Fuel flexibility with low carbon fuels

Drivers for decarbonization, enablers for renewables

A. Miliani

October 12th, 2022

Agenda

- Market Inputs
- Energy tarnsition scenarios and top level strategy
- Technology challenges
- Low carbon fuel roadmaps
- Recent experiences

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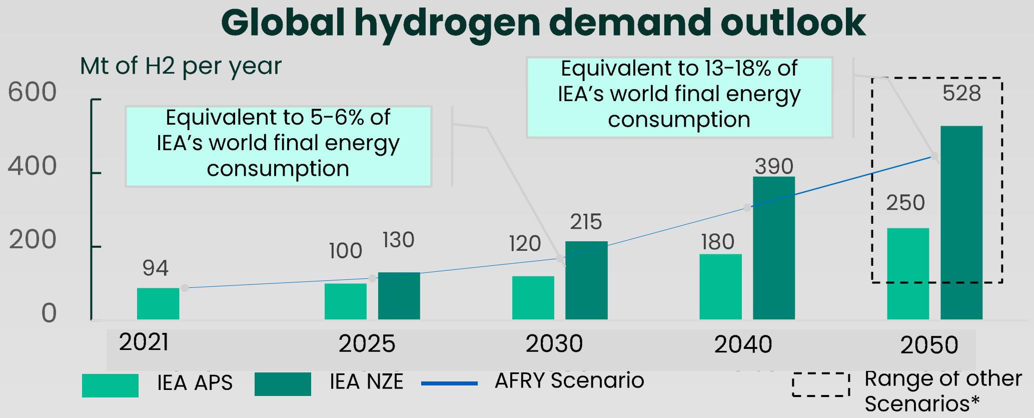
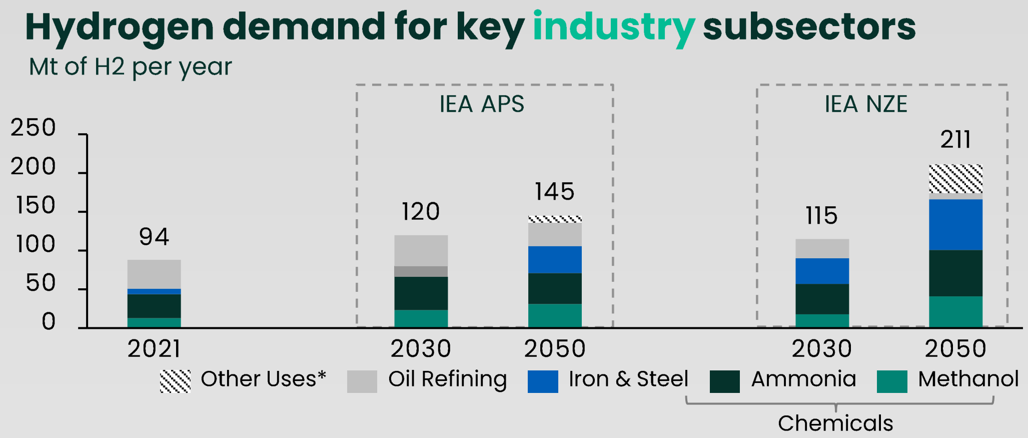
New Energy Vectors market overview





799 Hydrogen projects announced

- Ammonia, Methanol, Steel, Transportation, Syntetic Fuels, Grid Injection, Industry feedstock, Power
- Europa leads (>30%)

61% Green H2 Projects

550 MW Electrolysis capacity operational in 2021 (200MW China)
800 kt/year Low-carbon hydrogen capacity in 2021

26 MT Green H2 production capacity By 2030

Manufacturing capacity		End-use		Transportation
3.5 GW Electrolysis manufacturing capacity; +3.5 GW in 2022; (Europe & China leading)	**11 GW** Fuel cell manufacturing capacity in 2021 +2 GW in 2022 (Japan & Korea leading)	**59,000** FCEVs fleet on the road end-June 22; +50% sales in 2021; 700 hours operational	**425,000** Stationary fuel cells installed (Korea, US, Europe & Japan leading)	**3 H_2 shipping pilots** LH_2, clean NH_3, and LOHC shipped to Japan from Australia and the Middle East

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Top View Technology Strategy

Hydrogen

Present:
- Enhanced Diffusive combustor for High H2 percentages
- DLN Combustor for medium to Low H2 percentages

Long Term:
- DLN Combustor able to cover the entire H2 Blend

Ammonia

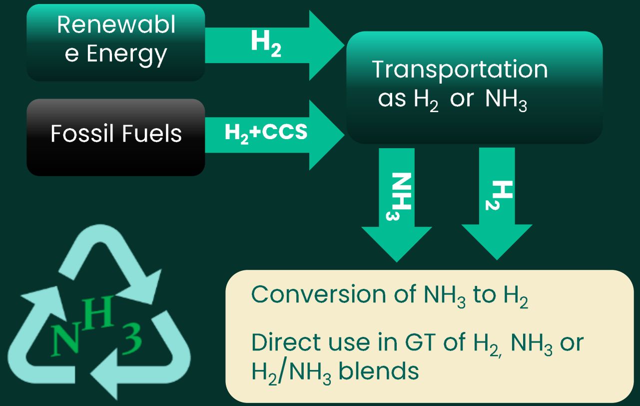
Present:
- Basic technology development combustor components

