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Use of Hydrogen as a Fuel Mix with Natural Gas in CCGTs – Technical and Cost Issues (*Materials-biased*)

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Content

- Hydrogen and Low Carbon Fuel – Decarbonizing all Sectors
- Low-Carbon Hydrogen Economy

- Hydrogen-Material Interaction (permeability, material damage mechanism)
- Damage to Equipment by hydrogen / related to it
- Challenges - Technical & Cost Perspective
- Opportunities

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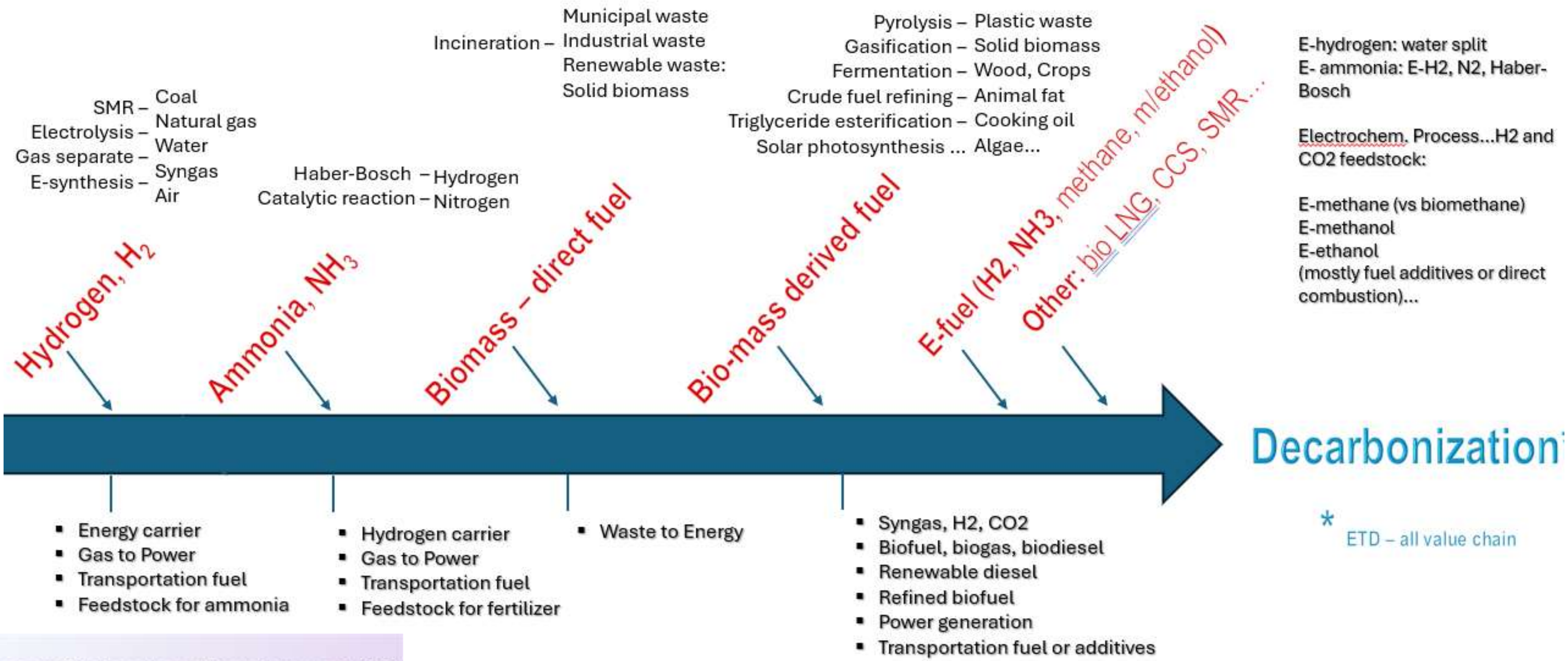
Hydrogen & Low Carbon Fuels

ETD Value Chain



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Low Carbon Hydrogen Economy
Power – Gas – Re-power

Low Carbon Economy based on Hydrogen Value Chain

- Renewable / Power Generation
- Power to Gas: H2 Production, Storage, Transmission / Transportation, Distribution
- Gas to Power: **Power Generation**, Mobility, Industry
- Industrial uses
- Feedstock

❑ Power to Gas:

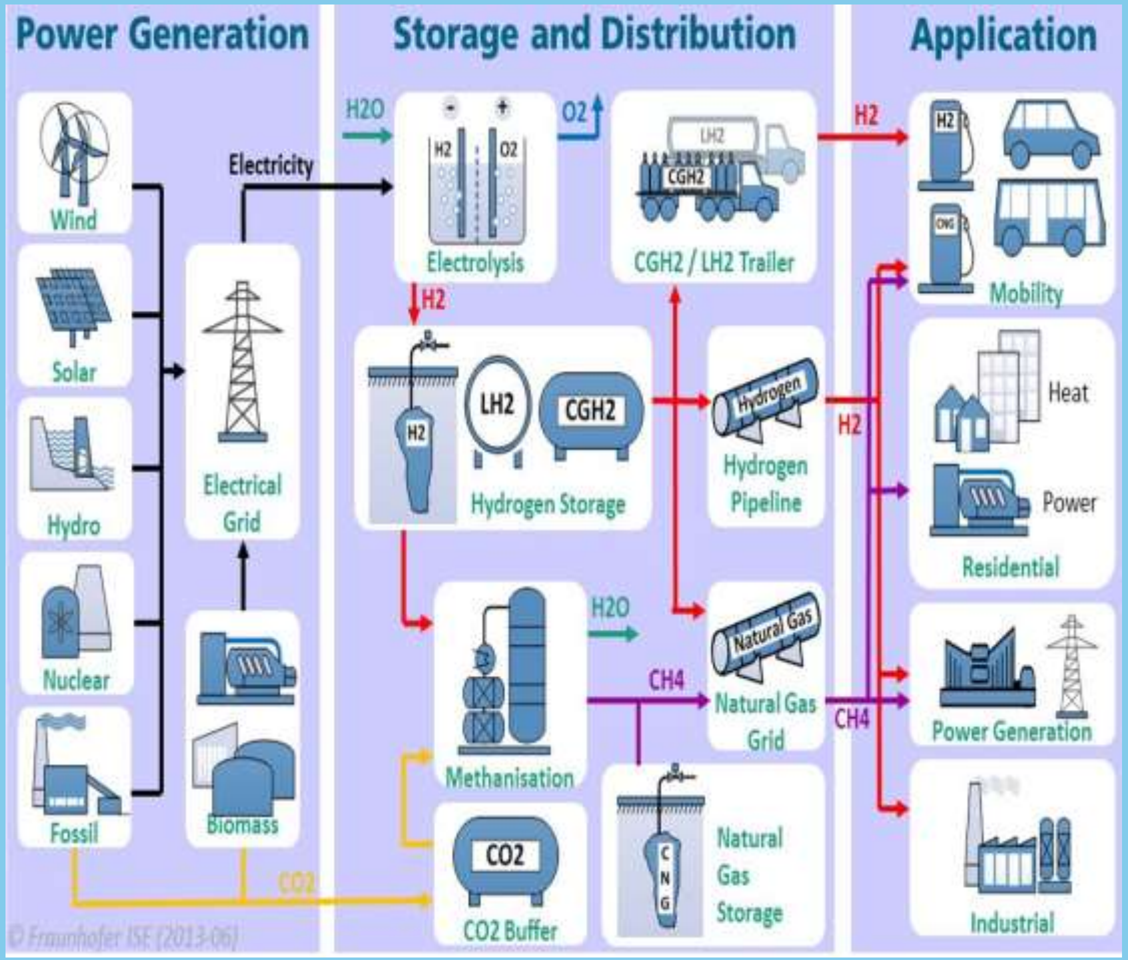
As an energy carrier:

- Converted H2 carries original renewable energy, and get transported to point of end use
- Pro de-centralized electricity generation – alternative to electricity grid.
- Pro renewable electricity grid integration & grid stability – alternative to BESS

❑ Gas to Power or Gas as a Feedstock:

As a carbon-free energy source or feedstock gas:

- Clean power generation: fuel cell, CCGT
- Clean domestic - district heating and power
- Clean mobility: Powering transport SOFC-H2V vs EV
- Greening industry: steel/cement-making by process heating and process electrification from renewable electricity
- *H2 as a feedstock: Greening ammonia and fertilizer production (non-Power2Gas)*



Ref: VUB and Siemens, The hydrogen story, 202

H2 Production (1/3):

Classified by technology:

- **Electrochemical:** Input electricity-powered decomposition of an electrolyte / water – electrolysis
- **Thermochemical:** Input process heat driven chemical decomposition of a feedstock – SMR, Gasification, Pyrolysis
- **Biological:** Photobiological production using algae / microorganisms by photosynthesis.

