Two Carbon-free Fuels:

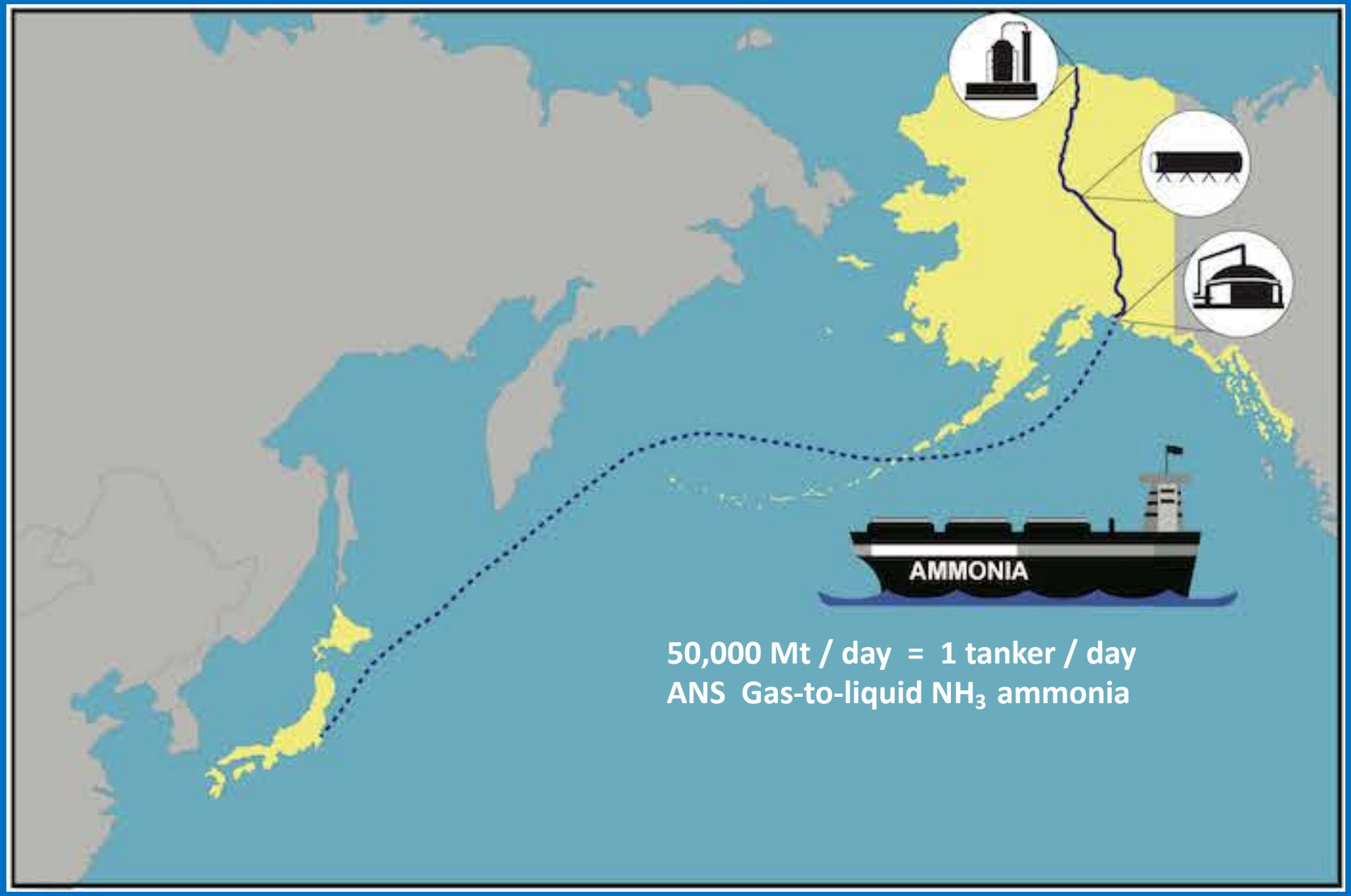
1. **Hydrogen (H2)**
   - **Electrolysis of H_2O**
2. **Anhydrous Ammonia (NH_3)**
   - **Electrolysis + Haber-Bosch**
   - **Direct from electricity, water, air**

- **Wind-source electricity**
- **Renewables-source electricity**
- **Energy carrier: "Transmission" export, import**
- **Energy storage: better than batteries**
- **Fuel: recover "work"**

Bill Leighty, The Leighty Foundation wleighty@earthlink.net www.leightyfoundation.org/Earth.php

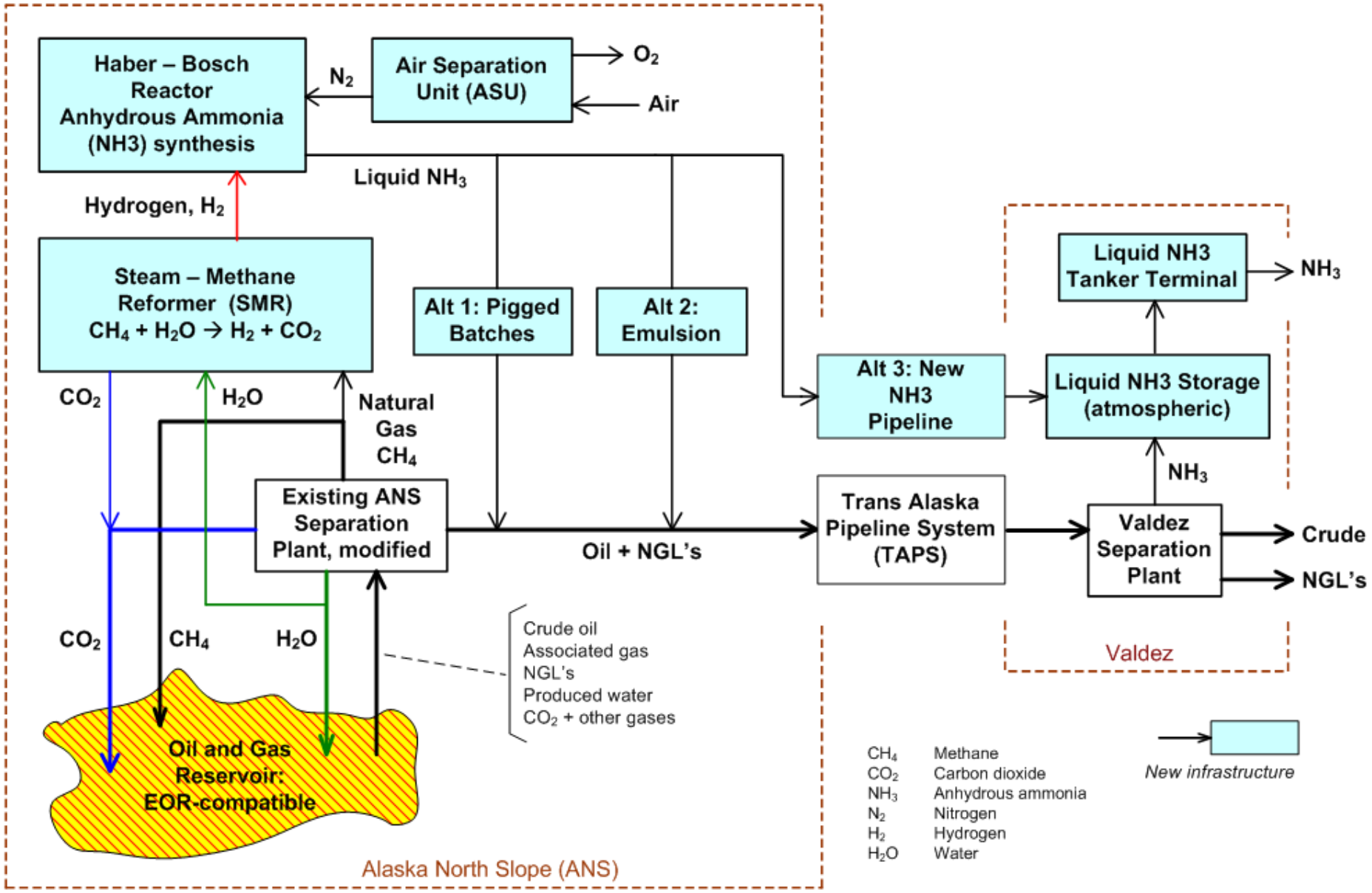
- **Entirely with electricity systems, “Grid” ?**
- **Obvious, default**
- **Assume primarily variable generation (VG) ?**
- **Possible, but tech & econ suboptimal ?**
- **Optimum mix: electricity, C-free fuels -- H_2 , NH_3**

Need diverse collaboration to roadmap: neglected, urgent !