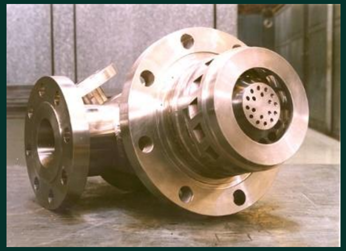
Long Term:
- Combustion system configuration development able to manage pure ammonia or a blend with CH4 or H2

Syngas

Present:
- On the Job adaptation of current combustion system to the specific gas composition

Designing building blocks to be used on majority of Bakerhughes gas turbine portfolio





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Challenges for H2/NH3 /C2+/Syngas fueled GTs

Hydrogen / C_2+ – High Reactivity

Ignition & Start-up (Safety)

Flashback

➡ **High flame speed, wide flammability range**

Flame detection

NOx abatement technology: wet and dry solutions

Higher Combustor pressure drop (lower GT Eff.)

Materials hydrogen embrittlement

Auxiliaries, Purge and Package Specific Design

Ammonia – Low Reactivity

Ignition & Start-up

Flame stability

➡ **Low LHV, low flame speed, narrow flammability range, high ignition temperature**

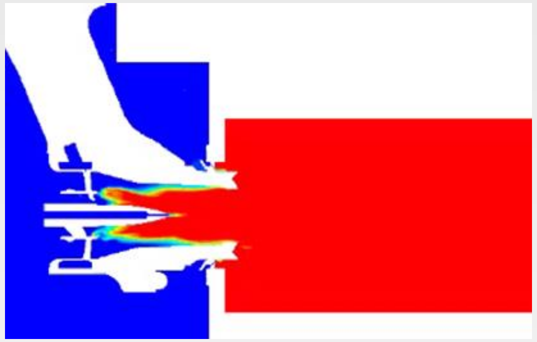
Potentially high NOx (fuel-bound nitrogen…); not abatable by dilution.

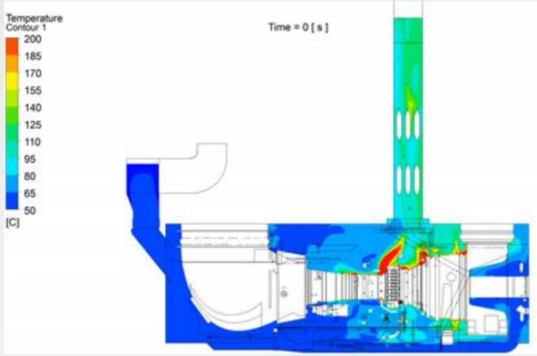
Higher Fuel pressure drop (lower MWI)

Toxicity (EHS issues)

Auxiliaries, Purge and Package Specific Design

Comparison of Natural gas and Hydrogen flames.





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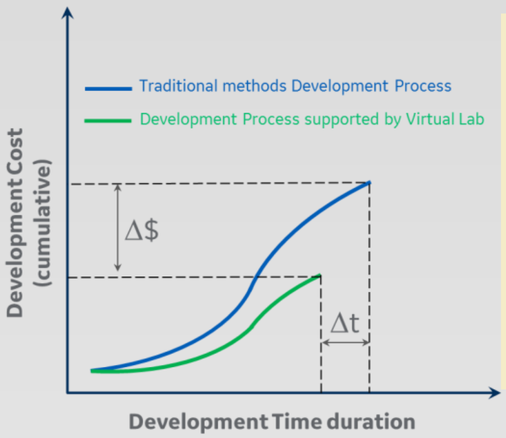
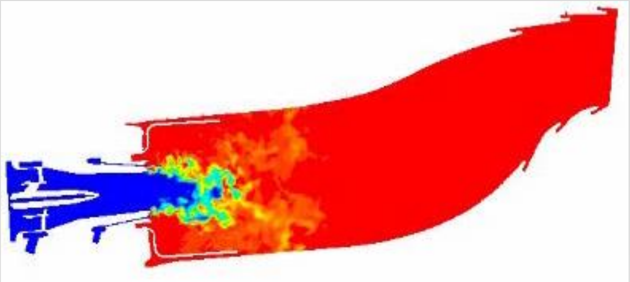
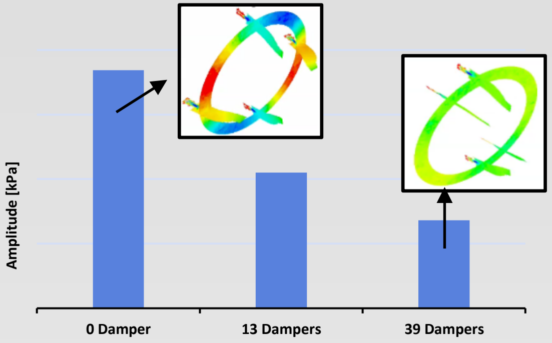
GT Development Enablers