Classified by energy:

- **Renewable energy:** Renewable electricity / process heat (wind, solar, hydro, geothermal, tidal, biological energy (biomass, algae)) used to produce hydrogen, green.
- **Fossil fuel energy:** Electricity or process heat (coal, oil, NG) used to produce blue (+CCU) grey hydrogen
- **Waste energy:** Electricity or process heat (waste to energy recovery) used to produce non-

or process heat

Electricity input to split water and enable Redox:

$H_2O \Leftrightarrow O_2\,(OH^-{}_{ox/anode}) + H_2\,(H^+{}_{red/cathode})$

Electrolysis

Heat input to enable Reforming - Redox:

$CH_4 + H_2O\ (steam) \Leftrightarrow CO + 3H_2$ – redox

Steam methane reforming , SMR

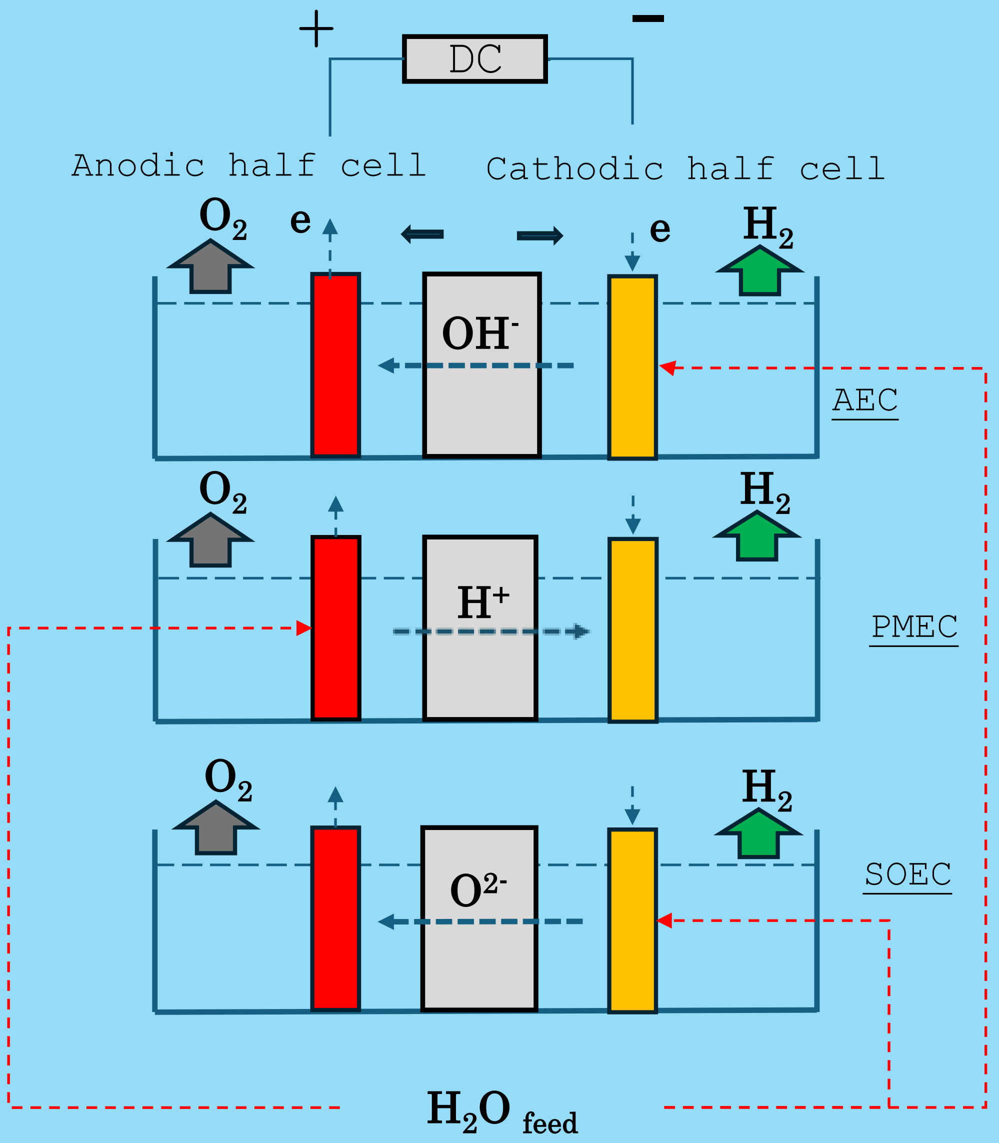
$CH_4 + CO_2\ (dry) \Leftrightarrow 2CO + 2H_2$ – redox

Dry methane reforming, DMR

❑ H2 Production (2,3/3):

Classified by process:

- **Steam Methane Reforming (SMR):** Grey H2 from methane reacting with steam at high temperatures (COx by-product).
  - **DMR:** Dry Methane Reforming using CO2 in lieu of steam.
- **Electrolysis:** Electricity (solar, wind preferred) driven electrolytic decomposition of water into H2 and O2 in electrolyzer.
  - **AEC:** Alkaline Electrolysis Cell
  - **PMEC:** Polymer / Proton Membrane Electrolysis Cell
  - **SOEC:** Solid Oxide Electrolysis Cell
  - DAE: Direct Air Electrolysis (extracting water in air for electrolysis)
- **Gasification:** H2-bearing syngas by heating coal//in oxygen.
- **Pyrolysis:** H2-bearing gases by heating and (thermal) decomposing biomass//no oxygen.



Gasification: Coal + oxidant ⇔ syngas, containing H_2
Pyrolysis: Biomass ⇔ H_2 +COx + volatile…

, nuclear energy, most

Hydrogen-Material Interaction
1. Hydrogen Permeability

Hydrogen-containing environment:

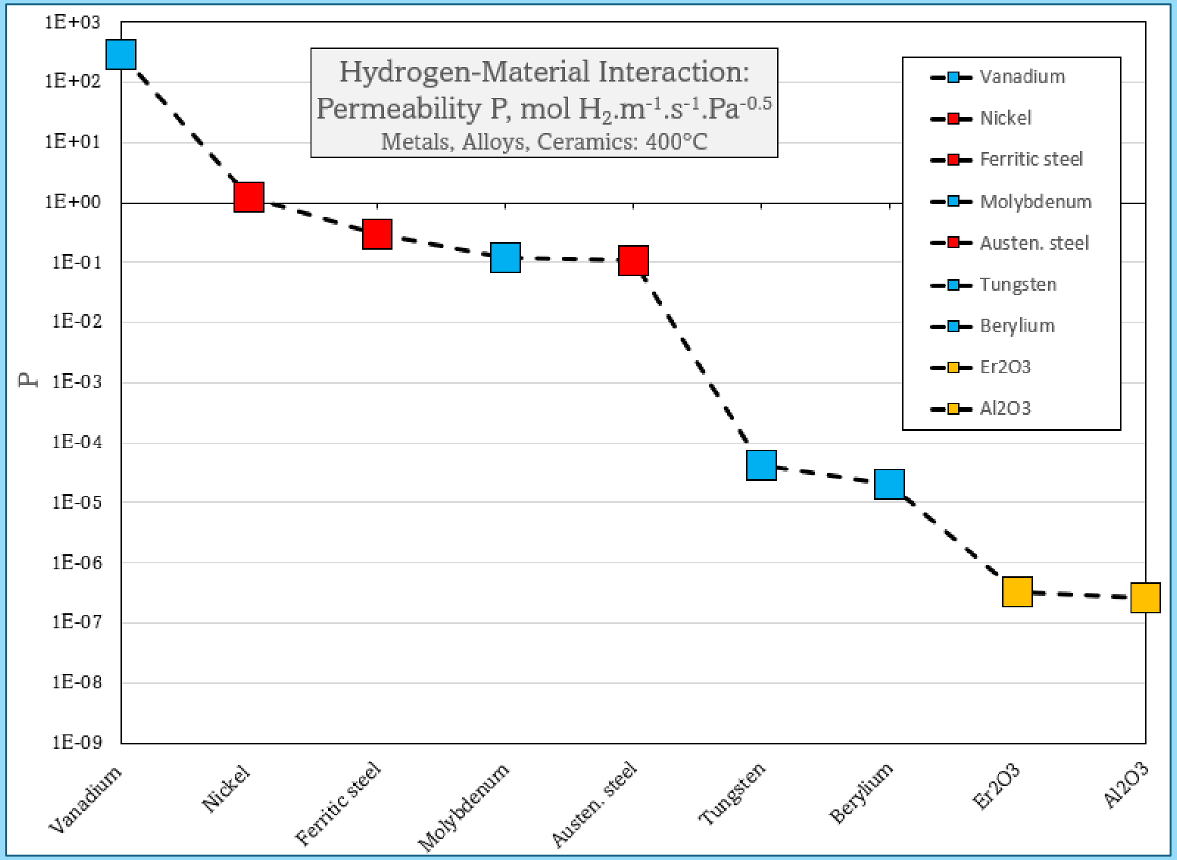
- Interaction Mode Determines How Fast Hydrogen Diffuses In Materials
- Material Structure Determines How Much Hydrogen is Tolerated (diffusible, trapped)
- Materials Suffer Damage when Hydrogen Permeability, p, Exceeded

H2 – Material interaction (2/4):