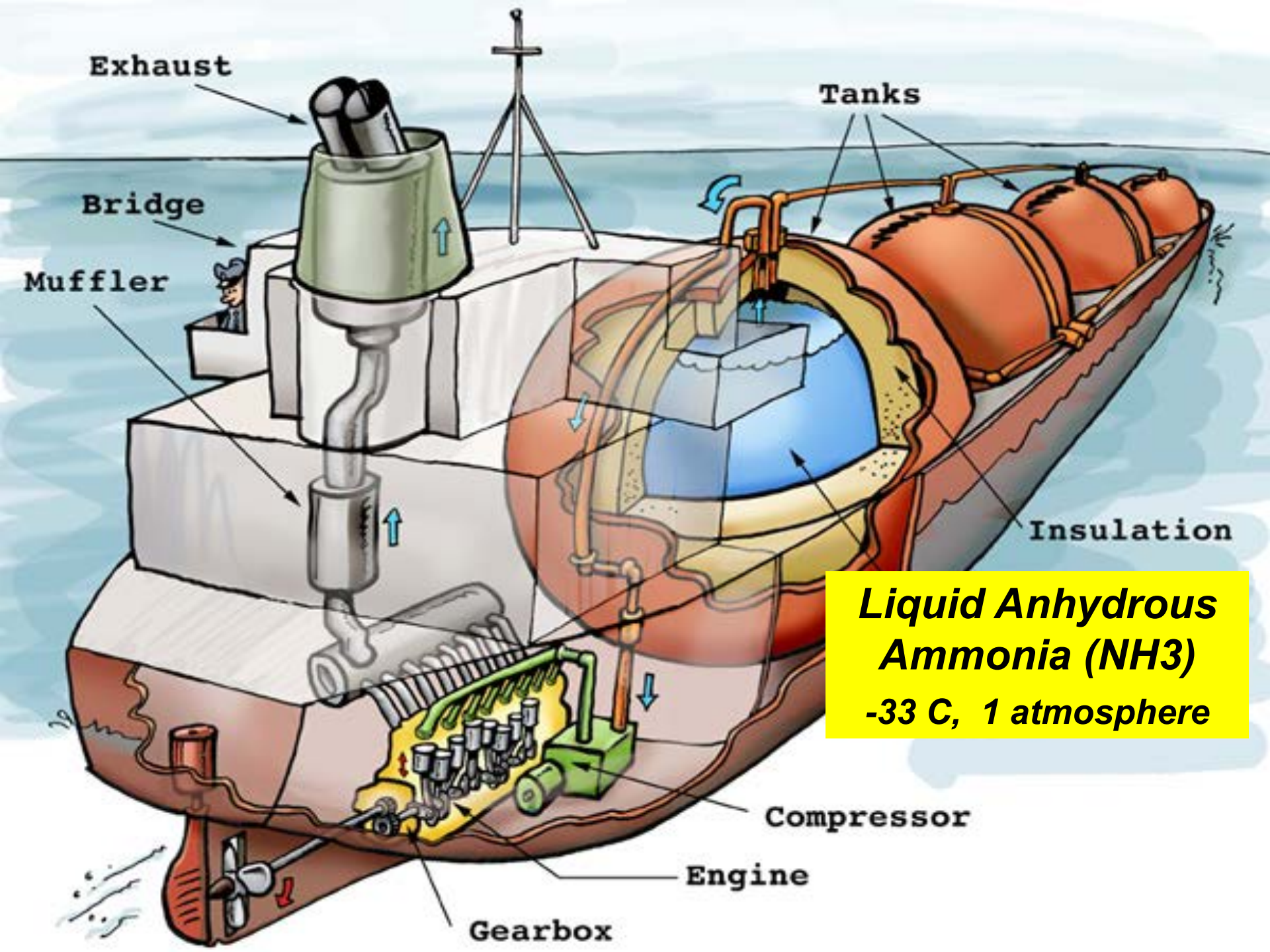
ANS Gas-to-NH3 → Export + AK markets

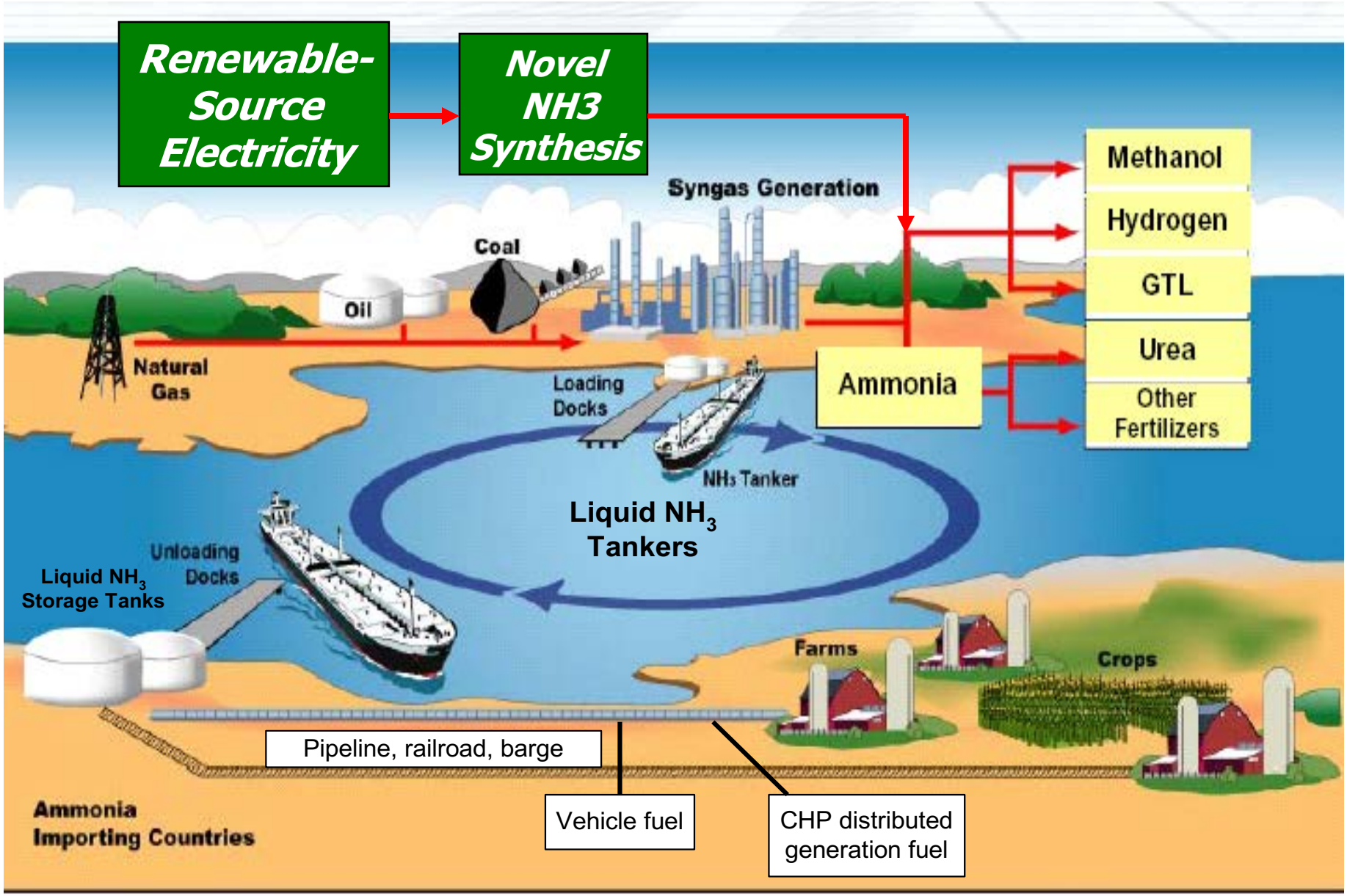
2 BCFD at ANS → 50,000 MtD at Valdez or Nikiski


Haber – Bosch Reactor Anhydrous Ammonia (NH3) synthesis
N2
Air Separation Unit (ASU)
O2
Air
Liquid NH3
Hydrogen, H2
Steam – Methane Reformer (SMR)
CH4 + H2O → H2 + CO2
Alt 1: Pigged Batches
Alt 2: Emulsion
Alt 3: New NH3 Pipeline
Liquid NH3 Tanker Terminal
NH3
Liquid NH3 Storage (atmospheric)
CO2
H2O
Natural Gas CH4
Existing ANS Separation Plant, modified
Oil + NGL's
Trans Alaska Pipeline System (TAPS)
Valdez Separation Plant
Crude
NGL's
Valdez
CO2
CH4
H2O
Crude oil
Associated gas
NGL's
Produced water
CO2 + other gases
Oil and Gas Reservoir: EOR-compatible
Alaska North Slope (ANS)
CH4 Methane
CO2 Carbon dioxide
NH3 Anhydrous ammonia
N2 Nitrogen
H2 Hydrogen
H2O Water
New infrastructure

Trans Alaska Pipeline System

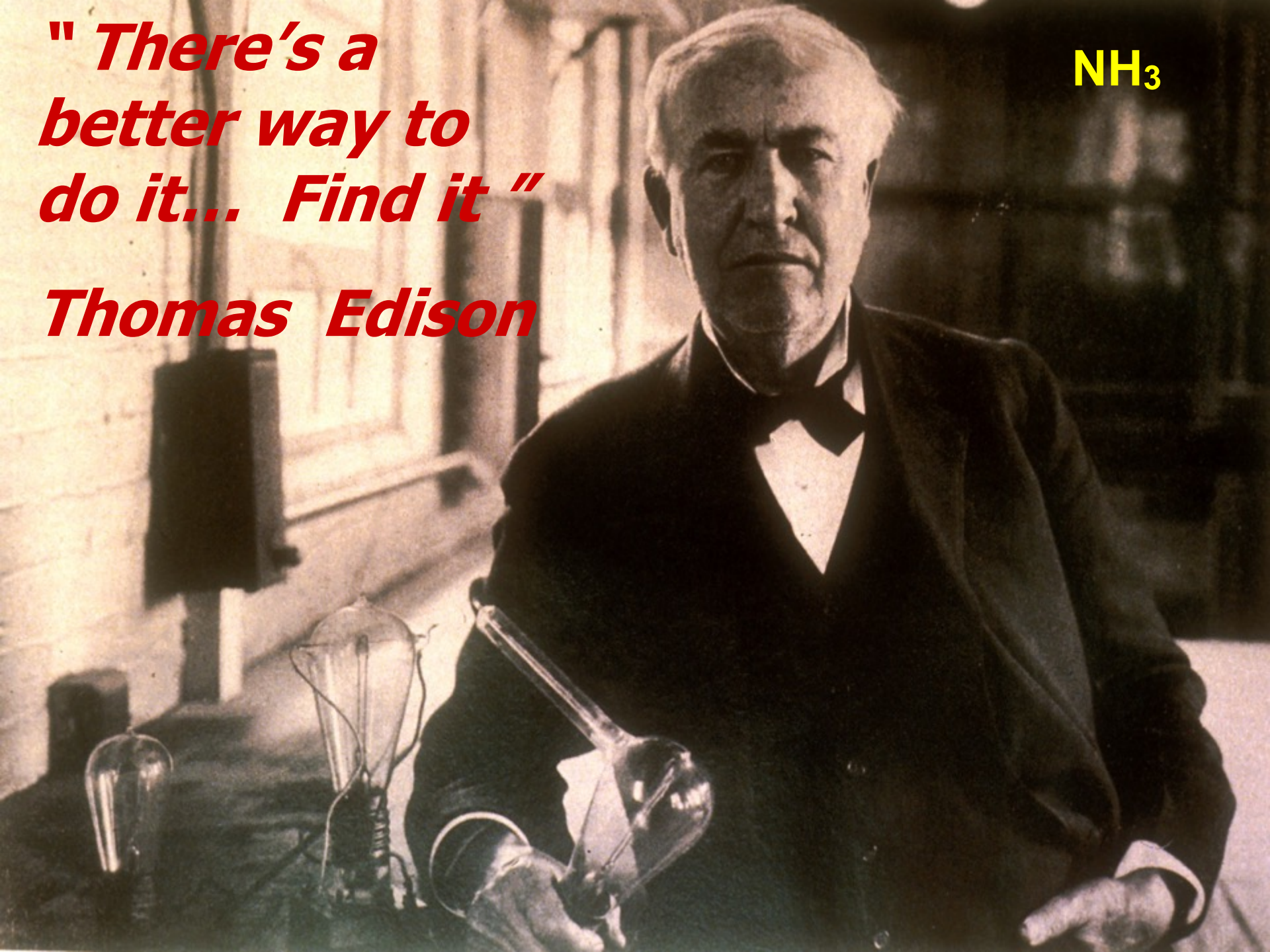
Valdez oil terminal

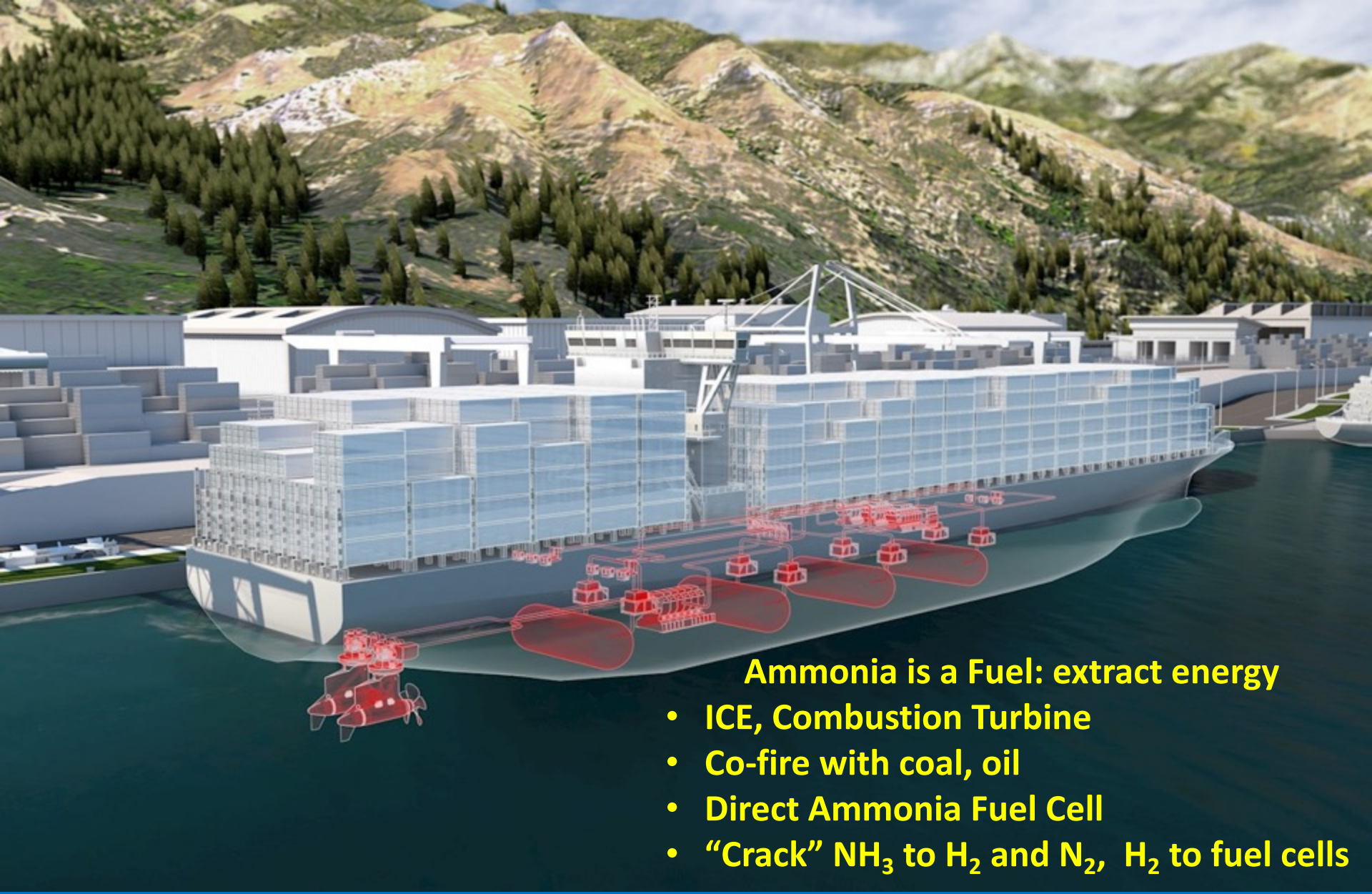

Exhaust
Tanks
Bridge
Muffler
Insulation
Liquid Anhydrous Ammonia (NH3)
-33 C, 1 atmosphere
Compressor
Engine
Gearbox



