°C, 1 bar, φ = 1</th>
<th>Methane</th>
<th>Hydrogen</th>
<th>Δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flammability Limits in Air (%vol Fuel, ‘LEL’ – ‘UEL’)</td>
<td>5 - 15</td>
<td>4 - 75</td>
<td>+ 6x</td>
</tr>
<tr>
<td>Laminar Flame Speed</td>
<td>0.36 m/s</td>
<td>2.2 m/s</td>
<td>+ 6x</td>
</tr>
<tr>
<td>Adiabatic Flame Temperature</td>
<td>1946°C</td>
<td>2108°C</td>
<td>+ 8%</td>
</tr>
</tbody>
</table>

How does this impact gas turbine combustion systems:

1) Wider Flammability Limits – Control of ignition system on start-up, safety of downstream equipment
2) Higher Flame Speeds – Increased risk of flashback (upstream flame movement) in premixed operation
3) Higher Flame Temperatures – Excessive NOₓ emissions, high metal temperatures, machine de-rating
**H₂ Combustion – Gas Turbine Research Centre**

- Experimental combustion at industrially-relevant conditions (elevated temperature and pressure)
- Gas mixing, optical diagnostics, emissions

**Project experience with H₂:**
- EU FP7 H2IGCC – up to 2 MW H₂
- EPSRC Flex-E-Plant – 15% H₂ in CH₄ (P2G)
- EPSRC Advanced Gas Turbine – Pure and dilute H₂-air
- BEIS Hy4Heat – Industrial Fuel Switching
- WEFO FLEXIS – Pure H₂, H₂-NH₃, and NH₃
- EPSRC SAFE AGT – Pilot-scale NH₃-H₂ GT development
- EU H2020 FLEXnCONFU – NH₃ and H₂ in P2G GTs

\[ u = 60 \text{ m/s} \]
\[ Re = 30000 \]
H₂ Combustion – EU FP7 H2IGCC Project

CH₄-Air
Stable Swirl Flame

85%H₂-15%N₂-Air
Swirl Flame Flashback Event

Experiments conducted at GTRC
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H₂ Power Generation – Ongoing Projects

1) HyNet and HyDeploy – Cadent Gas, Progressive Energy, others
H₂ Power Generation – Other Ongoing Projects

2) **Nuon Magnum CCGT Conversion Project** (Netherlands) – Mitsubishi, Vattenfall, Equinor, Gasunie
   - Aim to convert 440 MW CCGT to 100% Hydrogen by 2023 [15]

3) **EU H2020 “HotFlex” / “ComSOS” Project** (Austria) – Verbund AG, Sunfire, TU Graz
   - Utilize excess renewables to generate “green” hydrogen for blending with natural gas at 838 MW CCGT plant (Mellach) [16]

4) **EU H2020 ENABLEH2 Project** (UK) – Cranfield University, SAFRAN, Heathrow Airport, others
   - Evaluate liquid-H₂ for aviation utilizing micromix combustion technology [17]

5) **Japan’s “Basic Hydrogen Strategy”**
   - Develop and demonstrate H₂ blended, pure H₂, and pure NH₃ gas turbines by 2030 [18]
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Challenges and Research Opportunities

**Challenge:** The fully fuel-flexible combustor

100% Natural Gas to 100% H$_2$ (and their blends)

What fuel/air injection strategy avoids flashback and thermoacoustic instabilities with high efficiency and low emissions over the GT load range?

Can additive manufacturing play a role in novel combustor designs to improve cooling, mixing, and pressure drop?

What about safety? Start-up, flame monitoring, auxiliary components...build on vast H$_2$ process industry experience. HSL are certainly interested [19]
Challenges and Research Opportunities

Challenge: When should GT users (e.g. utilities) invest?

Retrofit vs. New Build

Do we strand existing CCGT assets by moving to $H_2$ blending or 100% $H_2$?

Should new-build CCGT be $H_2$-ready? The CCC thinks so [20]

When/if decarbonized $H_2$ will be ready to supply $H_2$ GTs at scale? Navigant report provides the pathways [21]

How to integrate $H_2$ GTs and $H_2$ storage? ETI have a view [22]

Is small-scale, decentralized $H_2$ GT CHP a viable alternative?
We are currently in the Hydrogen ‘Field of Dreams’

If you build large-scale, decarbonized hydrogen production....

....dispatchable, flexible, H₂ GTs will come!
Thank you!

www.cu-gtrc.co.uk
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Useful Resources and References:

[10] Linstrand, N., *This Swedish scientist works towards fulfilling Siemens’ 2030 hydrogen pledge*, Link
[17] Cranfield University, *ENABLEH2*, Link
[22] Gammer, D., *The role of hydrogen storage in a clean responsive power system*, Link