Hydrogen permeability, P:

$$P = KD$$

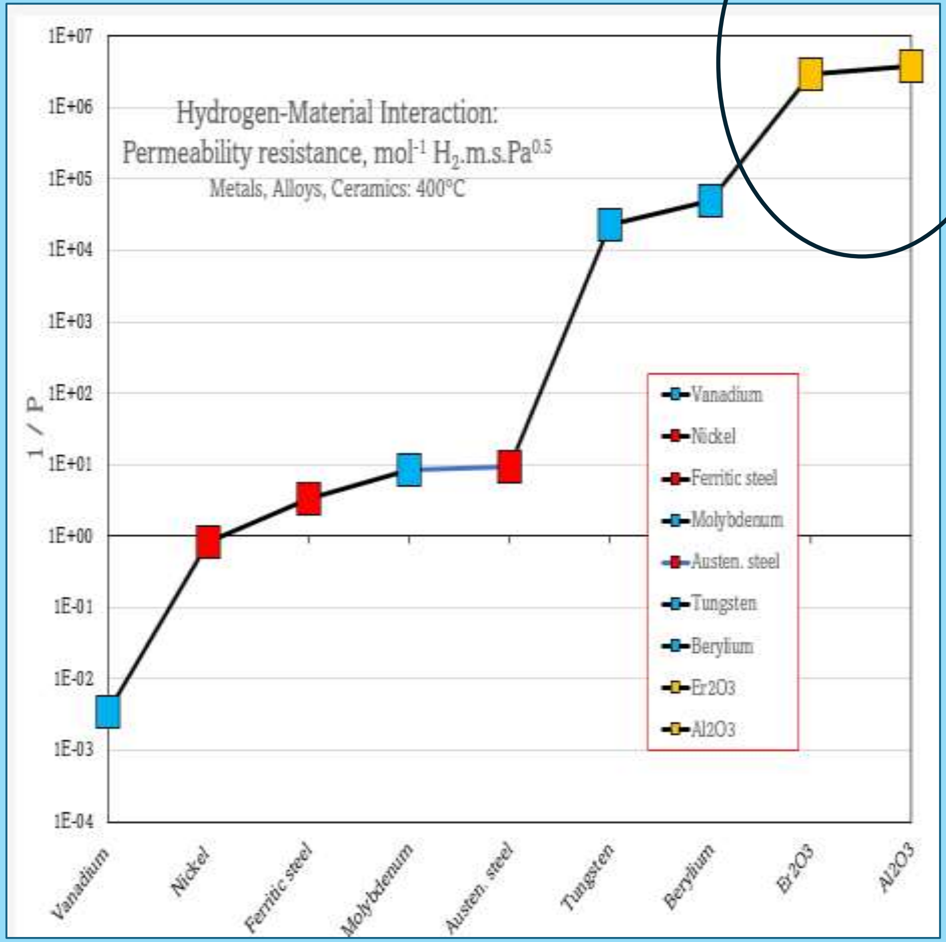
- Physical property measuring how much, fast H2 migrates (in material)
- A strong function: **Solubility (K)** and Diffusion properties, **Diffusivity (D)**
- (at surface and in bulk).
- Temperature effect: Increases with it
- Pressure effect: Increases with it (H2 partial pressure)
- Ceramics: Much less permeable (H2 lower D and lower K).
- uch more
r D, higher K).



H2 – Material interaction (3,4/4):

H2 Permeation Barrier:

- High Permeation Resistance - 1/P values
- Low surface interaction, low SCR (surface controlled)
- Slow hydrogen adsorption and absorption
- High bond strength – low BCR (bulk controlled)
- Slow diffusion (covalent bond) than metals (metallic bond)
- Insensitive to increases P, T relatively to metals
- **Typically, Ceramics or Dielectrics**



Hydrogen-Material Interaction
2. Hydrogen Damage Mechanism

Materials specific -

- Carbon, low-alloy and stainless steel
- Interplay of strength and ductility

Hydrogen damage mechanism (1/4):

- **HE - Hydrogen embrittlement:** Under stress, enhanced cracking due to H2 ingress / absorption lowering fracture toughness (*Condition: RT – 150oC, gaseous and chemically formed hydrogen*).
- **Hydrogen attack:** As in HE but at high T°C: H2 reacts with C from steel to form methane, causing internal gas pressurization while steel also decarburized (*Condition: higher temperature, gaseous and chemically formed hydrogen*).
- **Hydrogen blistering:** Fissure cracking by absorbed hydrogen forming via cathodic reduction in acid electrolyte (then re-combines and pressurizes at subsurface) (*Condition: Aqueous, electrochemical hydrogen, acid electrolyte*)
- **HIC – Hydrogen induced cracking:** As blistering but in a sour gas: atomic hydrogen from wet corrosion trapped (at voids, inclusion – MnS, and then recombines to form highly localized internal stress) causes stepwise cracking (*Condition: Aqueous, electrochemical hydrogen, wet sour gas*)
- **SSC – Sulphide stress cracking:** As in HIC but in H2S aqueous environment, whereby the formation of hydrogen is controlled by hydrogen sulphide (*Condition: Aqueous, electrochemical hydrogen, wet sour gas, oil field service*)

ansmission, damage to **IE**, and high-
attack less commonly

HE mechanism:

1. **Internal Pressurizing:** Absorbed hydrogen recombines to form gas bubbles to reduce fracture toughness
2. **HEDE:** Hydrogen enhanced de-cohesion – reduced cohesion and cracking resistance due to absorbed H
3. **HELP:** Hydrogen enhanced localized plasticity – Increased plastic deformation causing plastic collapse, reduced crack growth resistance, and decrease of the fracture toughness of the plastic deformation zone ahead of a crack tip.
4. Metal hydride formation, etc (less common)...

❑ Hydrogen damage mechanism (2/4):

Hydrogen embrittlement – alloying effects

Carbon and low-alloy steel:

- HE increases with strength and hardness
- C, Mo are beneficial
- Carbide beneficial as H-trapping site (VC, TiC, NbC)
- Tramp elements detrimental at GB (S, P)

Ferritic / martensitic steel:

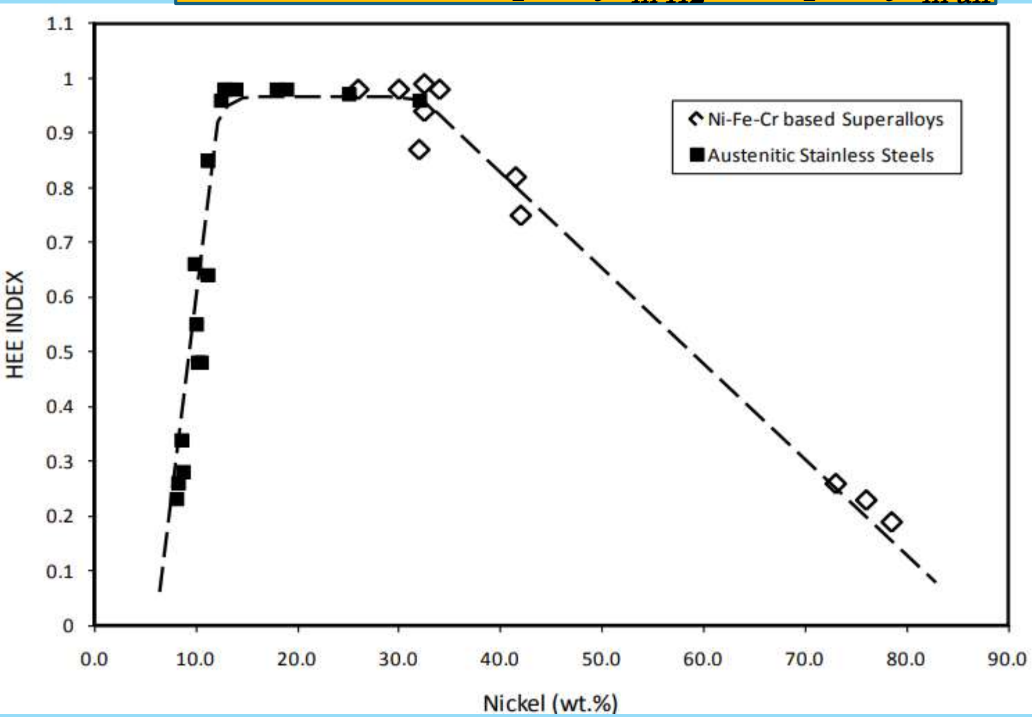
- Co and Ni beneficial
- Cr detrimental, the higher the worse
- Carbide beneficial by H-trapping

Austenitic steel:

- Ni most beneficial if not too high / too low
- Cr detrimental at high level
- VC beneficial by trapping

Hydrogen Environmental Embrittlement Index:

HEE index = Property $_{in\ H_2}$ ***/ Property*** $_{in\ air}$

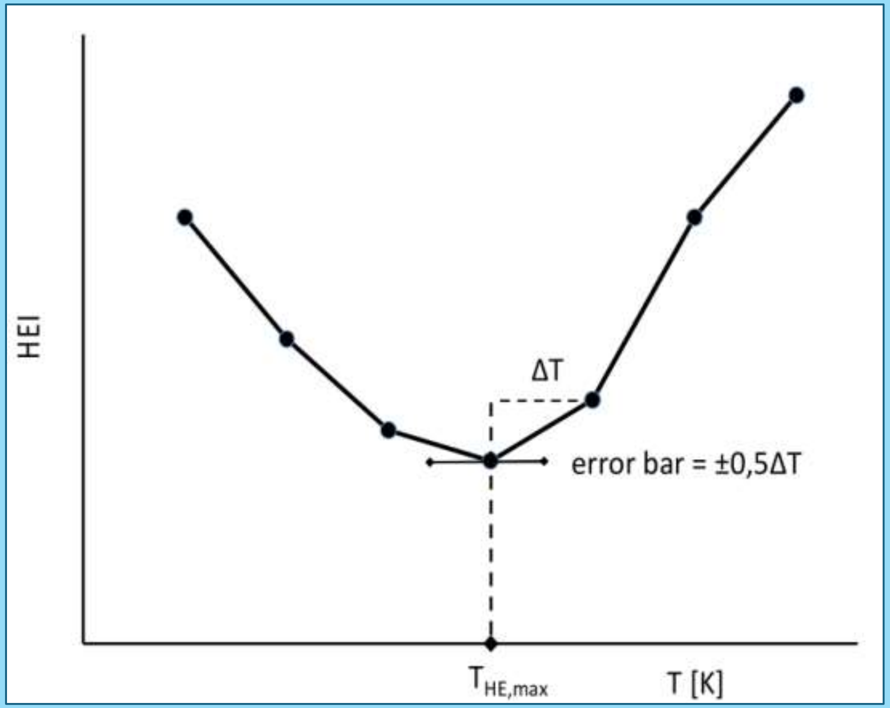


, Hydrogen Embrittlement, NASA report NASA/TM/2016-218602, April 2016

Hydrogen damage mechanism (3/4):