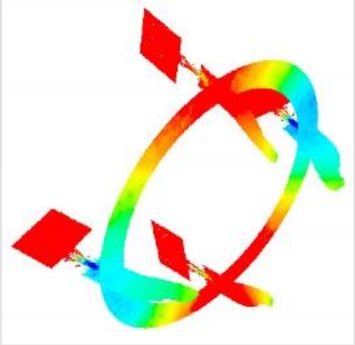
Virtual Lab Test (CFD)

- Thermo-fluidynamics assessment (RANS/LES):
  - Air split design, Emissions (NOx, CO) model
  - Blow-out & Flashback: design improvements
  - Heat Transfer by Conjugate (CHT)
- Dynamics by SED CFD & Thermo-acoustic (FTF)





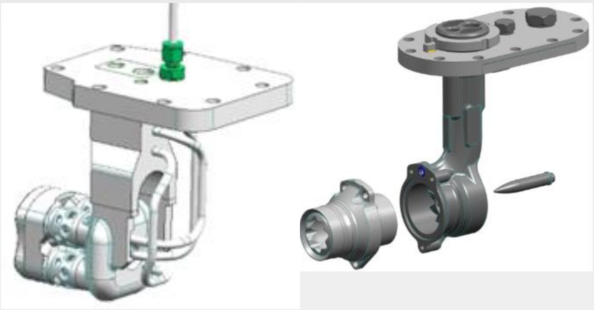
Combustion Dynamic Amplitude abatment as a function of dampers numbers



Acoustic mode (N=2) inside the combustor

Additive Manufacturing & Materials Testing

- Prototyping and Industrialization
- Burner sub-components
- Integral printed burners
- Next generation burners



Combustion Test Facilities

- SingleCup atmospheric pressure test
- SingleCup pressurized test
- Full-scale Annular Rig and Multican Rig
- Possibility to test a wide range of fuel compositions

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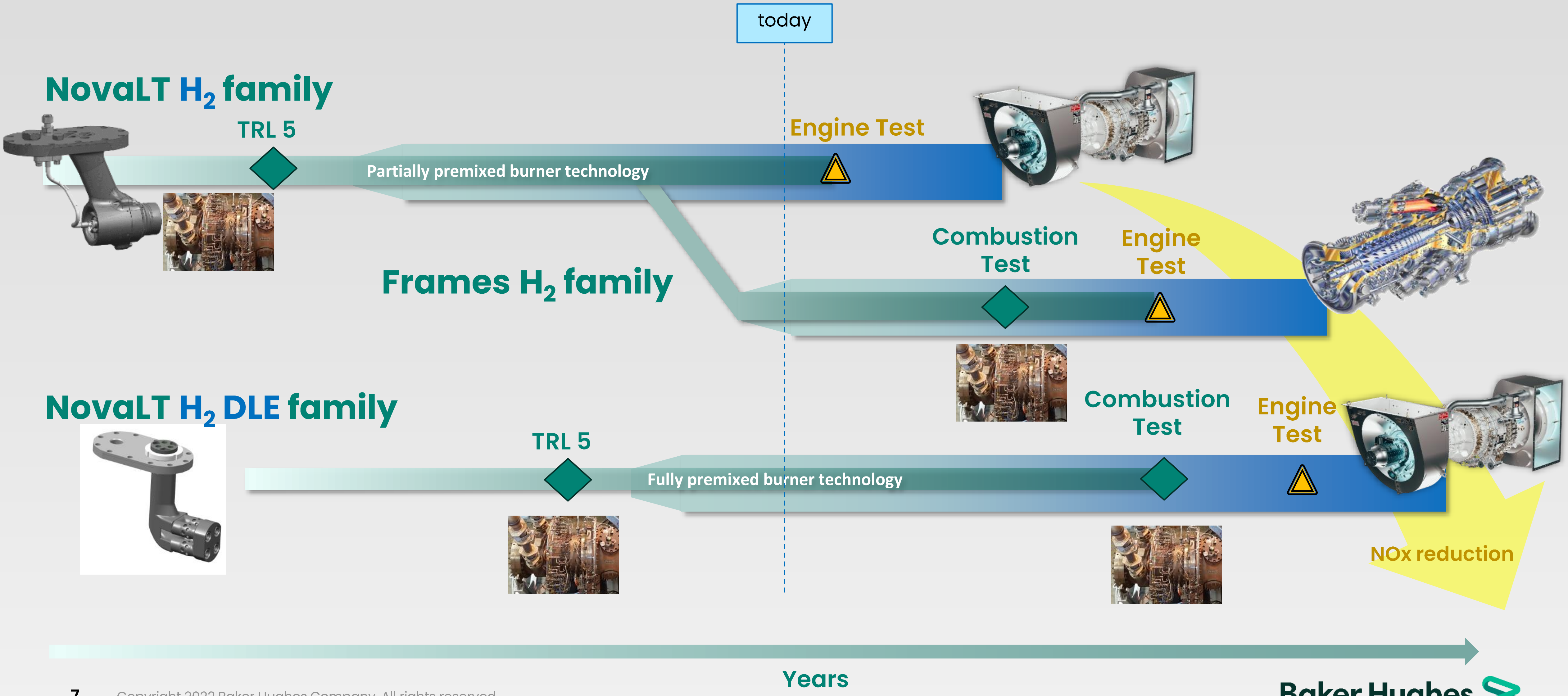
Low carbon fuels BH roadmap – H2 NovaLT & Frames