KBR
Energy and Chemicals

Aleutians wind to Japan via liquid fuel(s) tankers

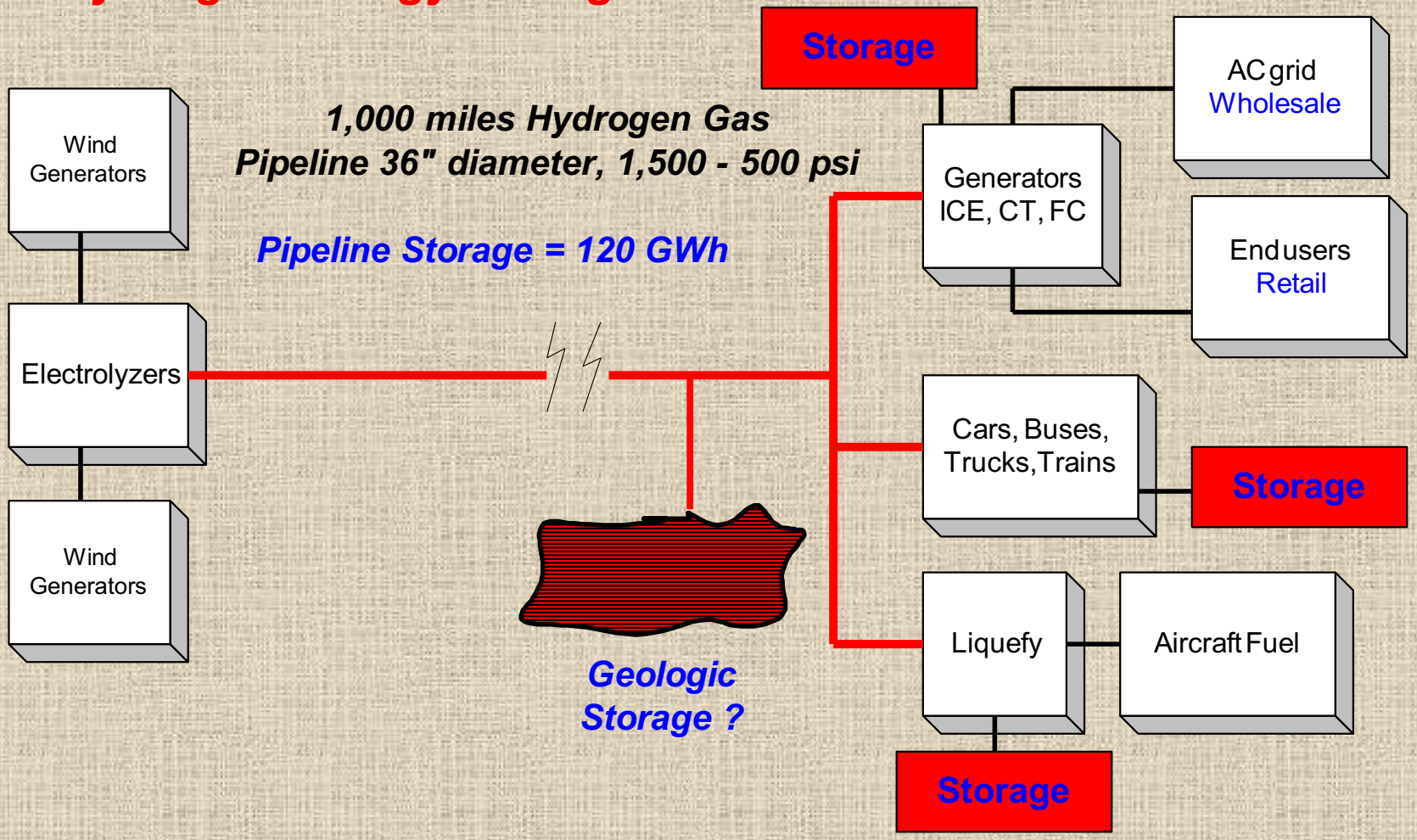

" There's a better way to do it... Find it "
Thomas Edison
NH_3

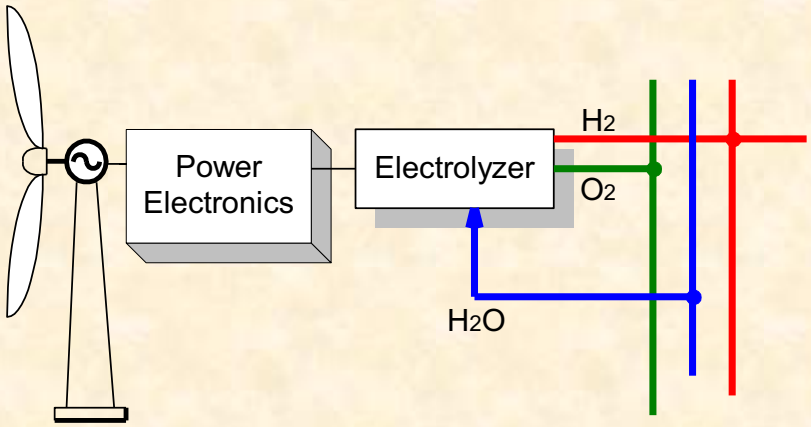


Ammonia fueled, Fuel cell electric drive container ship

Off – Grid, Dedicated

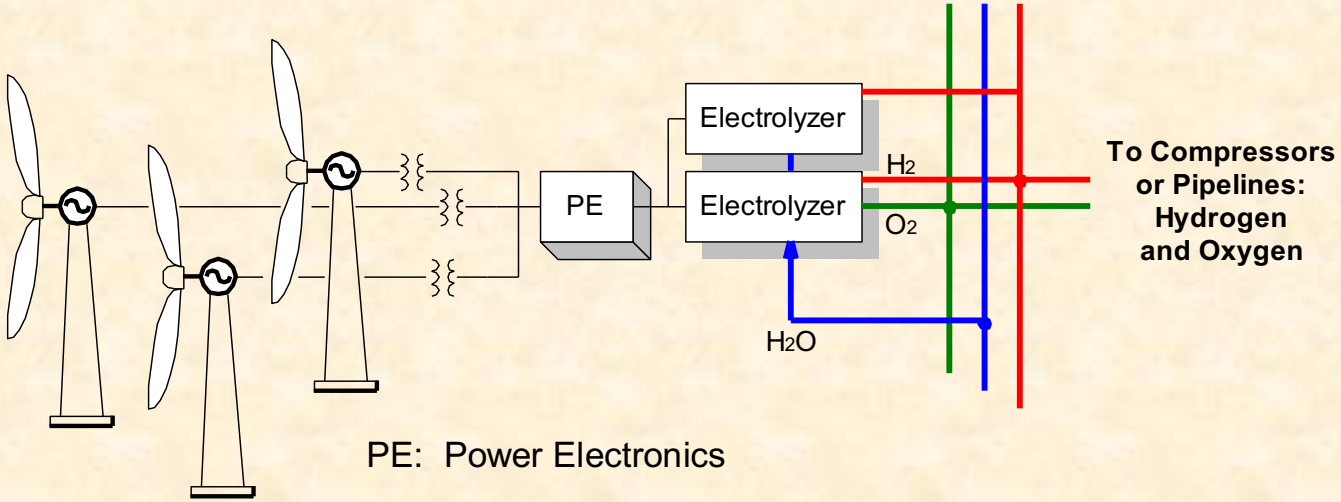
Hydrogen Energy Storage





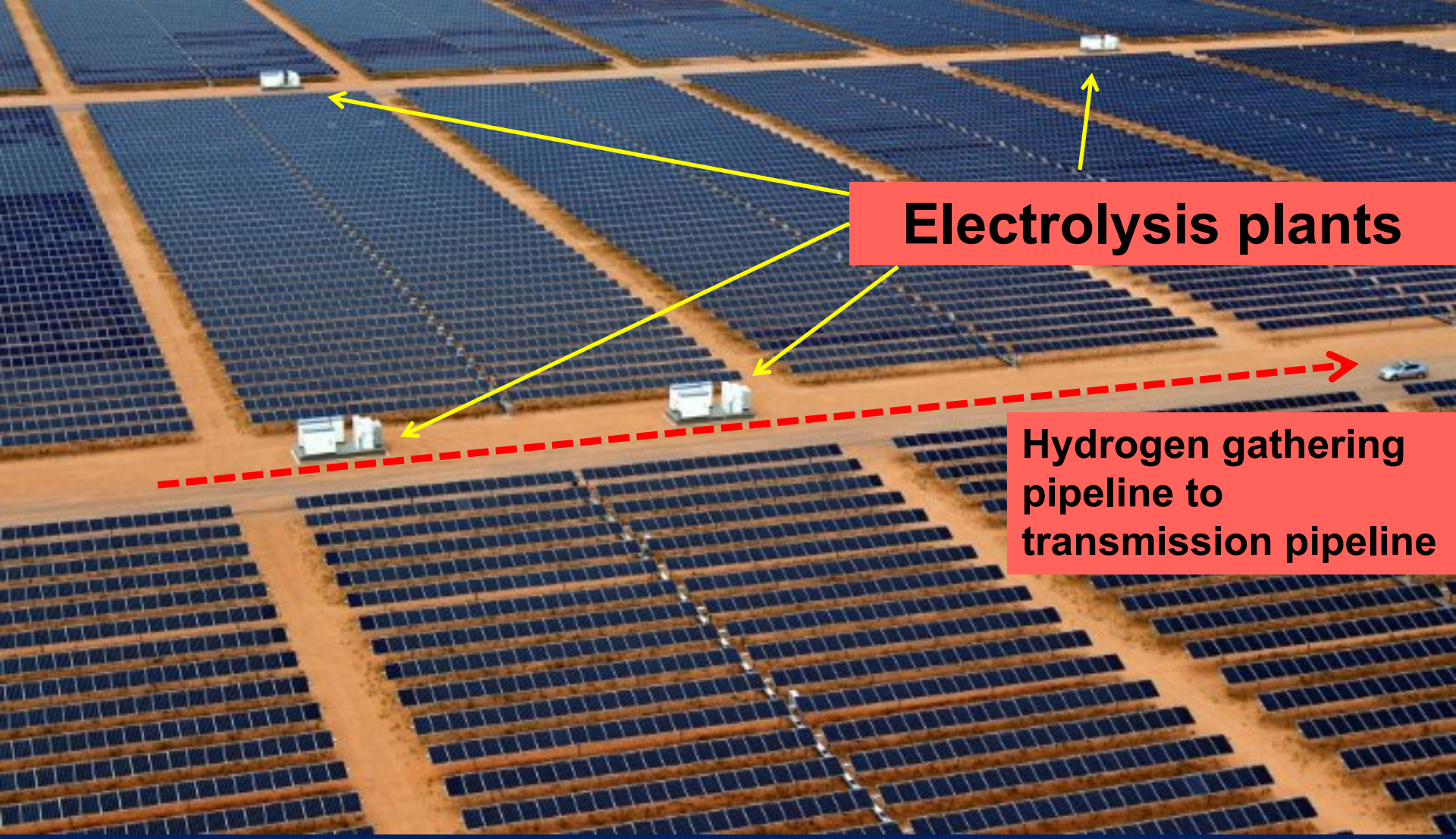