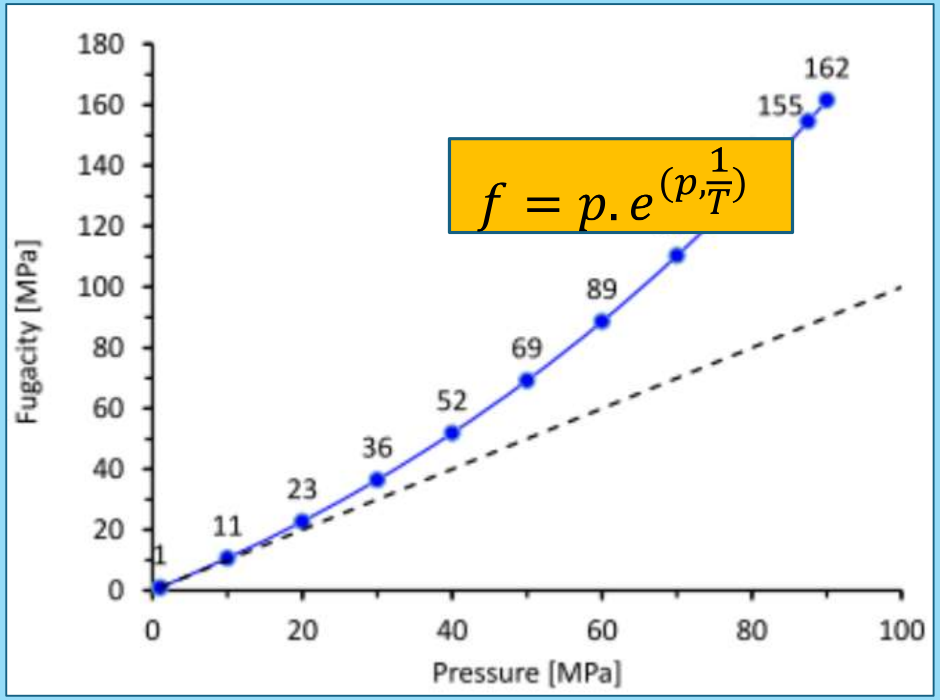
Effect of temperature, T

- At which maximum damage to properties: T_{HE} : *Damage level lower if temperature is higher or lower*



Effect of pressure, P, f

- At high pressure: Fugacity, ***f***, describes better H2 gas pressure effect (than ideal gas pressure, ***p***): Hydrogen damage to materials proportional to $HEI \sim m f^n$



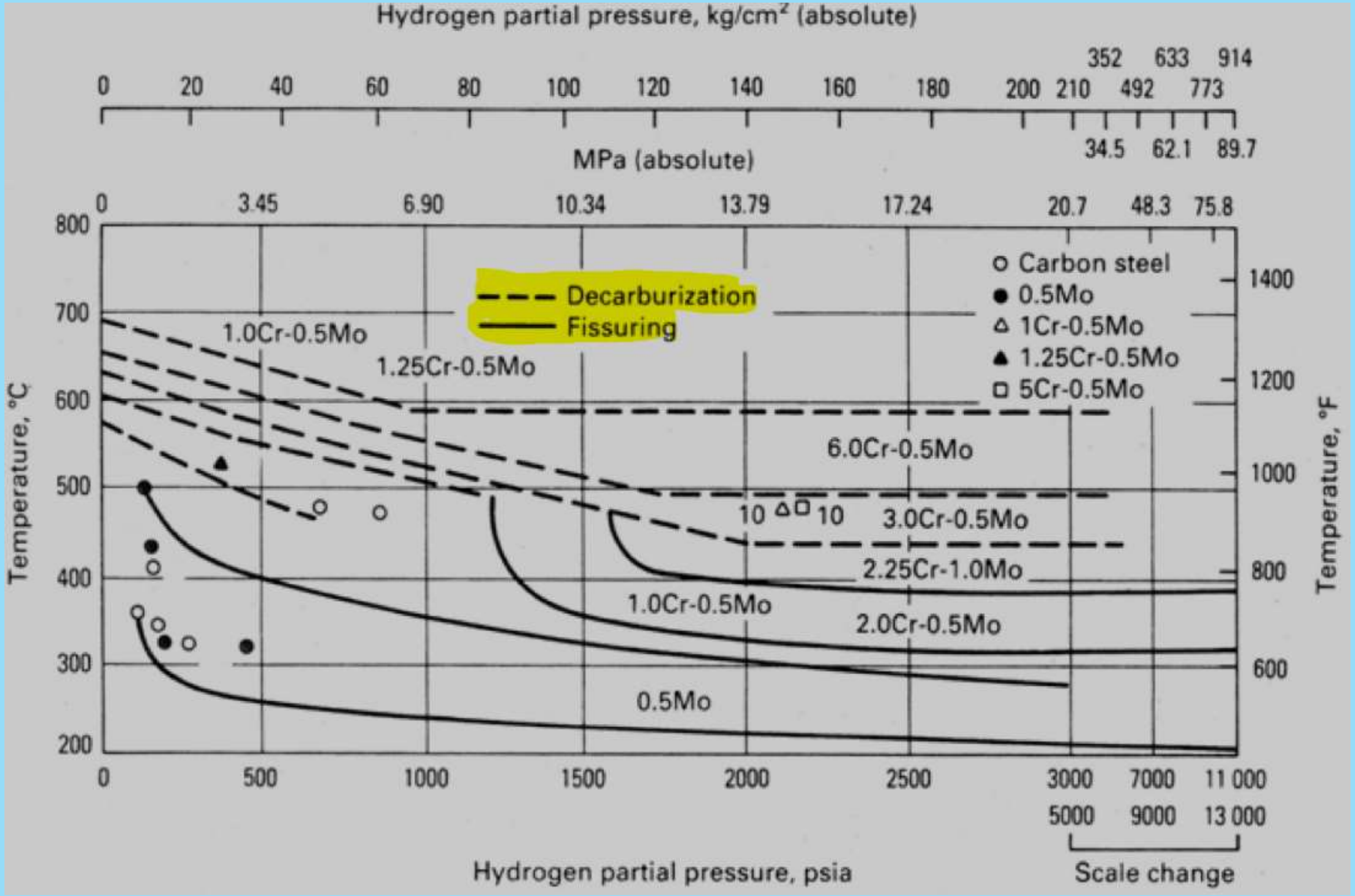
$$f = p.e^{(p,\frac{1}{T})}$$

Ref: University Stuttgart, University of Dortmund, and Fraunhofer IWM, in Literature Study of Hydrogen Influence, VGB 2021

❑ Hydrogen damage mechanism (3/4):

Hydrogen attack – alloying effect on methane formation, decarburization

- Simple carbides (Cementite, MoC) most vulnerable to reaction activated by diffused H
- VC, TiC, NbC more resistant to H reaction
- **Nelson curve:** Defining upper temperature and partial pressure limit for safe



Ref: [1] ASM Handbook, Vol.13, Corrosion, ASM International, Ohio, 1998; [2] API 941 Code Recommended Practice

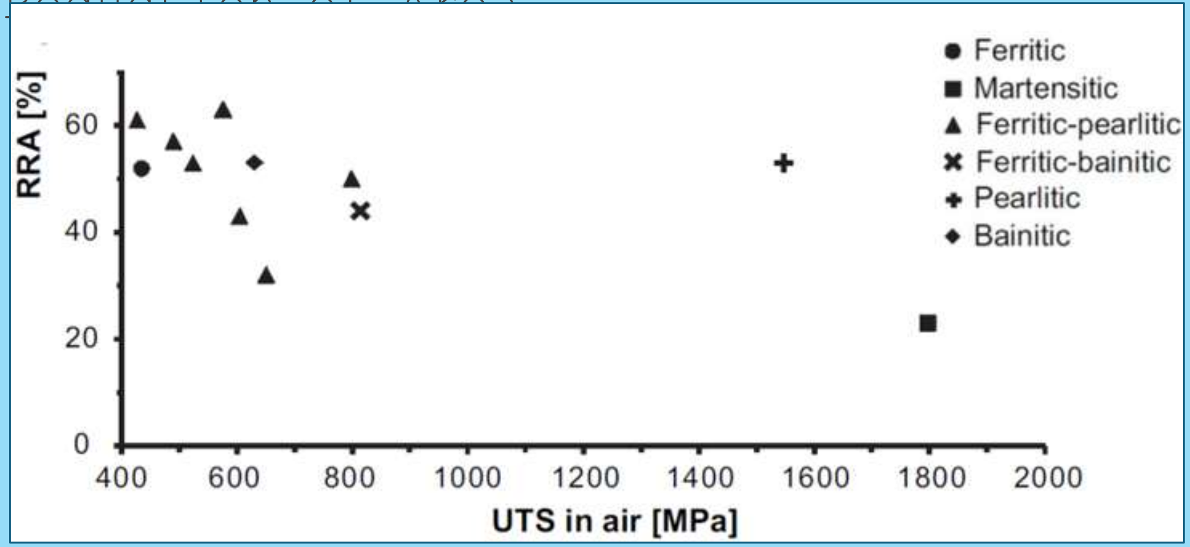
Hydrogen Equipment Damage
1. Hydrogen Containing Environment