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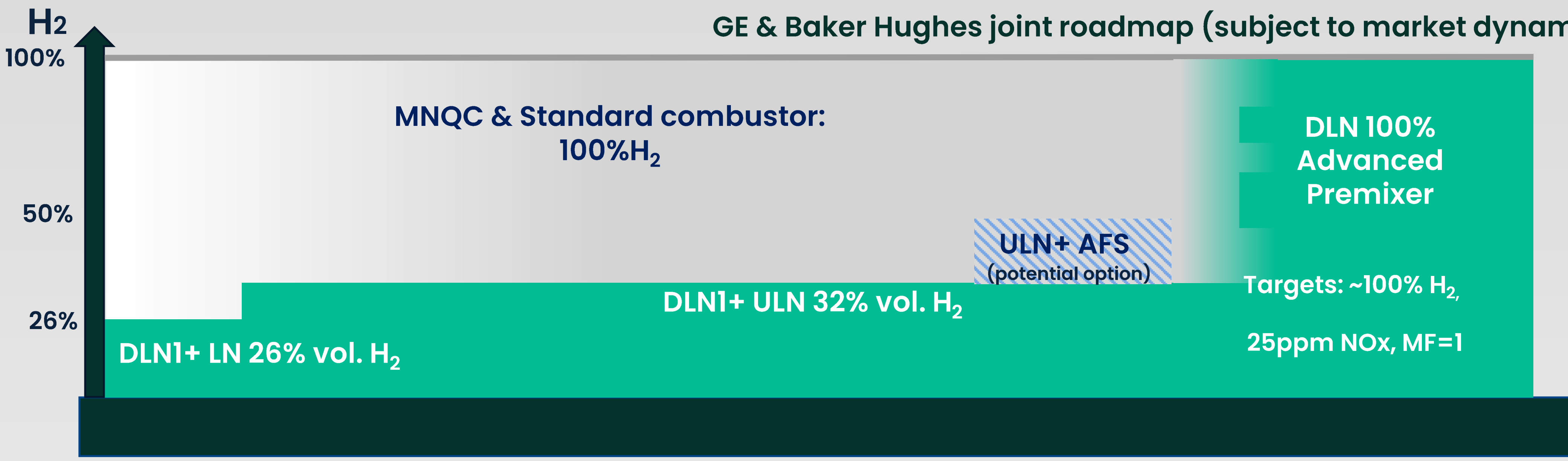
Low carbon fuels BH roadmap – H2 Large frames and Aero

GE & Baker Hughes joint roadmap (subject to market dynamics)



Fr6/1B

Fr7/1EA

Fr9/1E

0% | 25% | 50% | 75% | $100\%H_2$

Current DLE 1.5 Combustion

Validating H2 Capability
- LM6000 PF/PF1 = 35% Vol (*)
- LM6000 PF2 = 20% Vol (*)
- LM2500+G4/5 = 35% Vol (*)
- Rig testing complete
- GT/package field testing in process

Notes
- Capability for current production GT's
- Higher levels of H2 may require package updates for safety regulations

(*) For Quoting and Field Service Evaluation

Improved DLE 1.5 Combustion

Planned H2 Capability
- Production Models > 60% Vol
- Rig testing in process
- GT/package field testing in planning

Notes
- Optimize existing DLE 1.5 hardware for higher levels of H2
- Utilize existing GT HPC and turbines
- Higher levels of H2 may require package update for safety regulations

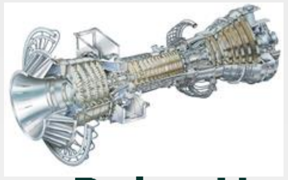
Advanced Combustion Systems

Planned H2 Capability
- All Models = 100% Vol
- Analytic modeling in process
- Rig testing in process
- GT/package field testing in planning

Notes
- GE Aviation and GE Research Center (GRC) collaborating on technology development for flight & land
- Optimized combustor for high hydrogen fuels while maintaining emissions and life
- Planning high H2 capability of existing DLE1.5 GT's through combustor/package upgrades