No grid connection

Renewable-source Electricity Generation

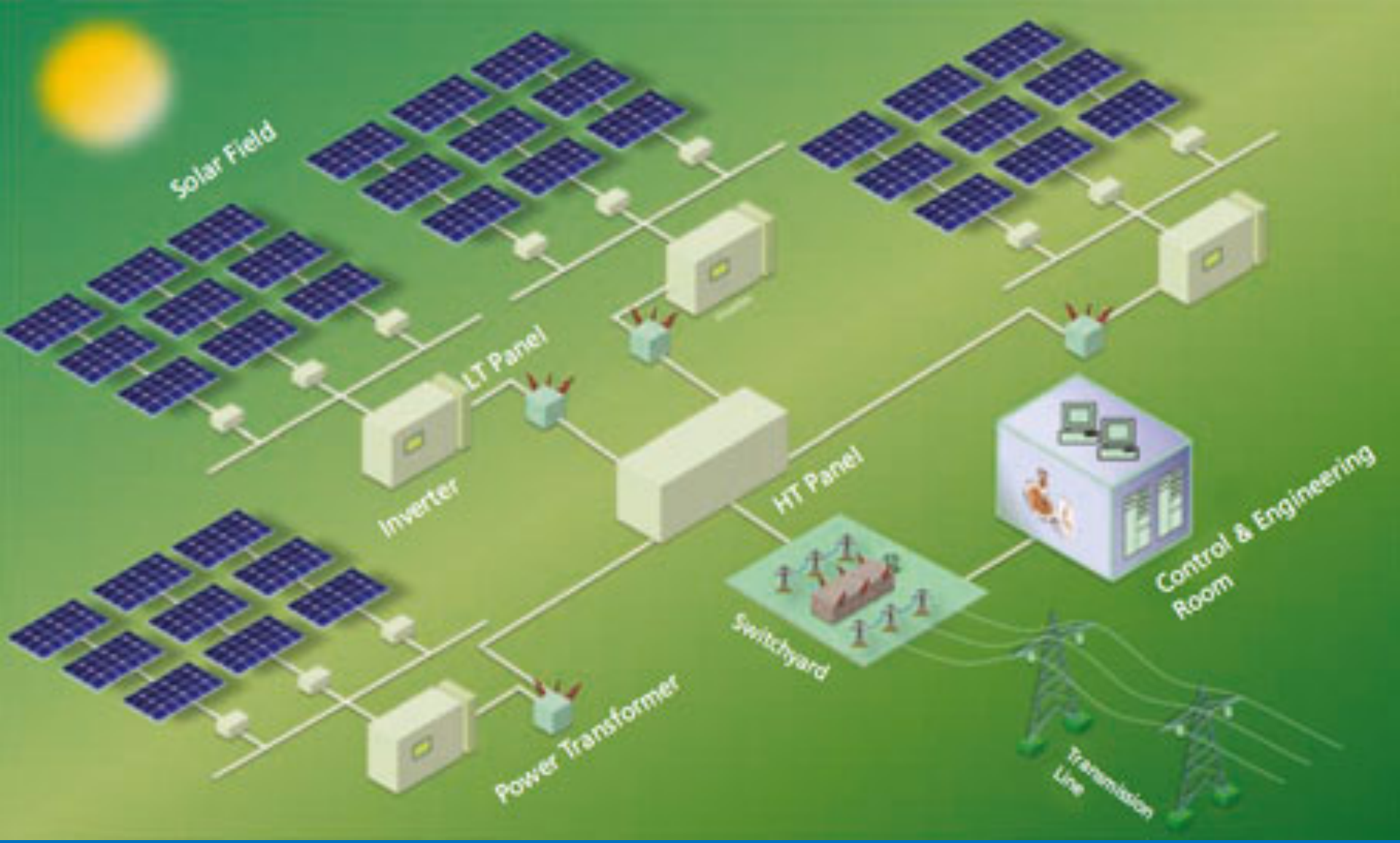


PE: Power Electronics

Topology Options: H_2 and O_2 Production and Gathering from Renewable Energy Generation

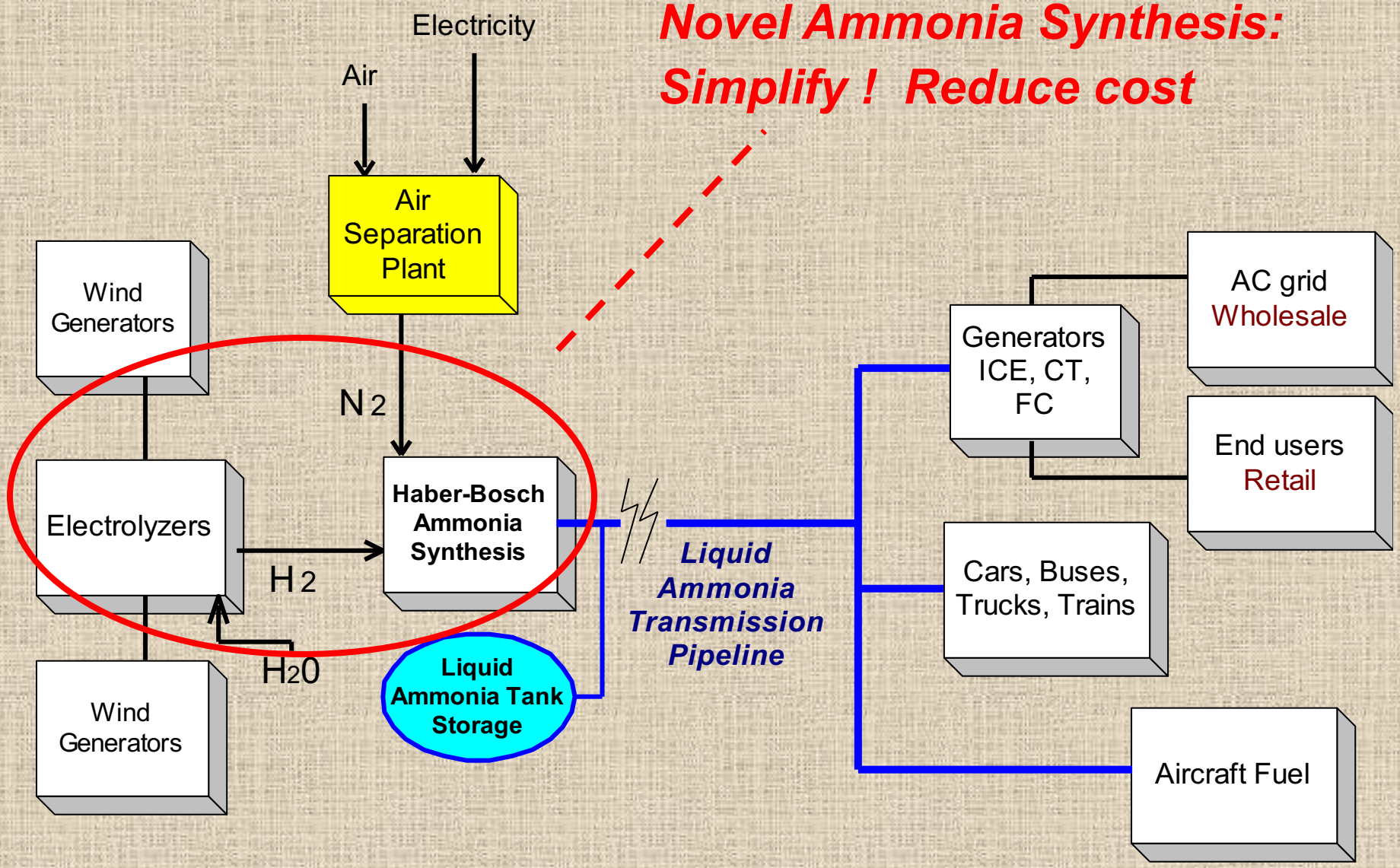


Dedicated to Hydrogen fuel production
No connection to electricity grid



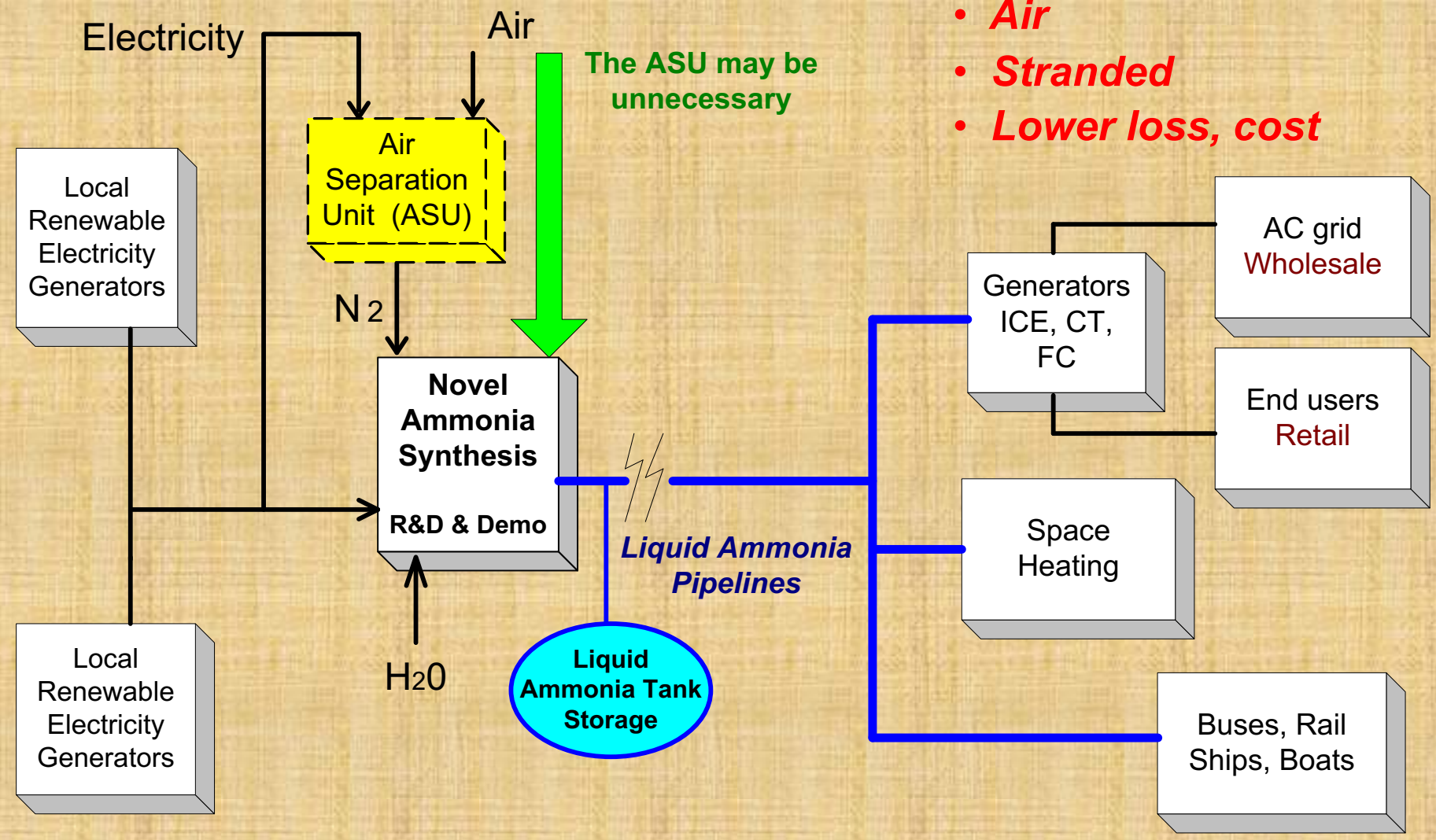
Grid delivery: Complex & Costly Infrastructure