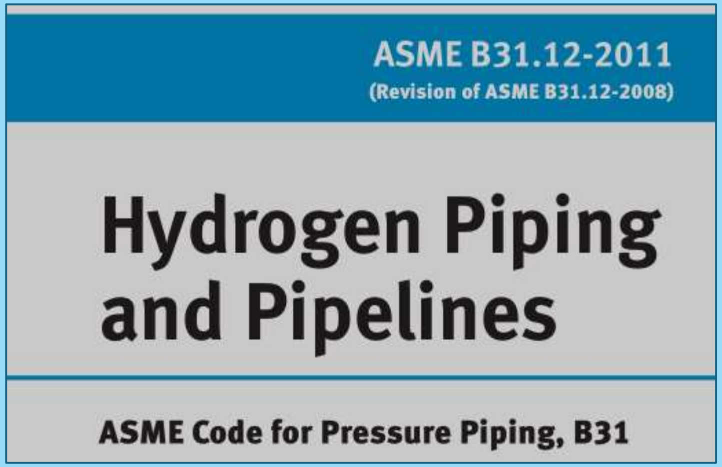
Upstream infrastructures:

- ❑ Pipeline
- ❑ Storage tanks
- ❑ Gas cylinders

Pipeline material, Effect of (1/4):

- **ASME B31.12 Code:** a comprehensive rule book – design, material, fabrication and inspection of hydrogen gas pipeline for transmission.
- **ASME B31. 8 Code:** Gas transmission pipeline.
- **Carbon and low-alloy steel:**
- All suffer hydrogen embrittlement, especially as strength increases
- Mechanical properties deduction: Relative: Reduction of Area





❑ H2 readiness – Repurposing existing NG pipeline steel for H2 transmission:

- Fatigue crack growth rate in H2 measured for existing NG pipeline steel
- The fatigue crack growth rate curve for hydrogen service piping, from B31.12 code
- All pipeline steel grades shown matching/better fatigue cracking resistance than required by B31.12 Code.
- Basically, all suitable for new application – **ready for transmitting H2 gas service**

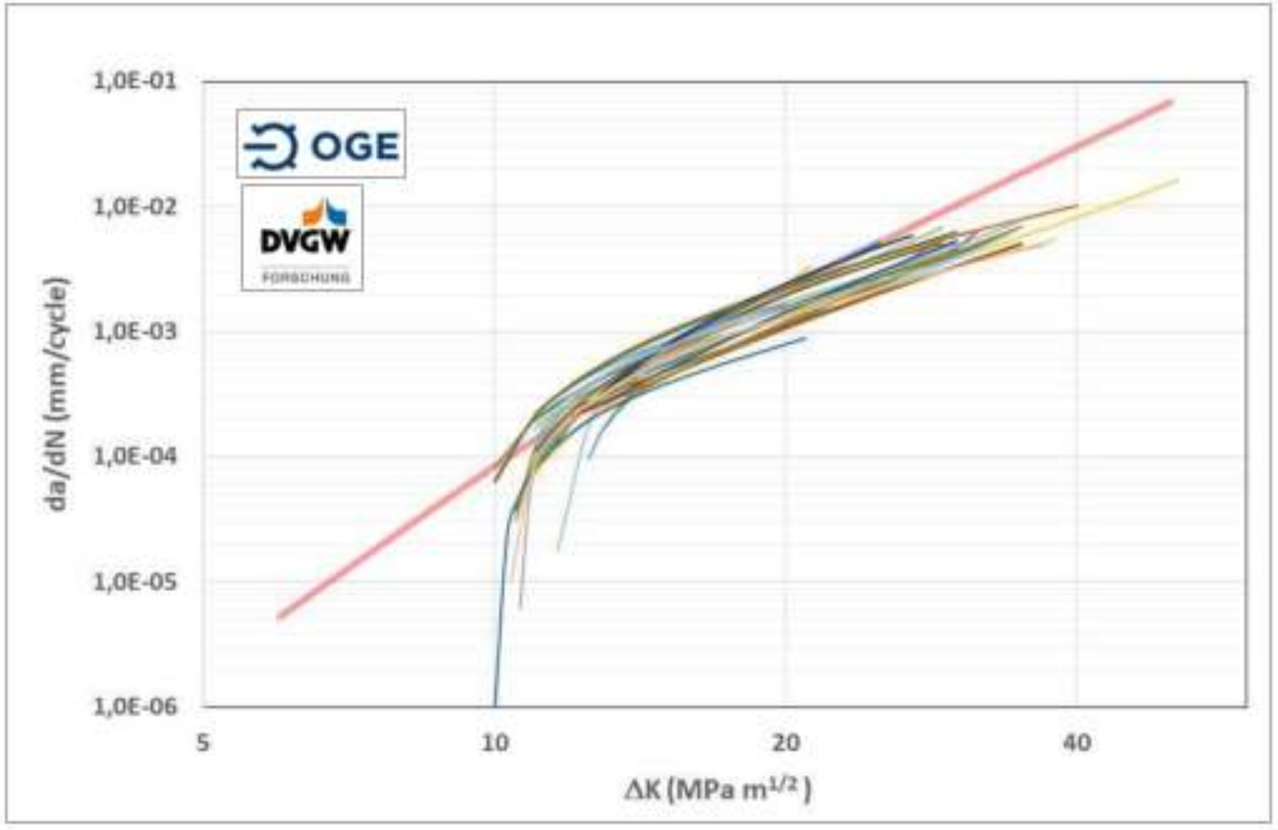
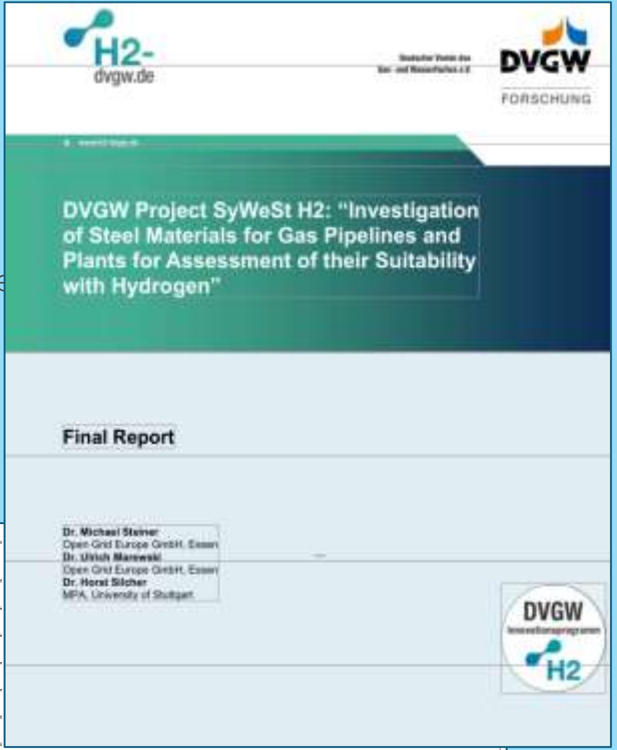


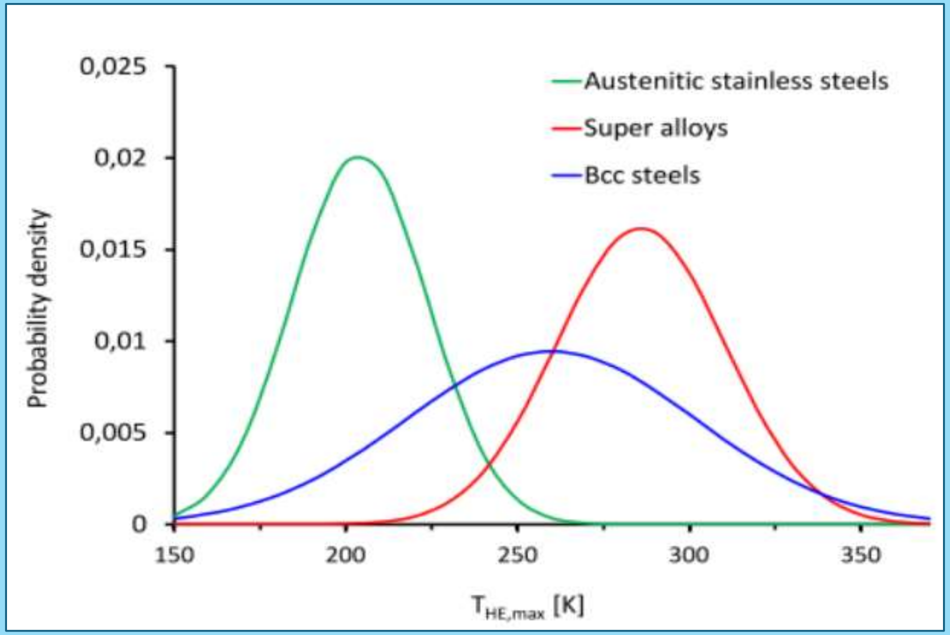
Figure 4.1: Established crack growth of the investigated materials in hydrogen (100 bar, R = 0.5)

