NH_3 cracking - technology de-risking accelerates time to markets

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Agenda

1. **The Air Liquide Group in brief**

2. **Status of NH_3 cracking and LC NH_3 production**

3. **Wrap-up and conclusions**

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The Air Liquide Group in brief

2023 Key Figures

~66,300
EMPLOYEES(1)

PRESENT IN
60 COUNTRIES(1)

MORE THAN
4 MILLION
CUSTOMERS & PATIENTS

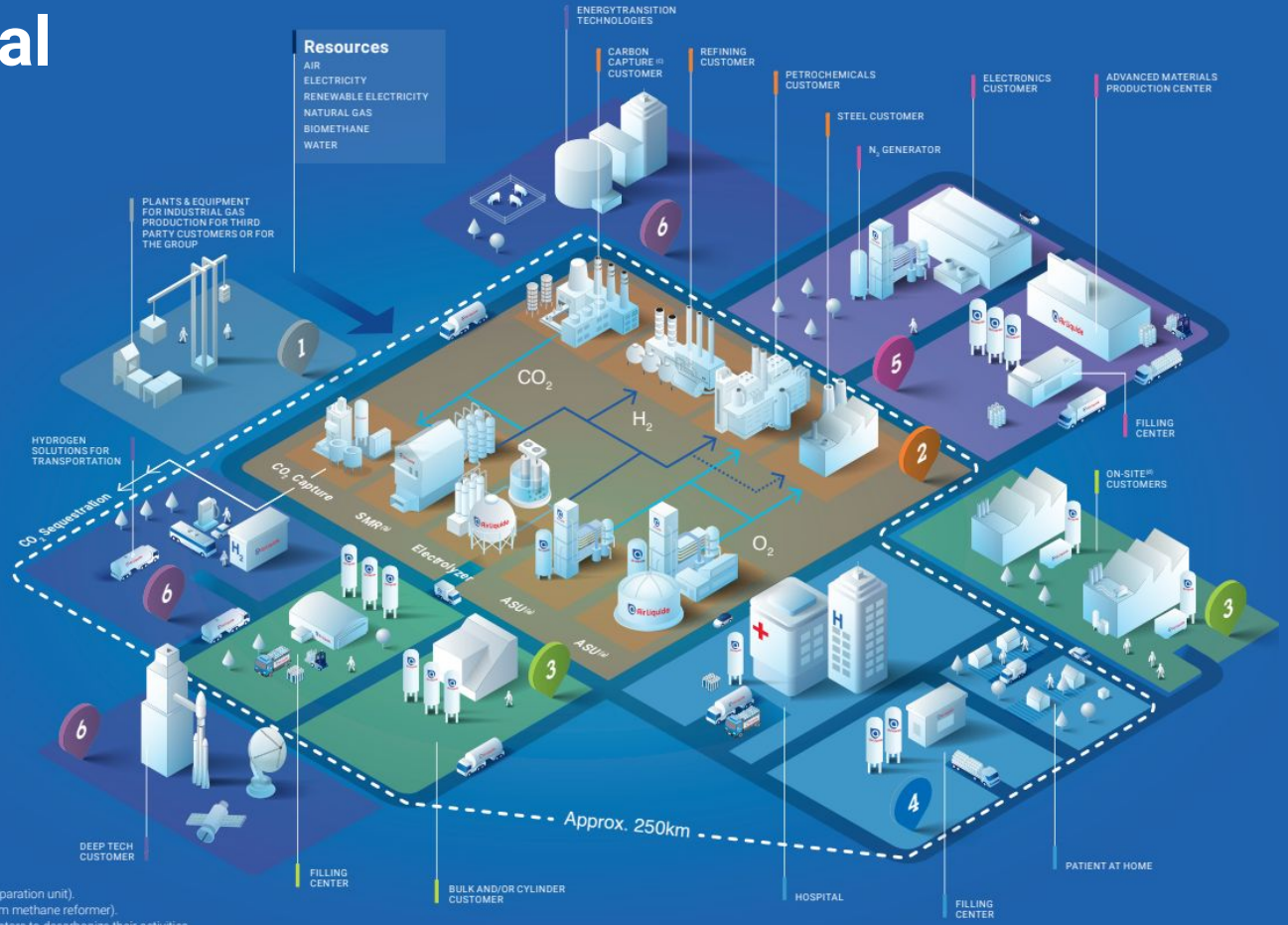
REVENUE
€27.6bn

NET PROFIT (GROUP SHARE)
€3.1bn

INVESTMENT DECISIONS
~€4.3bn

(1) Figures as of July 23, 2024

Industrial model



(a) ASU: air gases production unit (air separation unit).
(b) SMR: hydrogen production unit (steam methane reformer).
(c) Carbon Capture: for hard-to-abate sectors to decarbonize their activities.
(d) On-site: small gas generator on the customer site.