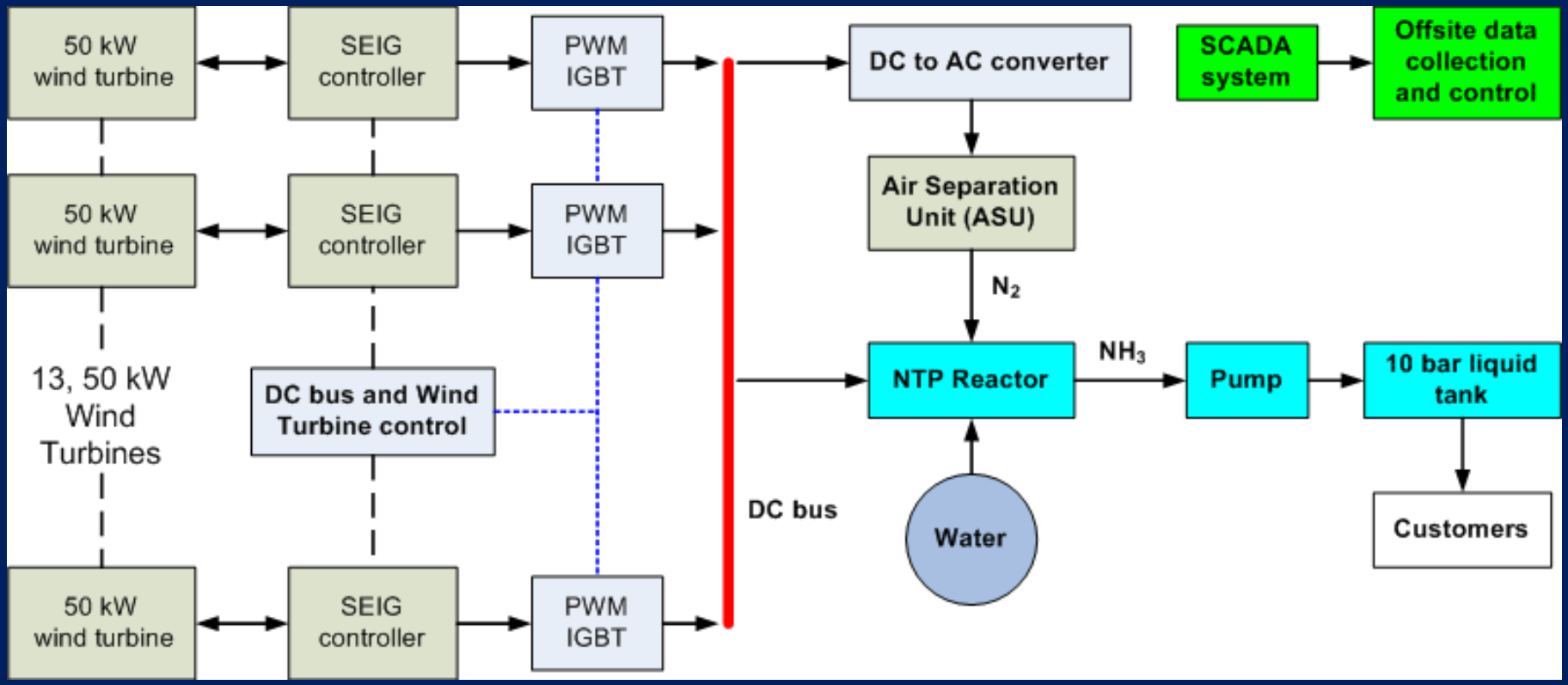
RE Ammonia Transmission + Storage Scenario
Electrolysis + Haber – Bosch (EHB)



Novel Ammonia Synthesis

- *Electricity*
- *Water*
- *Air*
- *Stranded*
- *Lower loss, cost*





Off - Grid
Anhydrous Ammonia (NH3)
Fuel production

’09 ARPA-E “Grids” Goal: $100 / kWh

Total storage = 380 GWh

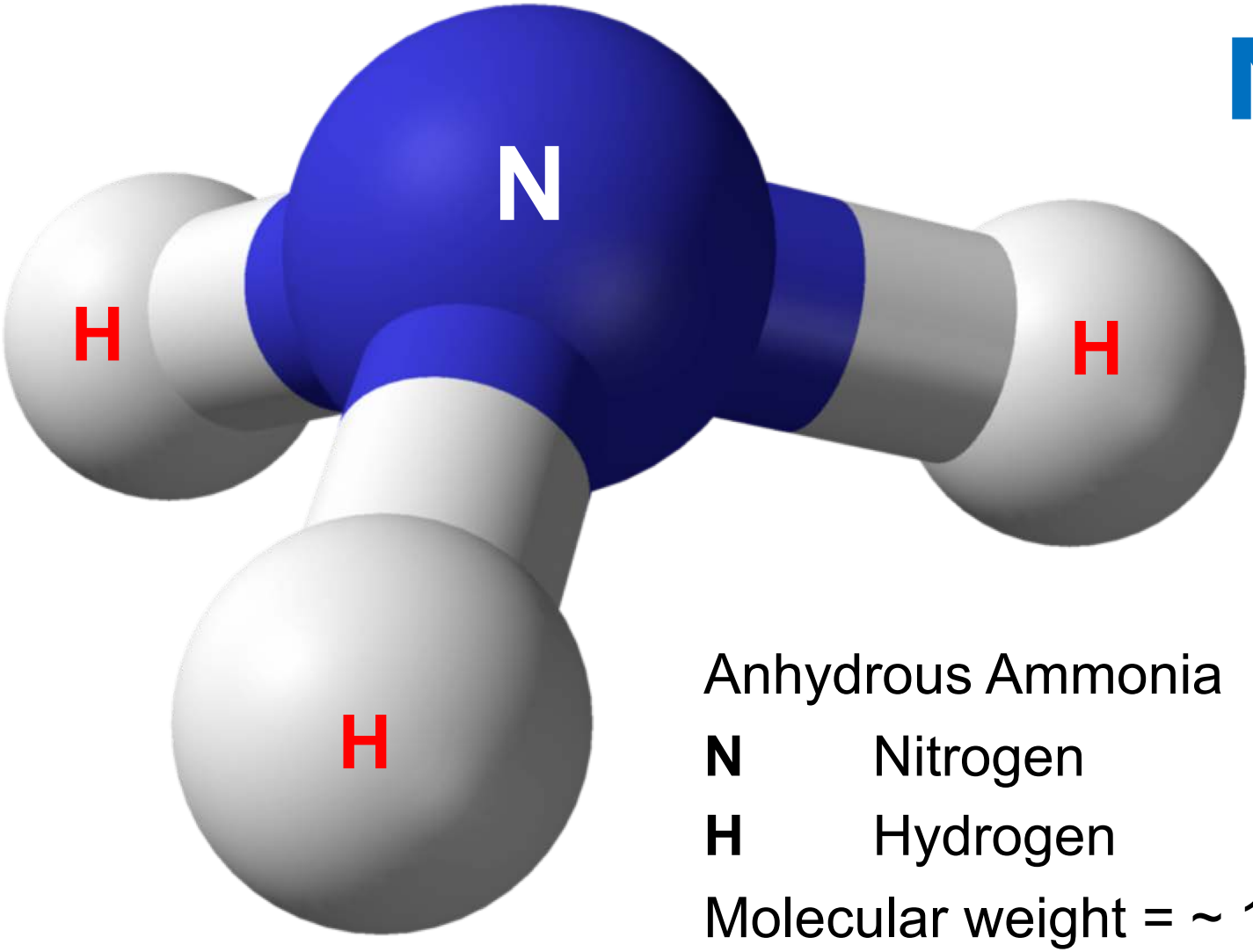
Liquid Ammonia (NH3)

“Atmospheric” Liquid Ammonia Storage Tank (Corn Belt)

-33 C 1 Atm

Each: 30,000 Tons, 190 GWh $ 15 M turnkey

$ 80 / MWh = $ 0.08 / kWh capital cost



NH_3

Anhydrous Ammonia **NH_3**

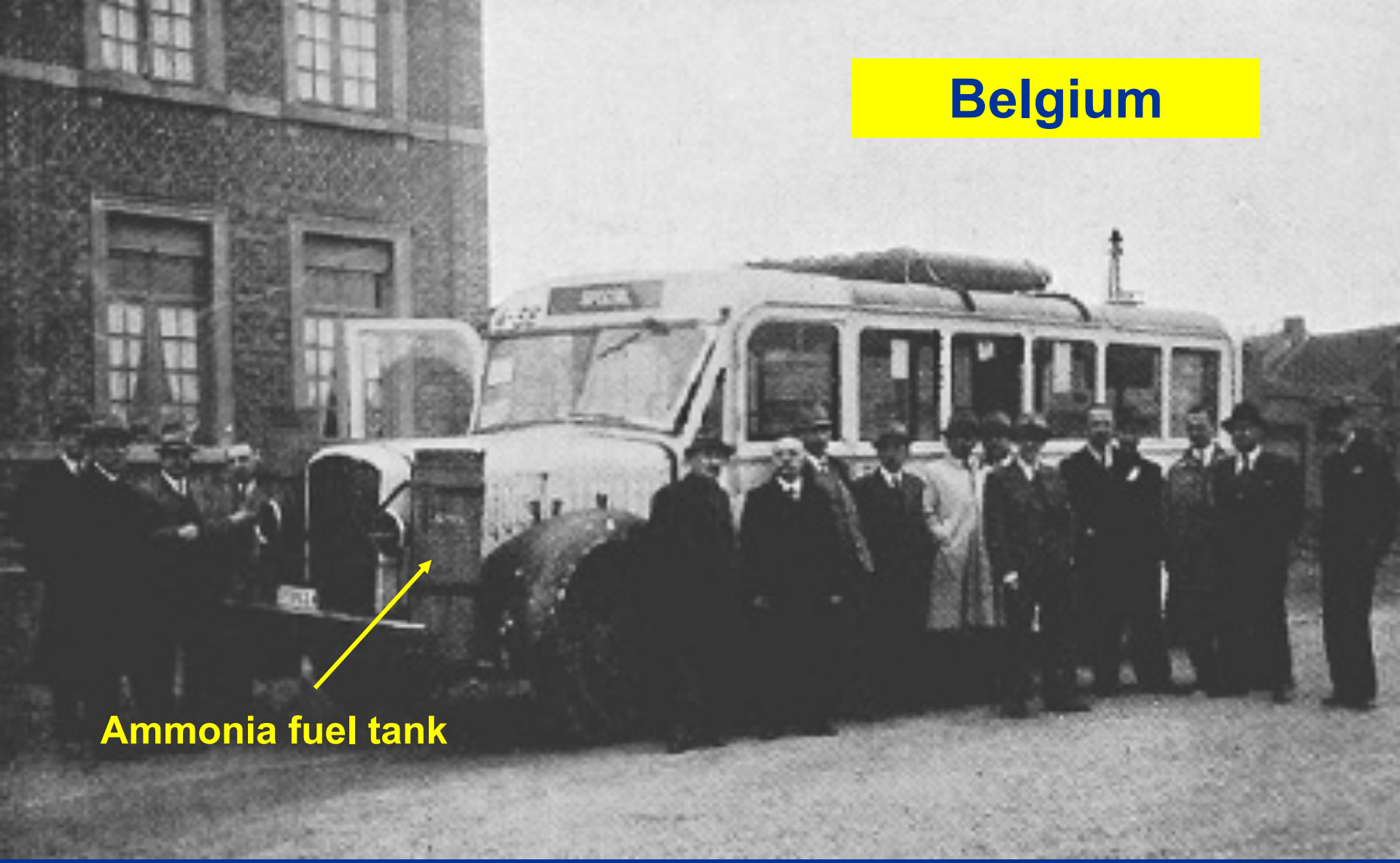
N Nitrogen

H Hydrogen

Molecular weight = ~ 17

18% **H** by weight: “other hydrogen”

$NH_3 + O_2 = N_2 + H_2O$



Ammonia Fueled Bus: Thousands of Problem-free Miles

1943

X-15 rocket plane: NH3 + LOX fuel

Mach 6.7 on 3 Oct 67

199 missions

1959 - 68

Liquid Hydrogen – LH2
100 H atoms

Liquid Anhydrous Ammonia – NH3
170 H atoms

USDOE ARPA-E "REFUEL" R&D

- Eliminate electrolyzer and Haber-Bosch reactor
- NH3 synthesis directly from electricity, water, air
- Lower capex + O&M costs, higher efficiency
- 13 NH3 synthesis & cracking projects
- KIER, WA State Univ