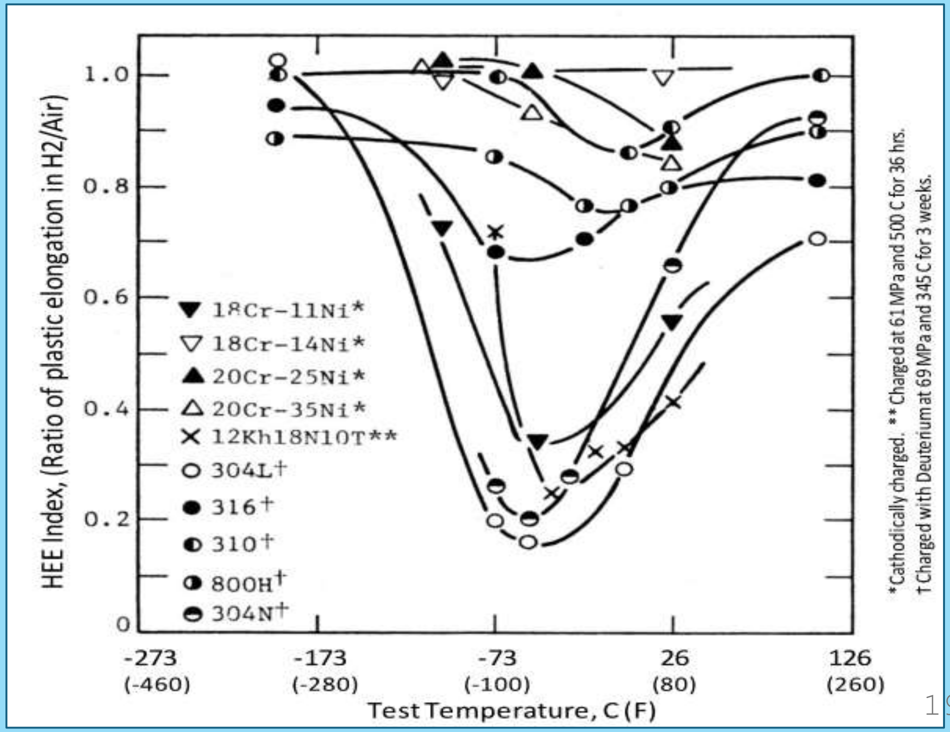
Code N



❑ Storage tank material, Effect of (2/4):

- **ASME BPVC VIII div.3 Code:**
- Appendix KD-10 stipulates Rules for Construction of High-pressure H2 Vessels
- Austenitic stainless steel of construction for large stationary H2 storage tanks
- Design temperature well below / away from T_{HE} to avoid embrittlement
- High-risk temperature envelop narrower for austenitic stainless than for carbon/low alloy steels (body-centered cubic).





Ref: [1] University of Stuttgart etc, 2021. [2] T. Michler et

Hydrogen Equipment Damage
2. Hydrogen Induced Environment (CCGT)

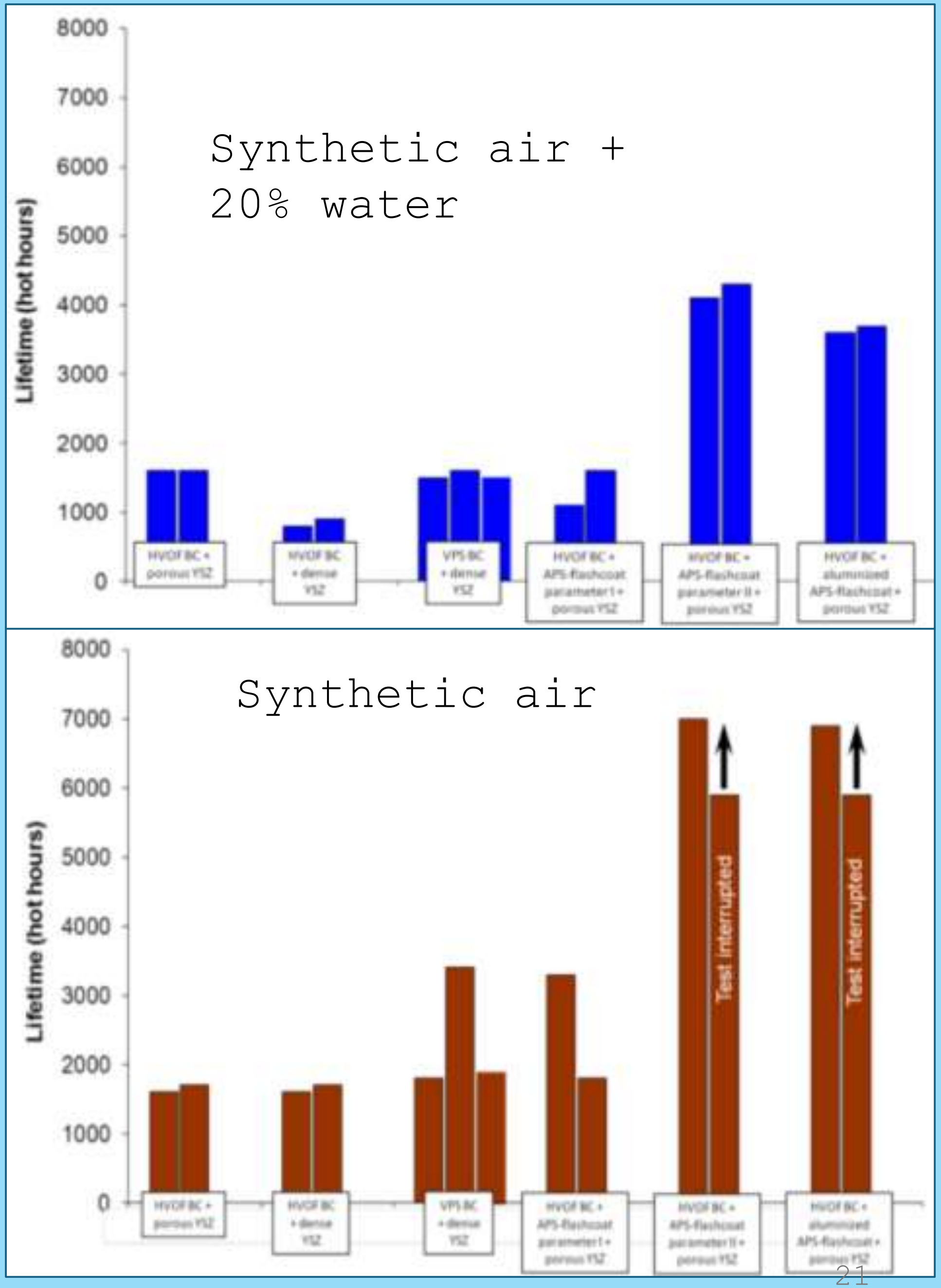
End-use, CCGT:

- High T, P, Moisture hostile environment created – *aftermath of H2 burn-out*
- Material damage as a result of more elevated T, P, Moisture
- Accelerated creep, fatigue, SCC, flue gas erosion and down-time corrosion expected
- GT HGP Components
- TBC
- HRSG Components

❑ Effect on Gas turbine material (2/6):

TBC:

- **Higher gas temperature** exceeding 1200oC may de-stablize the current YSZ topcoat, due to activation of ZrO2 phase transformation, causing TBC cracking and spall off from phase-transformation induced dilation.
- **Water vapour** increases TBC loss in isothermal oxidation test at 1050oC, in synthetic air + water vapour. Due to rapid TGO forming atop bond coat.
- **Condensation** water absorption due to high affinity of the porous Zirconia topcoat ? ! possibly?
- *Affected part: HGP heat shields segments, inlet end blades & vanes, rotor and stator segments.*



ef: University Stuttgart, University of Dortmund, and Fraunhofer IWM, in Literature Study of Hydrogen Influence , VGB 2021

❑ Effect on Gas turbine material (3/6):

Effect of water vapour on TBC:

- Water vapour reduces TBC life under oxidation

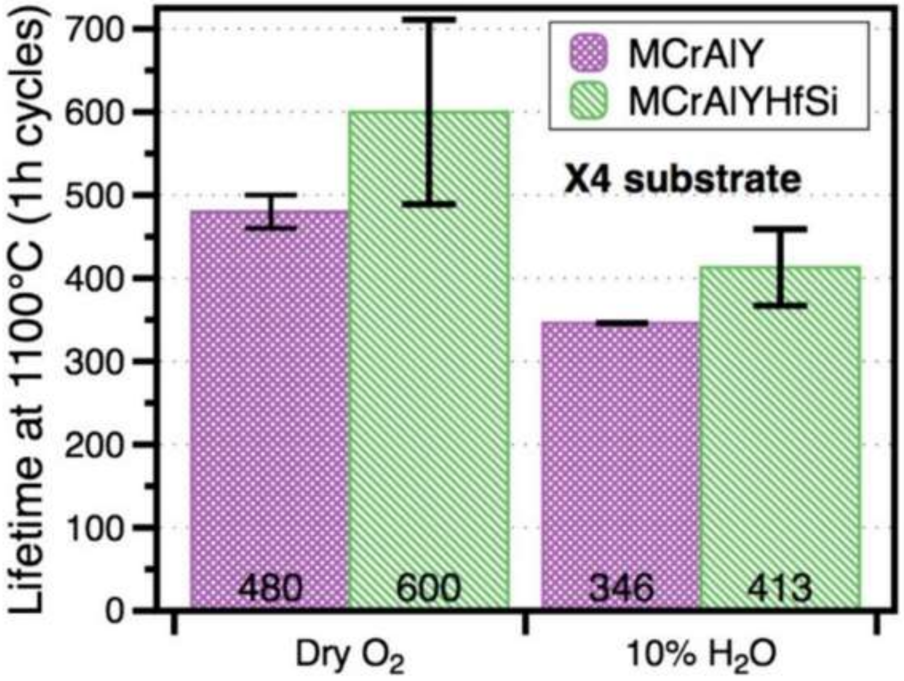


Figure 3. Comparison of the effects of the environment (dry oxygen or air + 10 vol.% H_2O) and high-velocity oxy-fuel spray processed (HVOF) bond coat composition on average air plasma sprayed (APS) TBC life of specimens on alloy X4 during 1 h furnace cycles at 1100 °C [17].