Abatement of CO_2: Setting a trajectory to reach Carbon Neutrality

Air Liquide Commitments

Air Liquide

CO_2 emissions **start decreasing** in absolute value (Scope 1 & Scope 2)

Reach **Carbon Neutrality** before **2050** (including Scope 3)

~2025 — 2035 — 2050

-30% Carbon intensity in kg CO_2/€ EBITDA[(a)] **vs 2015**

Decrease scope 1 & 2 CO_2eq emissions in **absolute value** by **-33%**[(b)]

(a) at 2015 exchange rate and excluding IFRS16 for greenhouse gas emissions scopes 1 and 2

(b) from 2020 Market based emissions of 32.5 million tonnes CO2eq (Scope 1+2)

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Status of NH_3 cracking and LC NH_3 production

Pivotal techno enablers of our decarbonisation mission

Decarbonizing our H_2/CO assets

- **CO_2 capture on existing units**
  - A large range of in-house technologies
    - Amine, Cryocap, Rectisol
  - Potentially combined with biofuel
  - Applied from industrial sources for 40 years
    - More than 3Mt/a captured today in over 25 countries for IM
- **Development of CCS offer**

Hydrogen from electrolysis

- **Development of large scale electrolysis**
  - More than 35 electrolysers in operation since 1990
  - Largest PEM (20MW) in operation in Canada since 2021
  - Several large scale (100MW+) electrolysers under development
- **Partnerships for electrolysis**

SIEMENS energy

Energy imports

- **Europe & Asia expected to remain short on energy**
  - Large amounts of REN required to meet Fit for 55
  - Electrification competes with hydrogen production
- **AL works on the development of different energy carriers**
  - NH_3, LH2, (LOHC)
  - NH_3 as first mover

Port Jerome - in operation
Kairos@C - FID
Several FEEDs for cement

Becancour - 20 MW in operation
Trailblazer - 20 MW in operation
Normand`hy - 200 MW FID

NH_3 cracking industrialization
Studies/FEEDs for LC NH3
Studies/FEEDs for NH3 cracking

Why NH3 cracking closes a gap in the H2 ecosystem

REN NH3 to REN H2

- **Most relevant REN H_2 route to import REN power for local REN H_2 production**
  - to leverage existing electricity price differentials
  - to compensate REN Power intermittency
  - to meet the EU REN / RFNBO* targets, imports are needed
- **Higher REN H_2 price requires strong regulatory support**

LC NH3 to LC H_2

- **LC H_2 only relevant for significant price differential between "local" and "imported" natural gas and sequestration cost**
- **Partial cracking of relevance to use LC NH_3 as energy carrier**
  - Heat / power / cogen decarbonisation
  - To compensate REN Power intermittency
- **LC H_2 significantly cheaper than REN H_2**

*) RFNBO" means renewable liquid and gaseous fuels of non-biological origin. It is a product group of renewable fuels defined in the Renewable Energy Directive (Art. 2.36). These fuels are produced from renewable energy sources other than biomass

~~Grey NH3 to grey H_2~~

Why to demonstrate Ammonia cracking at industrial scale?

1 On paper it looks simple …

Strong similarity between Steam Reforming and Ammonia Cracking for H_2 production!

Steam Reforming

Natural Gas + Energy $_{+ \text{Steam}}$ -> **Hydrogen** + Carbon Dioxide

Ammonia Cracking

Ammonia + Energy -> **Hydrogen** + Nitrogen

- Less endothermic (= reduced heat flux)
- No coking
- No steam
- No CO_2

… so, why bother when we master Steam reforming?

2 … but there are relevant challenges

Technology

- Risk of tube embrittlement (nitridation), but no metal dusting
- NO_x formation in case of NH_3 firing
- Catalyst life-time and performance levels

Industrial track record:

- Small scale metallurgical applications (low efficiency)
- D_2O-production via $NH_{3-x}D_x$ (high pressure)

Not sufficient return of industrial operating experience to fully de-risk a large-scale design

ARCAS Demonstration at industrial scale to de-risk Ammonia Cracking

Demonstration of the *complete* process at industrial scale and "real life" conditions with a focus on

- **Ammonia Cracking catalyst performance**
- **Ammonia Firing (firebox modeling, NO_x)**
- **Testing of next-generation reactor tubes**

Leveraging our global R&D and E&C network, the test campaigns will enable to reach "FID grade TRL" thanks to

- **Benchmarking of kinetic and combustion models**
- **"Real life" experience**
- **Validation of optimized flowsheet (e. g. Ru vs. Ni, Cryo-separation vs. PSA)**

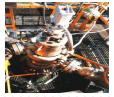
This unit is key for safe and reliable supply of Hydrogen to our large-scale customers

Technology pathways for Low Carbon H_2 and NH_3

Feedstock

- Natural Gas
- Biogas
- Refinery Offgas
- LPG
- Naphtha
- Residual Oil
- REN Electricity

Gas Production

- SMR / SMR-X™ 
- ATR 
- Gas POx 
- MPG 
- Electrolyzer 
- ASU 

Gas Conditioning

- Isothermal Shift 
- CO Shift HT- / MT- / LT- / 

CO_2 Removal

- Solvent Based CO_2 Removal Recticap™ 3rd party Amine (Rectisol™) 
- Cryogenic CO_2 Removal Cryocap H_2™ Cryocap FG™ 