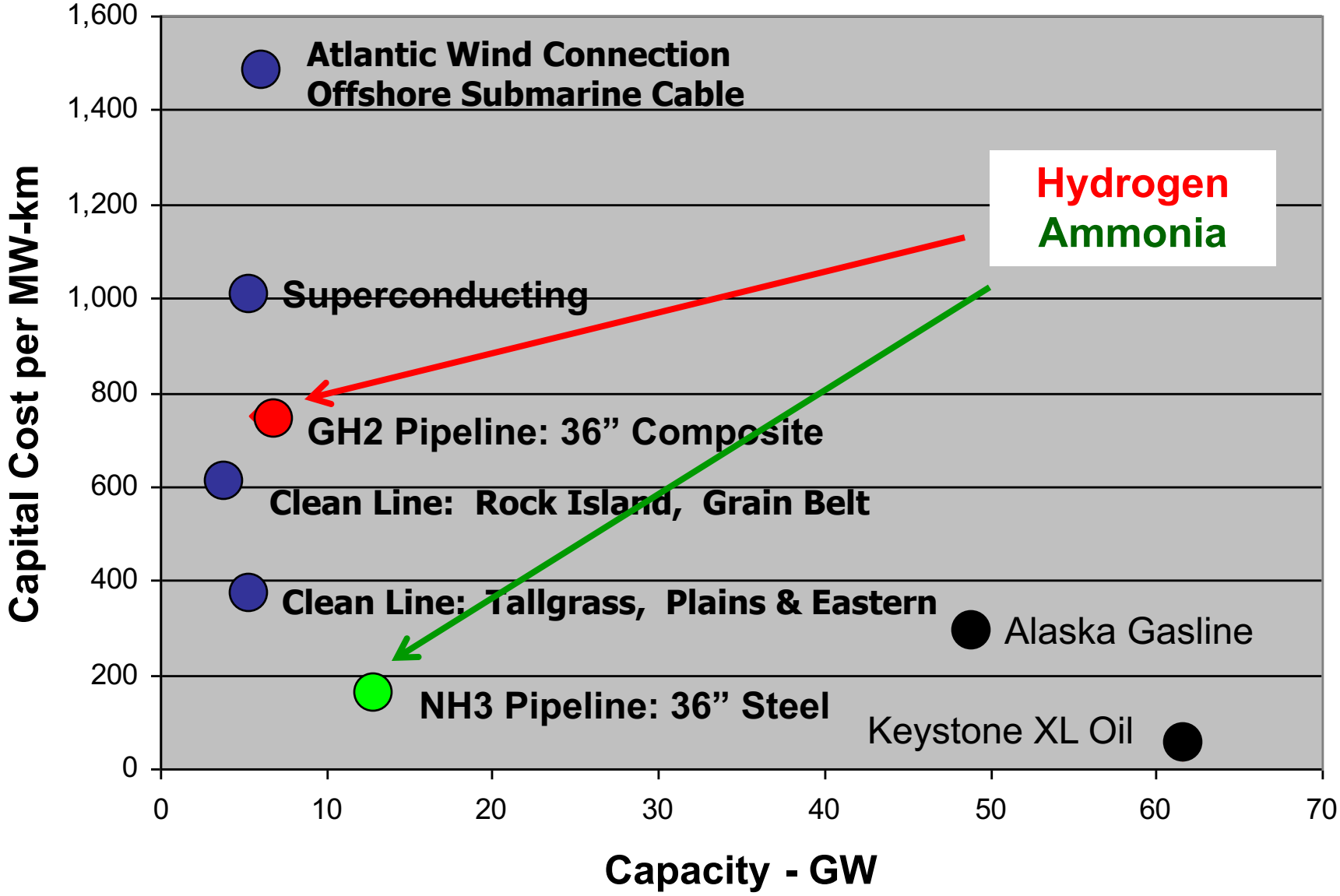

200 Ton “propane” tanks for liquid ammonia
~ 10 bar pressure

"Atmospheric" Liquid Ammonia Storage Tank (Corn Belt)

-33 C 1 Atm

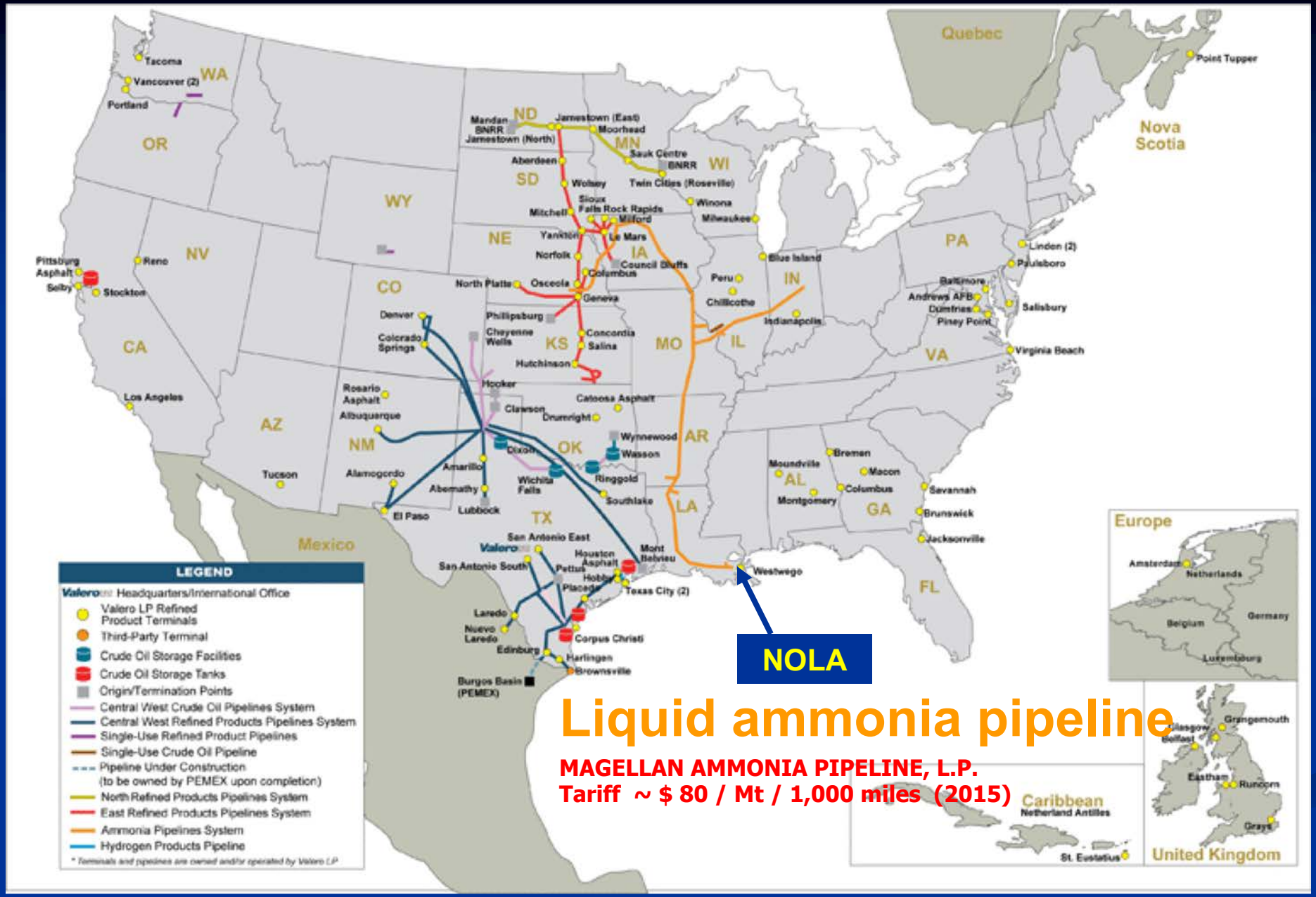
Each: 30,000 Tons, 190 GWh $ 15M turnkey

$ 80 / MWh = $ 0.08 / kWh capital cost



Transmission capital costs per MW-km compared

Pipelines have large capacity and provide large storage



Valero LP Operations

2016

Strategic Innovation Promotion Program

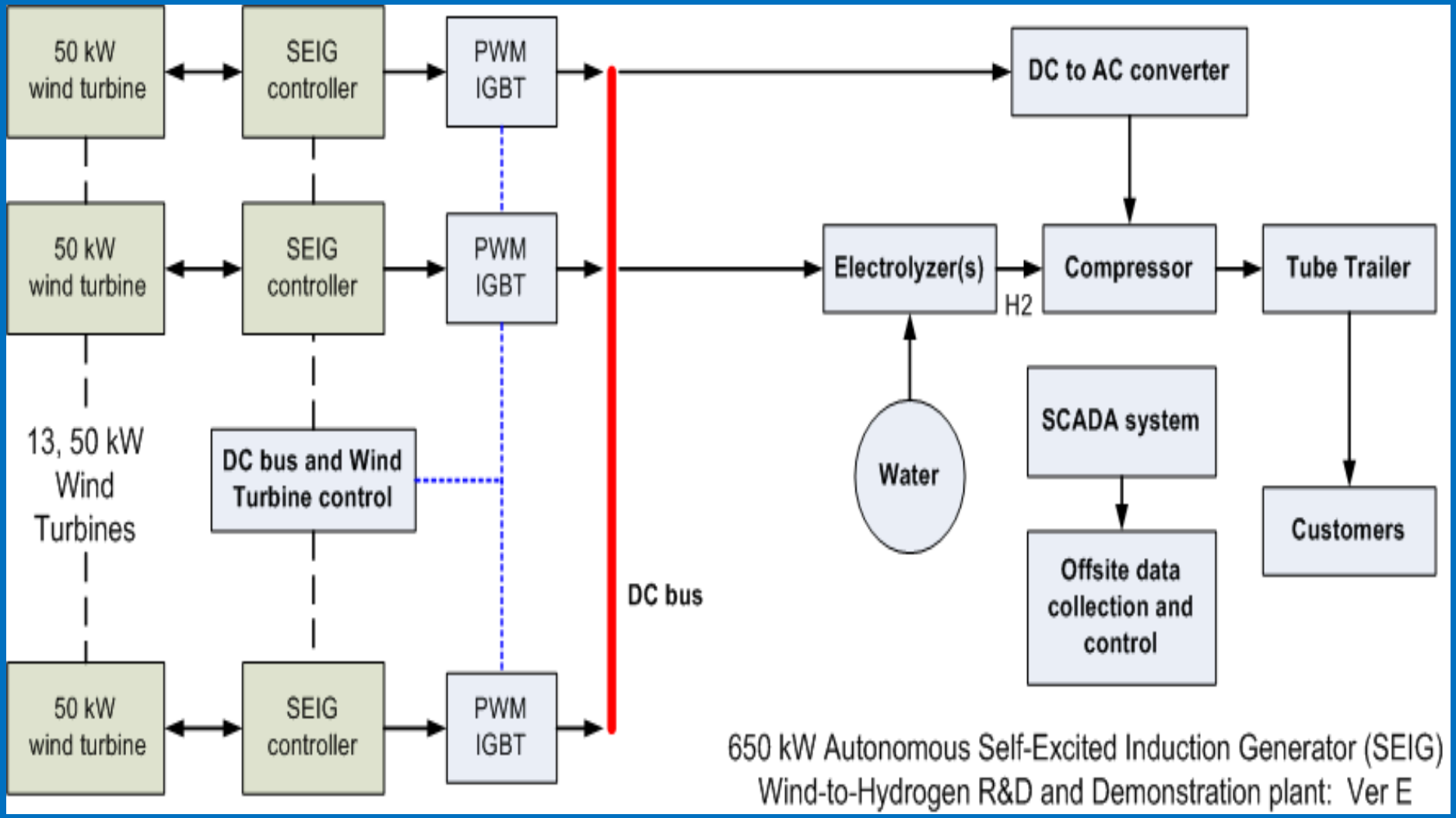
SIP

- **Liquid Hydrogen (LH2)**
  Kawasaki
- **Ammonia (NH_3)**
  Sumitomo
- **Organic Hydride (MCH)**
  Chiyoda