LM2500

LM2500+



LM6000

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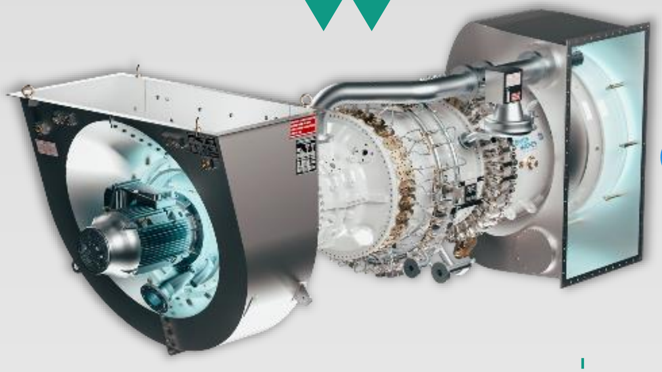
"Ammonia-As-Fuel" – BH technology plan

Assuming NH3 as Energy Carrying / Storing medium

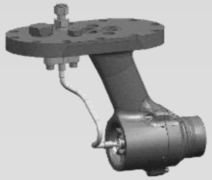
Pure NH_3 as GT Fuel

OR

Flexible fuel mixture H_2 / NH_3

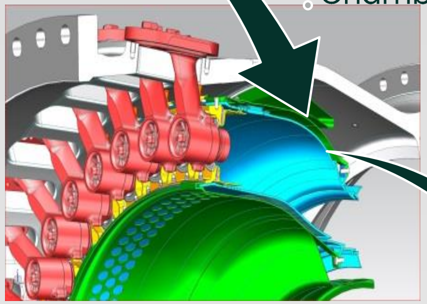


With Contained NOx emissions



Drop-in

- Burner adaptation
- Fuel system upgrade
- Chamber adaptation



Combustion System development

- Burner new design
- Chamber new design
- Staged combustion

Combined Cycle optimization

Combustion system Concept

Combustion System Detailed design

Engine/Aux System Design

Ready for GT devlopment

BH program

Atmospheric Tests

Pressure test

Full Combustion test

Concept design

Preliminary design

Detailed design

Engine System design

FLEXnCONFU*

EU funded project

GTRC Single Cup Test

GT HW upgrade for H2 combustion

H2 & NH3 CCGT performance simulation

Scale-up of full-scale plant concept with H2 & NH3 (preliminary GT design)

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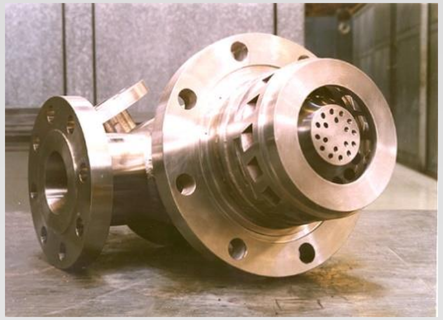
*This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N° 884157

Syngas Experiences and Approach

Bioelettrica project (1999 – 2000)

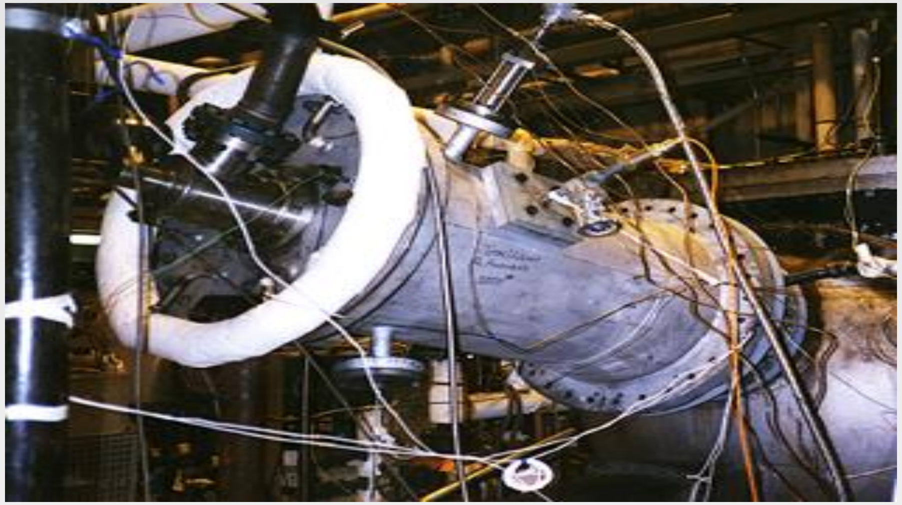
SYNGAS APPROX COMPOSITION :