Ref: K.Chen et al, The effect of high temperature water vapour on degradation of hot section components of gas turbine engines, Coatings, Vol. 11(2021)1061 (and ref therein)

❑ Effect on Gas turbine material (4/6):

TBC - Water vapour damage mechanism:

- **Increased oxidation by steam:** TGO formation at topcoat-bond coat interface
- **Bond coat defect formation:** Steam reacting with bond coat by volatile hydroxide and bond cavity formation
- **Bond coat rumpling:** TGO, aided by cavity defect, causing bond line rumples as it thickens, leading to internal stress and topcoat spalling (loss)

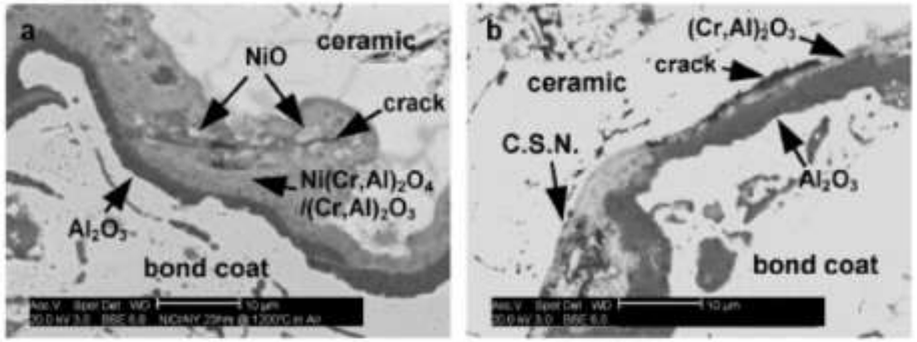


Figure 6. SEM images of crack nucleation via void formation in $(Cr,Al)_2O_3$-$Ni(Cr,Al)_2O_4$-NiO (**a**), and at the interface between ceramic topcoat and $(Cr,Al)_2O_3$ (**b**) after 23 h in air at 1200 °C [25].

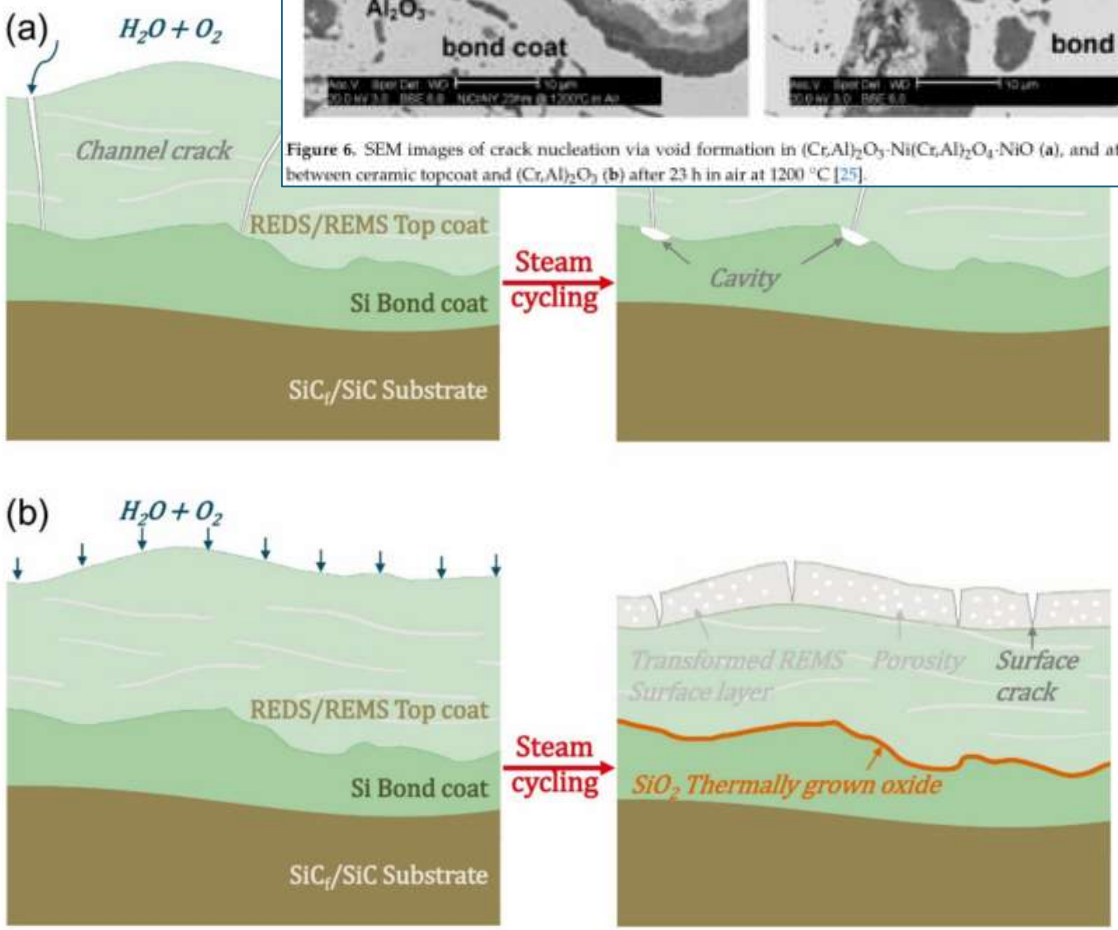


Figure 9. (**a**) Premature failure via interface delamination through channel cracks; (**b**) intrinsic failure via coating spallation at topcoat surface [53].

Ref:B.Lv, Z.Qu et al, Water vapour volatilization and oxidation induced surface cracking of thermal barrier coating system, Ceramics International, 47(2021)16547

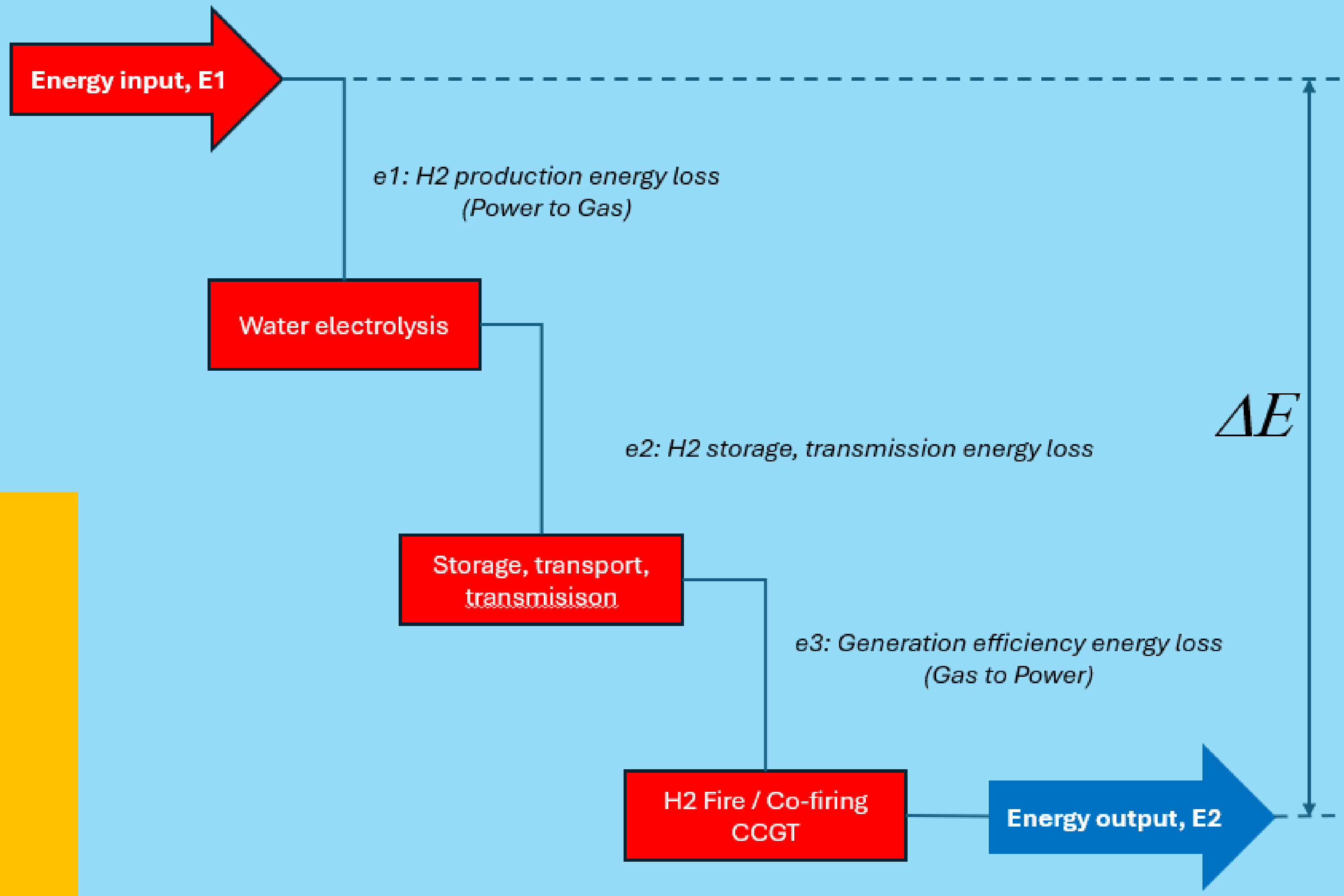
Challenges
1. Materials 2. Life Cycle Costs