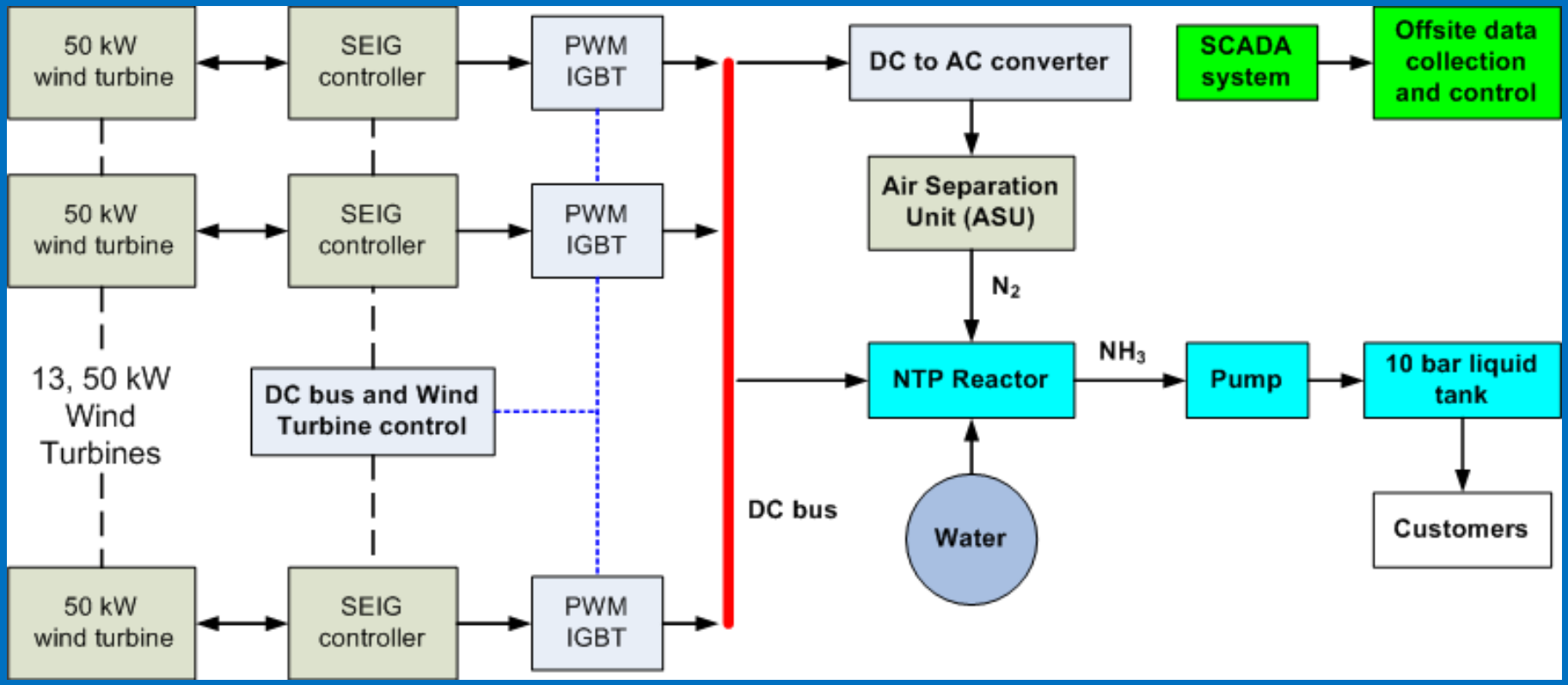
Proton Ventures BV, Netherlands

www.protonventures.com

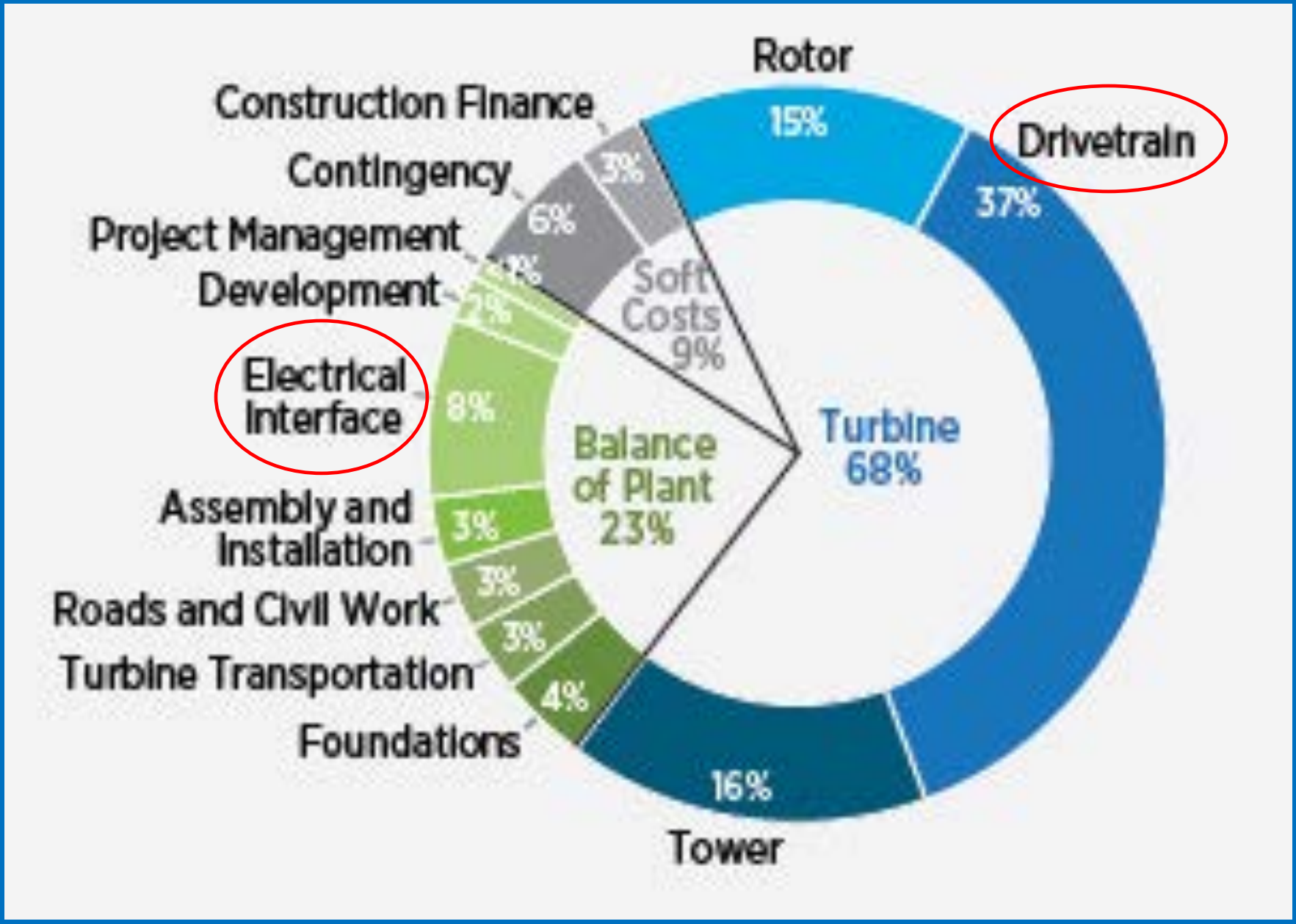
Floating Offshore
Deep water, multi - MW



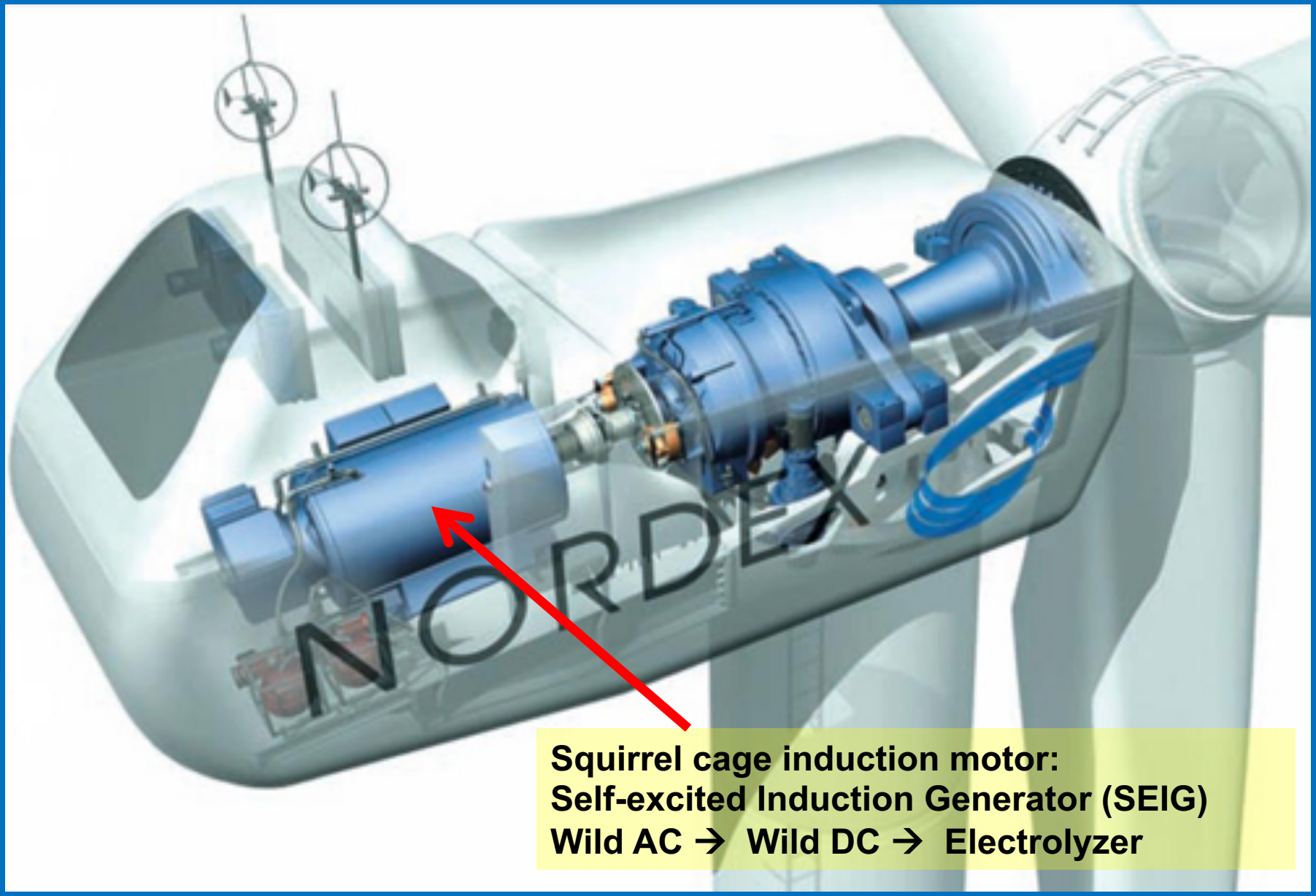
Reduce Hydrogen cost
Off - Grid
Self-Excited Induction Generator (SEIG)