COMPONENT	%VOLUME
CH_4	5
CO	22
H_2	16
N_2	44
CO_2	13
LHV	**6.4 MJ/kg**



NOx @ 15%O2 < 25 ppmvd ---- CO @ 15%O2 < 70 ppmvd

With steam steam / fuel ratio > 1.2



Some experience on BH GT Portfolio

Syngas	PSI	Tampa	El Dorado	Pernis	Sierra Pacific	ILVA	Schwarze Pumpe	Sarlux	Fife	Exxon Singapore	Motiva Delaware	IRCC	Star Chem
H_2	24.8	37.2	35.4	34.4	14.5	8.6	61.9	22.7	34.4	44.5	32.0	46.84	40.0
CO	39.5	46.6	45.0	35.1	23.6	26.2	26.2	30.6	55.4	35.4	49.5	1.13	1.0
CH_4	1.5	0.1	0.0	0.3	1.3	8.2	6.9	0.2	5.1	0.5	0.1	0.75	9.0
CO_2	9.3	13.3	17.1	30.0	5.6	14.0	2.8	5.6	1.6	17.9	15.8	0.06	6.0
N_2 + AR	2.3	2.5	2.1	0.2	49.3	42.5	1.8	1.1	3.1	1.4	2.15	40.82	43.0
H_2O	22.7	0.3	0.4	--	5.7	--	--	39.8	--	0.1	0.44	10.40	--
LHV, - Btu/ft^3	209	253	242	210	128	183	317	163	319	241	248	139	203
- kJ/m^3	8224	9962	9528	8274	5024	7191	12,492	6403	12,568	9,477	9,768	5,480	8000

BH standard approach

Feasibility Inquiry → Combustion-Sign-Off → Inquiry-to-Order → Standard Requisitio n process