- Upstream end (hydrogen infrastructures)
- Downstream (CCGTs)

- Hydrogen and new Low-C Fuels with Life Time Cost challenges
- Cost from upstream from renewable power plant construction: CAPEX
- Cost from lifetime, Energy and Material Consumption: OPEX
- Cost from downstream fuel logistics from source to end users
- Cost added due to competition with existing fuel tariffs: Fuel pricing
- Cost from fuel handling on site, energy and efficiency loss in Gas to Power

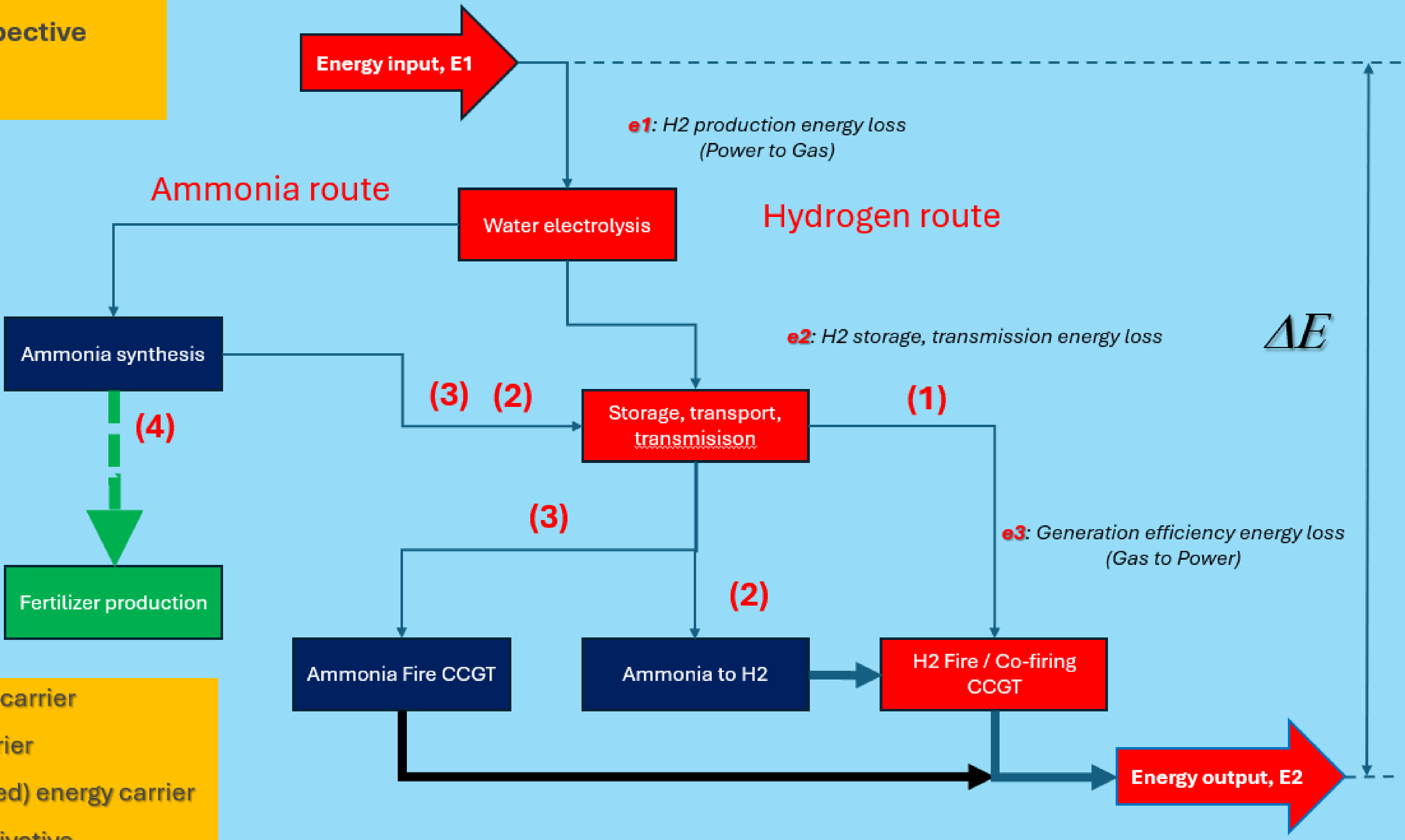
- **Cost / Life Cycle Path:**
  - **Energy Loss Perspective, Qualitative**
  - **Green H2:**

- Energy loss to Production
- Energy loss to Storage, Transport…
- Energy loss to Firing in CCGT/GT

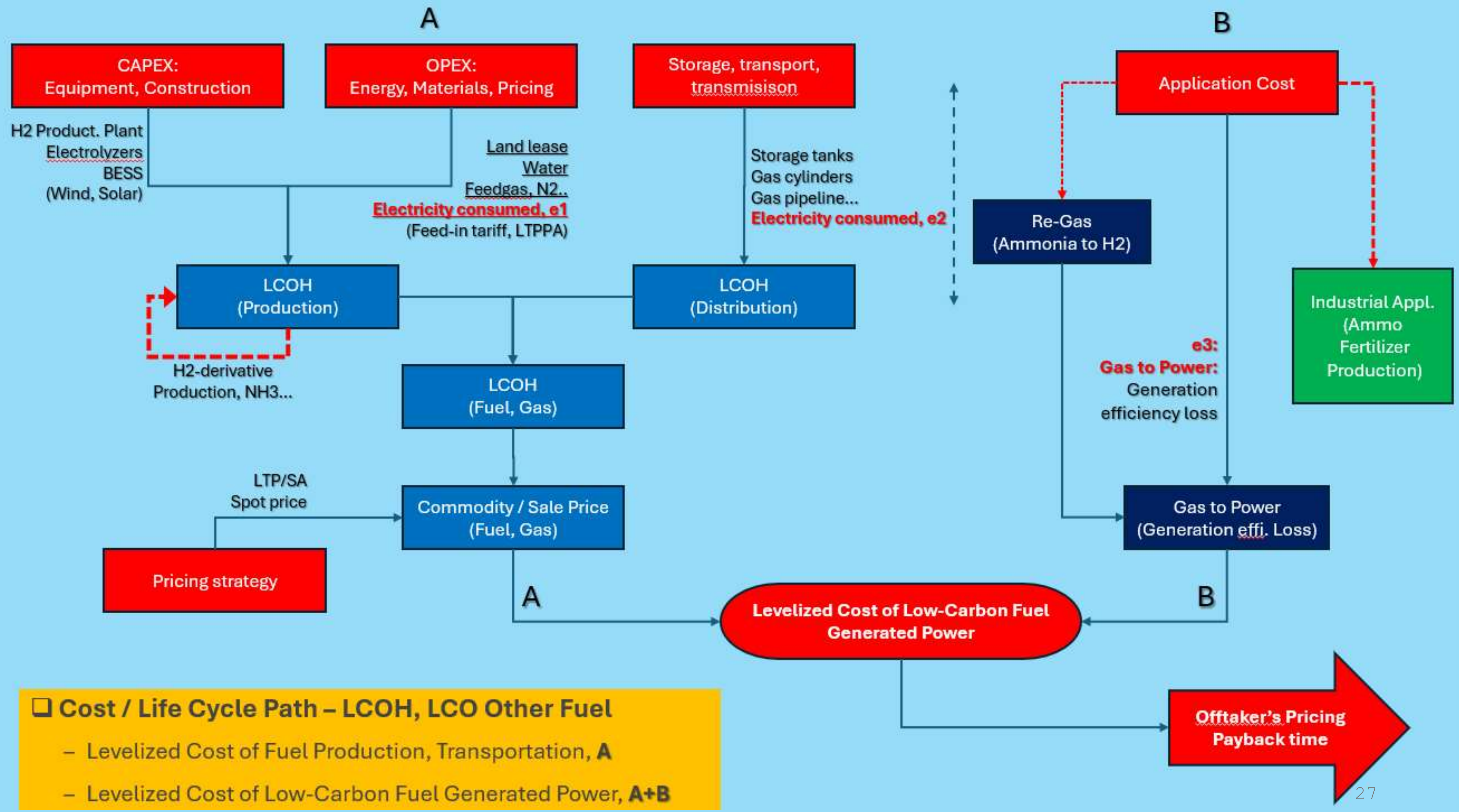


❑ Cost / Life Cycle Path:

- Energy Loss Perspective
- H2 vs Ammonia



1) Hydrogen as energy carrier
2) Ammonia as H2 carrier
3) Ammonia as (reduced) energy carrier
4) Ammonia as H2-derivative



❑ Cost / Life Cycle Path – LCOH, LCO Other Fuel

- Levelized Cost of Fuel Production, Transportation, **A**
- Levelized Cost of Low-Carbon Fuel Generated Power, **A+B**

Opportunities
Power Generation and Beyond

Hydrogen Valuation Chain :

- Large-scale production and new infrastructure: Pipelines, re-fueling stations, and storage facilities
- Hydrogen-derived fuels: For renewable electricity integration and grid stability
- Reducing high CAPEX and OPEX costs
- Policy regulation to provide leniency

Diversifying Application:

- **Decarbonization a Global / not Sectorial or Territorial** Goal
- **Power generation** sector continues to progress, but need bountiful green fuel to be available first
- Decarbonizing heavy-polluting **Steel-making** industry – LHF (low hanging fruit) – by RE-enabled electrification
- **Fertilizer** production from coal or NG-derived H2 can be de-carbonnised easily

Ammonia

large-Wind/Solar/Nuclear Power are not available first

Thank you very much.