Off - Grid
Anhydrous Ammonia (NH3)
Fuel production

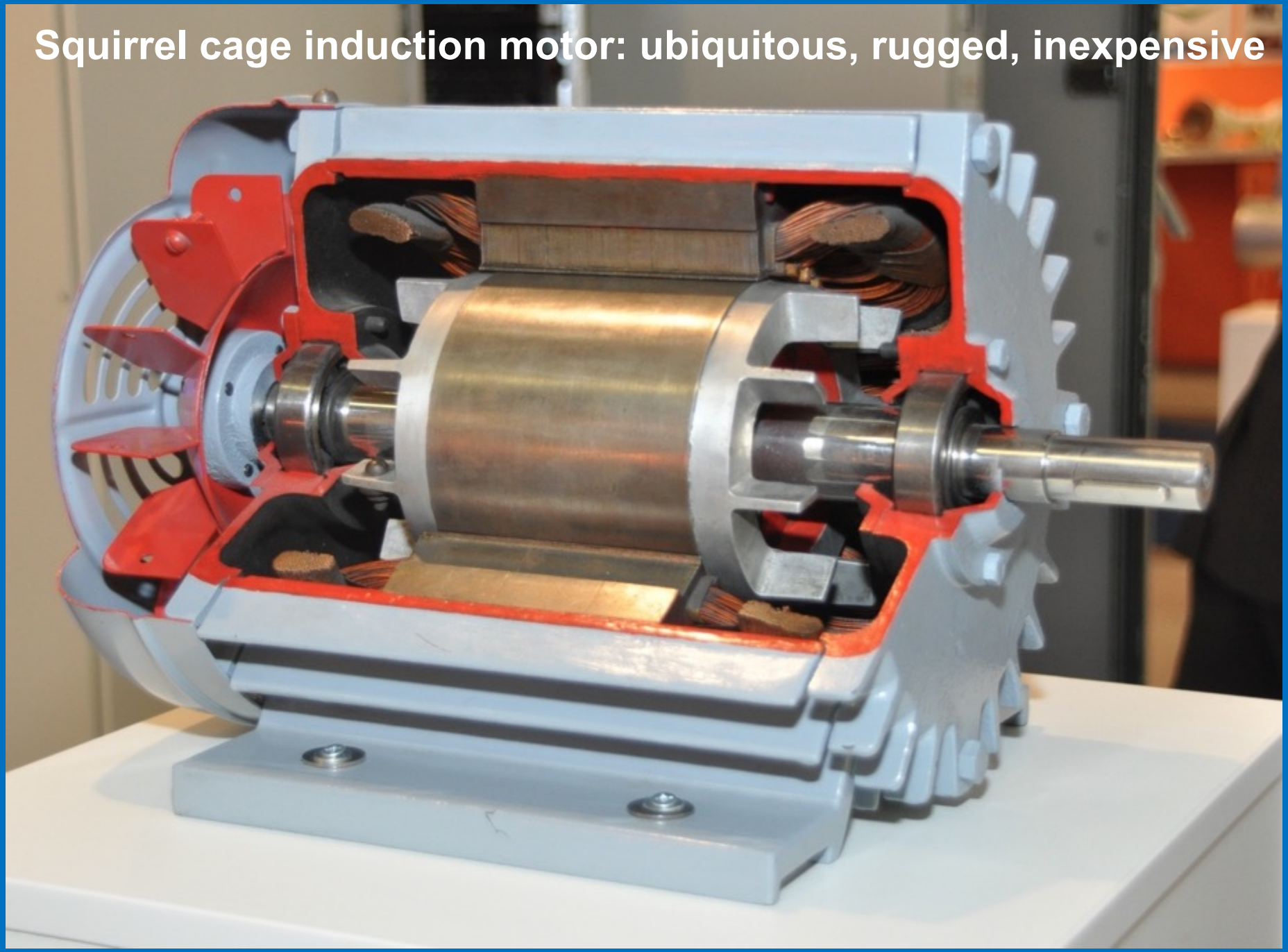


Installed CAPEX: land-based, utility-scale

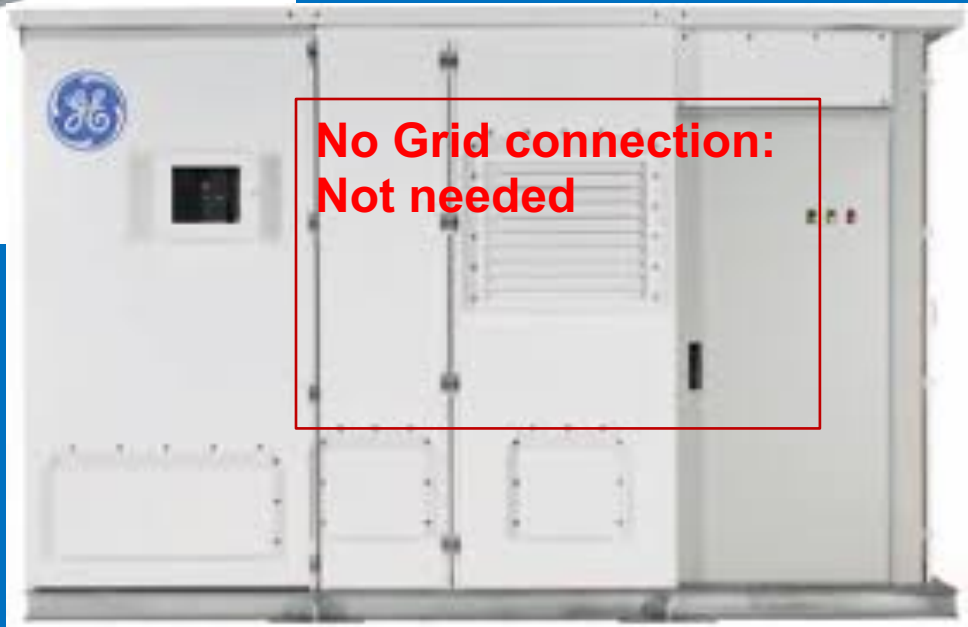


Dedicated Hydrogen Production: No Grid Connection

Squirrel cage induction motor: ubiquitous, rugged, inexpensive



Grid-quality AC power electronics



No Grid connection:
Not needed

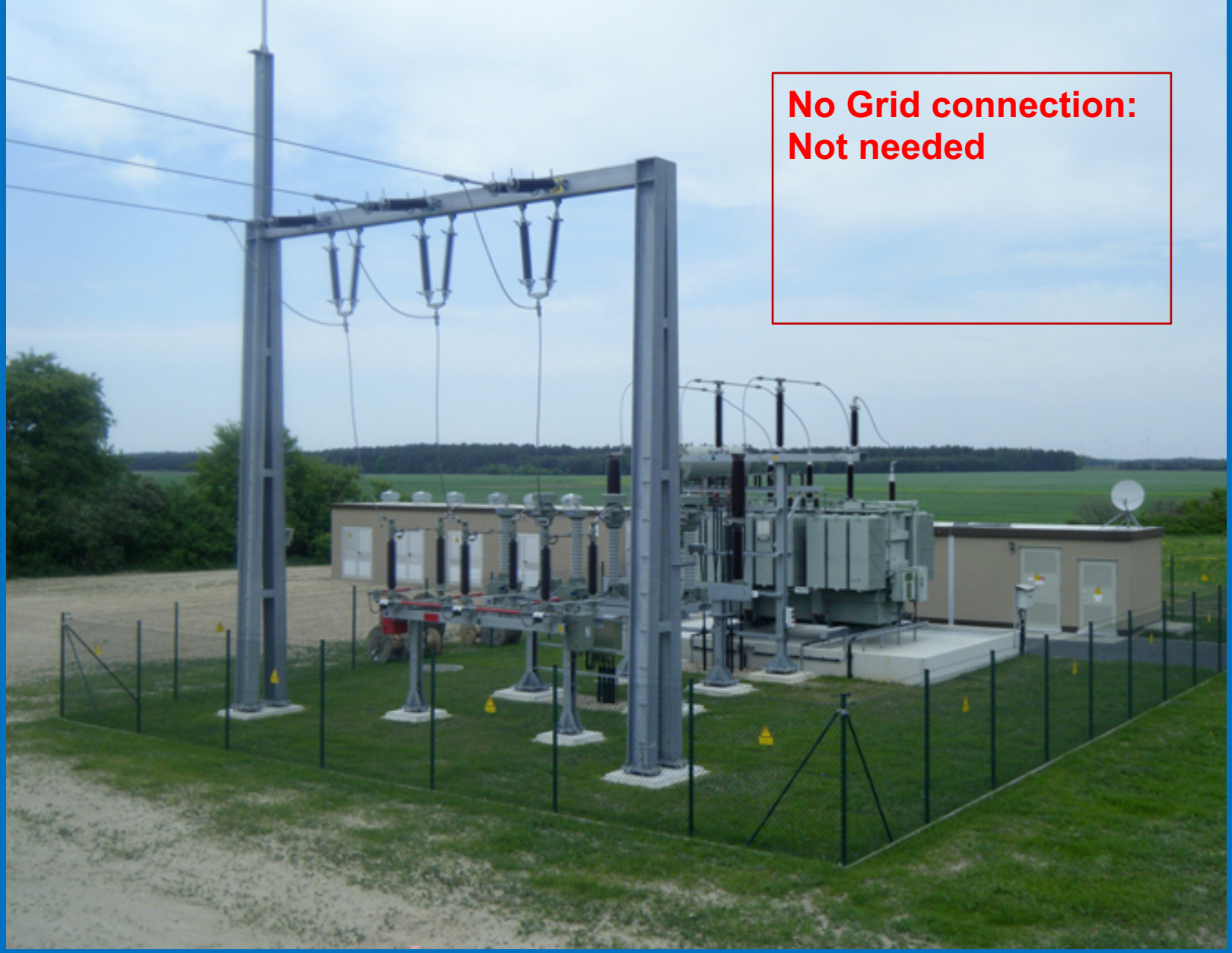
1 MW solar inverters

Grid-quality AC power electronics

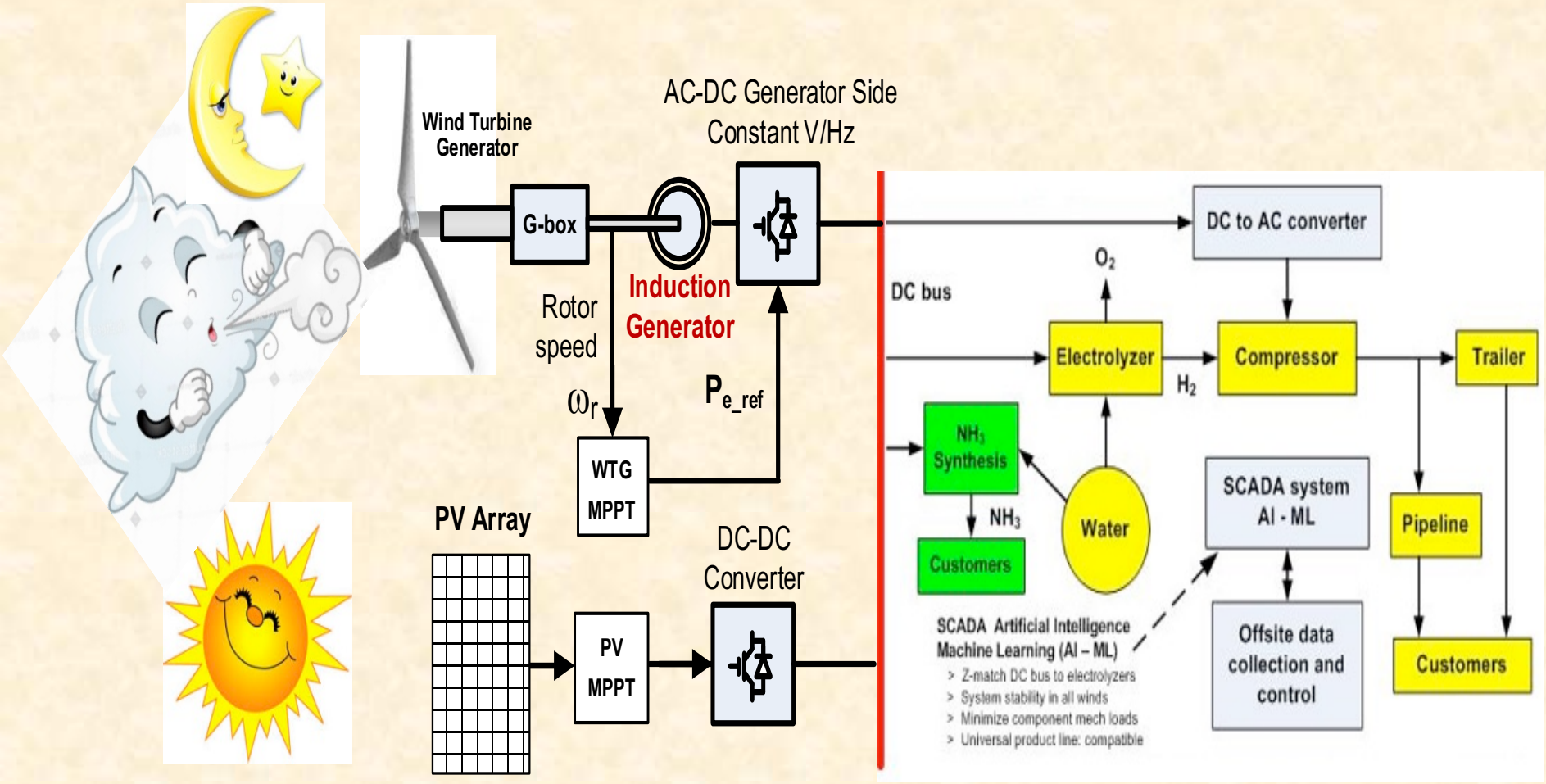
No Grid connection: Not needed

ABB ACS800 low voltage wind turbine converter

Transformer: high O&M cost



Substation + transmission feeder



Synergistic wind + PV → H_2, NH_3

- **Co-located, single plant**
- **No Grid connection; pipeline export**
- **Diurnal, seasonal**
- **Dedicated hydrogen, ammonia production**

TESLA 20 MW / 80 MWh battery
SCE Mira Loma Battery Storage Facility, Ontario, CA
Cost: undisclosed. @ $ 400 / kWh = $ 32 Million

TESLA 100 MW / 129 MWh battery
South Australia
“Cost me over $ 50 million” (if failed) -- Elon Musk
129 MWh @ $ 50 million = $ 390 / kWh capex

Global total 2017 = 103 GWh / year (Bloomberg)
Global total 2021 = 278 GWh / year

- **Hydrogen: 1 salt cavern @ $ 15-20 million = 90 GWh**
- **Ammonia: 1 liquid tank @ $ 15-20 million = 200 GWh**

Two Carbon-free Fuels:

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