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Recent Development

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NovaLT16 H2 FAR test 2022

27 Jul '22 — 27 Aug. '22

Test start — Test end

8 test days

45 fired hours

30 start/stop cycles

20 – 100% Hydrogen blend tested

7.2 tons of burned H_2

350+ instrumentation

5 combustor configurations

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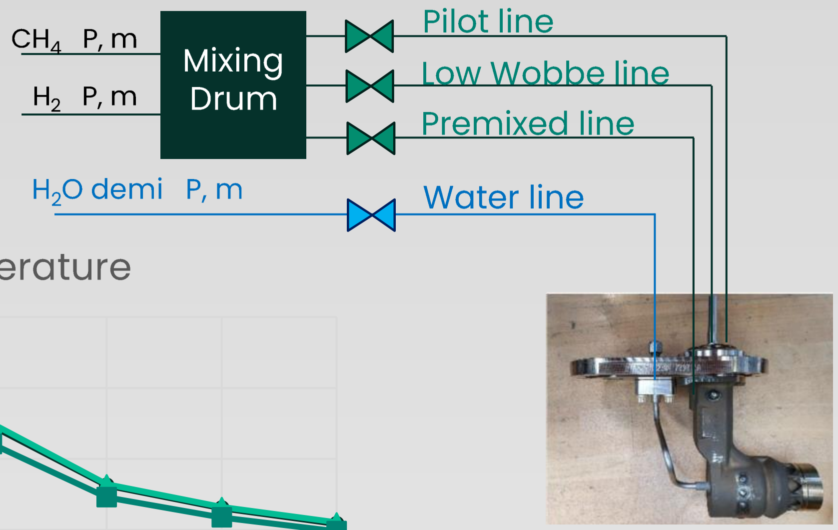
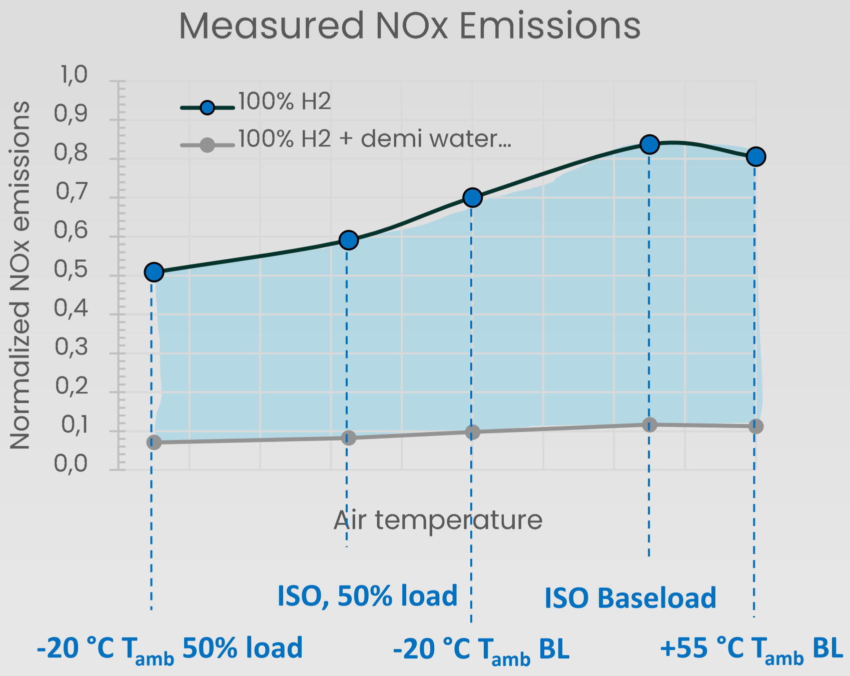
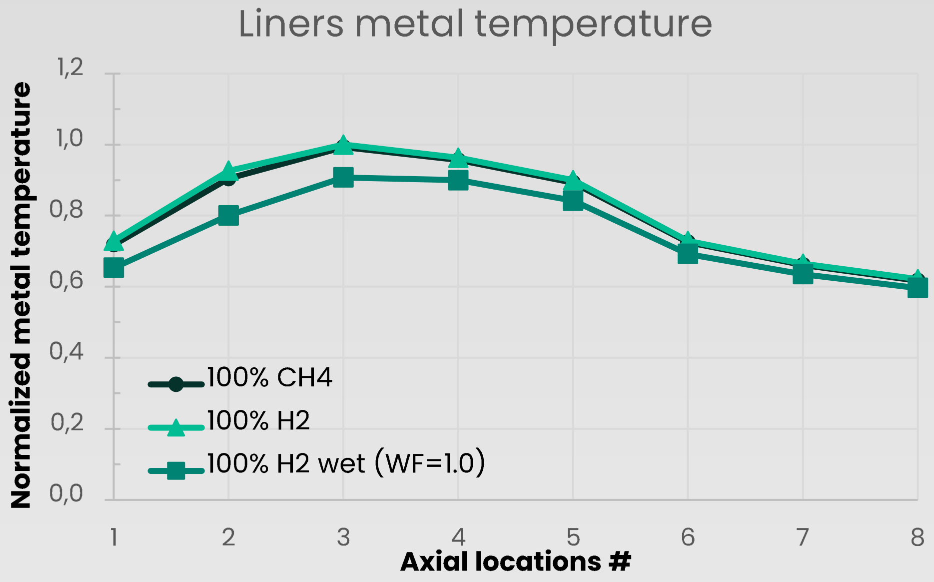
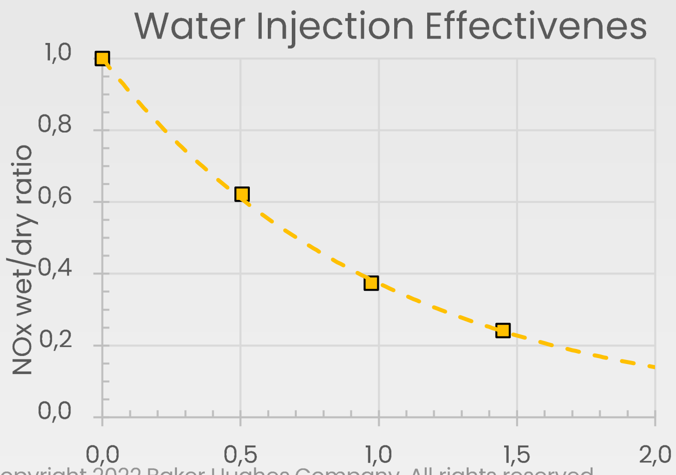
Multi fuel burner - NOx Emissions









- NOx emission below target
- Development still ongoing to further reduce emissions
- Robust behaviour against flashback / FH limits for 100% H_2 fuel
- Ability to work with any CH4/H2 blend
- No relevant pressure pulsations found during test
- <u>Applicable to LT and Frame Engines</u>