Gas Purification

- H_2 PSA 
- Liquide N_2 Wash 

Gas Products

- H_2
- CO_2

Liquid Products

- H_2 Liquefier 
- CO_2 Liquefier 

H_2

NH_3 3rd party Technology

N_2

Ammonia Cracking

- NH_3 Cracker 

New Technology Brick

Pave the way towards LC NH3 via partnering

Air Liquide & KBR combining expertise to offer **ATR-based low-carbon ammonia and hydrogen technology solutions**

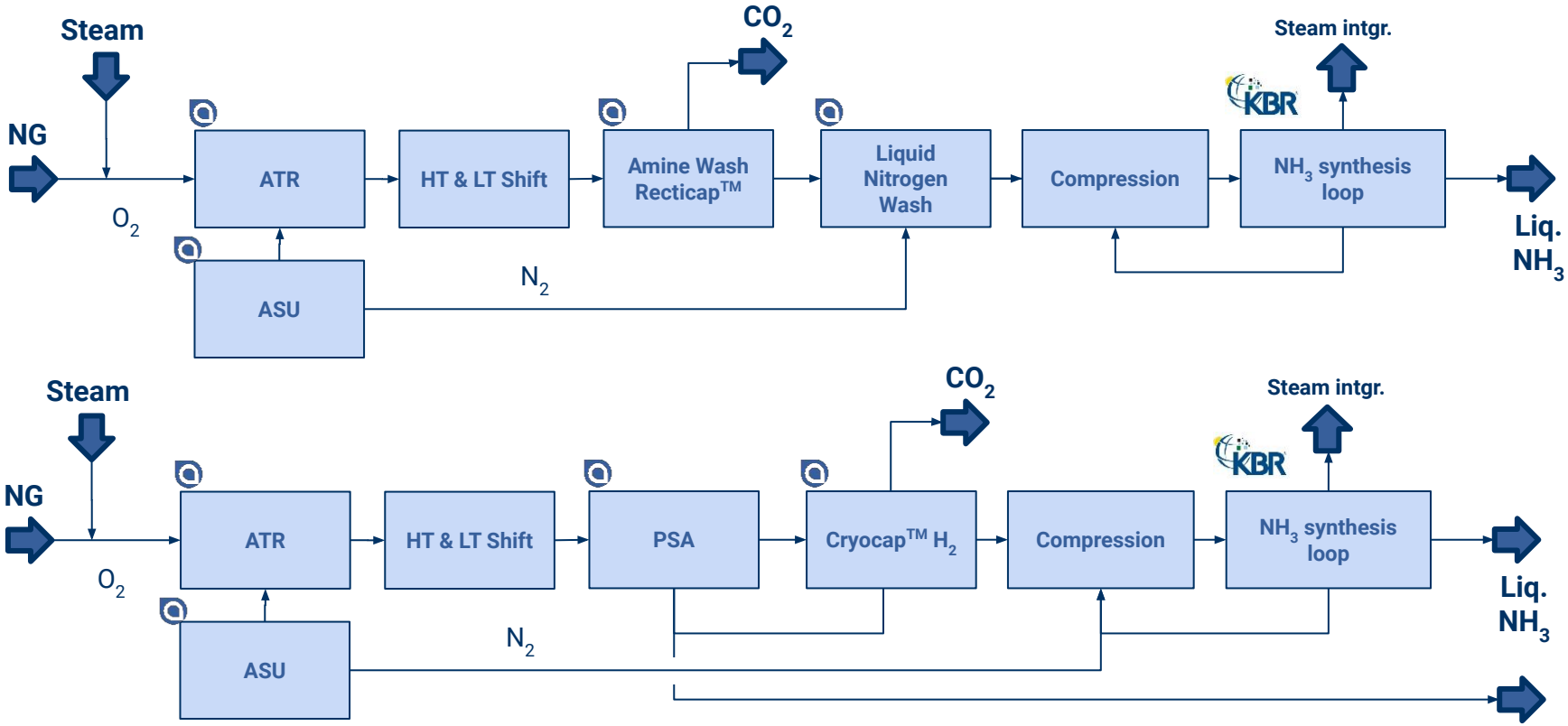
Air Liquide is providing its unique expertise and proprietary Autothermal Reformer (ATR) Technology

KBR brings its mastery and world leadership in ammonia production technology

ATR with carbon capture for large scale H2 and Ammonia production

With a simplified single train production process to facilitate carbon capture of up to 99%

Air Liquide & KBR integrated Low Carbon Ammonia



>95-99% Global Scope 1 capture rate with ATR is achievable without CO_2 capture from flue gas

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Wrap-up and conclusions

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1. **De-risking technology of NH_3 cracking at scale is a key milestone towards commercialization**
   - Our industrial demonstrator “ARCAS” will deliver first H_2 molecules late 2024
   - Air Liquide is the most advanced on the design & demonstration of NH_3 cracking for H_2 production

2. **First FIDs using AL NH_3 cracking technology possible as early as H1/2025 upon close-out of the ARCAS test program**

3. **In parallel, we work on several REN/LC NH_3 projects (engineering stage)**
   - to close the upcoming demand gap
   - to enable and to demonstrate the whole supply chain including certification

Thank you