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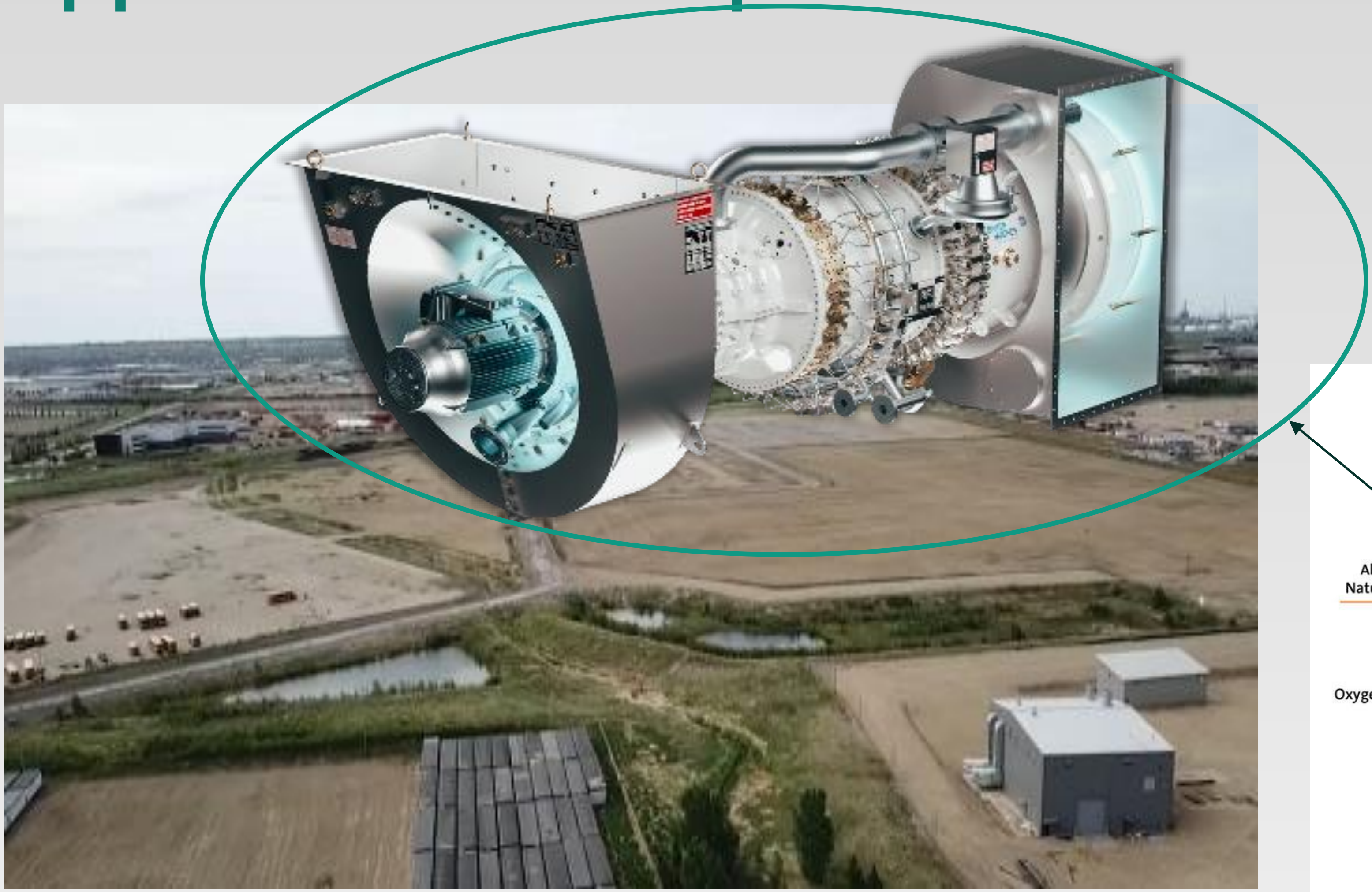
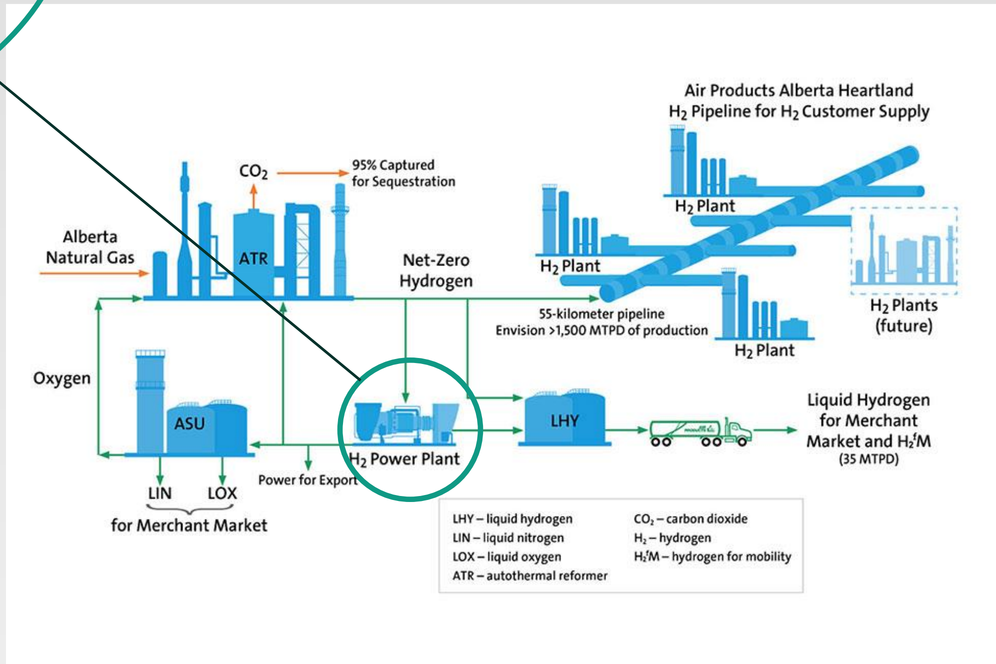
Application Exhample – Blue H2 Edmonton, Canada



Partnering with world hydrogen industry leaders to lower the cost of production and accelerate the adoption of hydrogen as a zero-carbon fuel



Providing 100% hydrogen fueled NovaLT16 gas turbine technology to Air Products

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