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Dynamic Analysis of Casale Green Ammonia Synthesis Process

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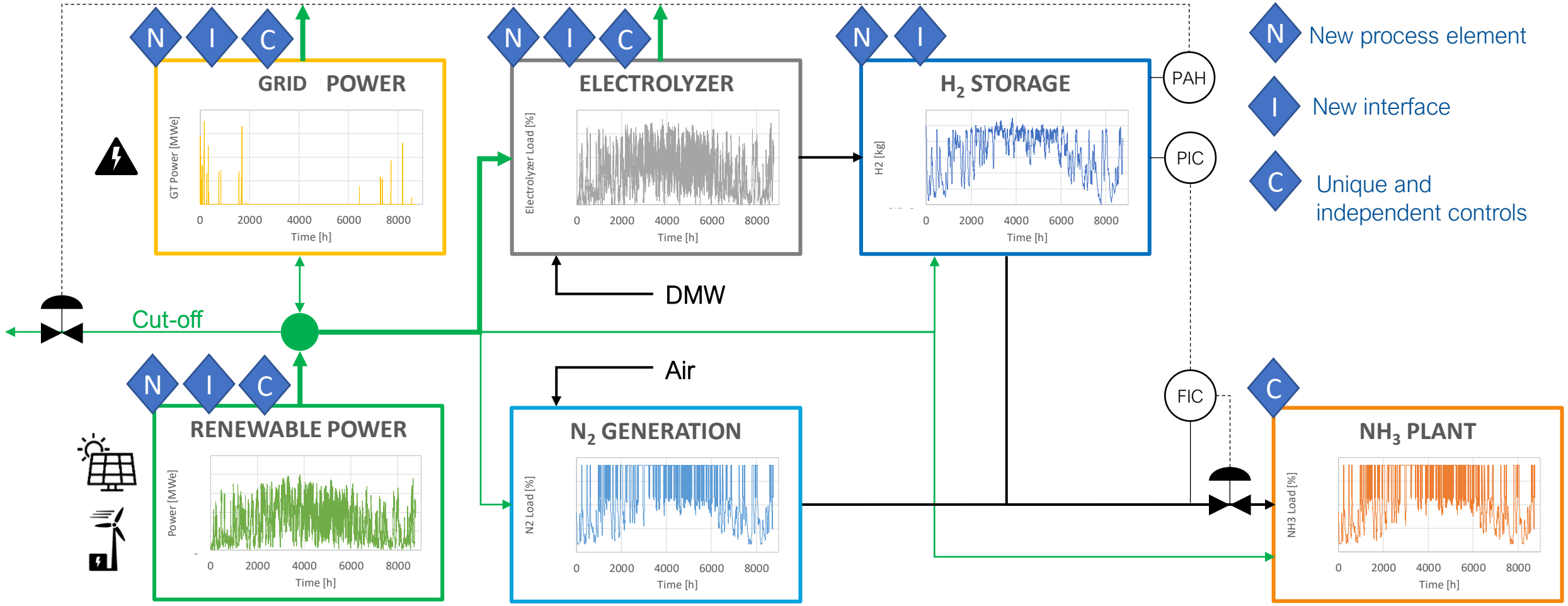
How Green Ammonia is different from a conventional ammonia process?

Energy source is renewable "kWh" that often fluctuates
Hydrogen comes from water electrolysis
Nitrogen is generated using renewable energy

Plant excludes upstream hydrogen generation from natural gas/coal
Hydrogen and nitrogen flows fluctuate, storage to balance variability
System configuration and process control is unique

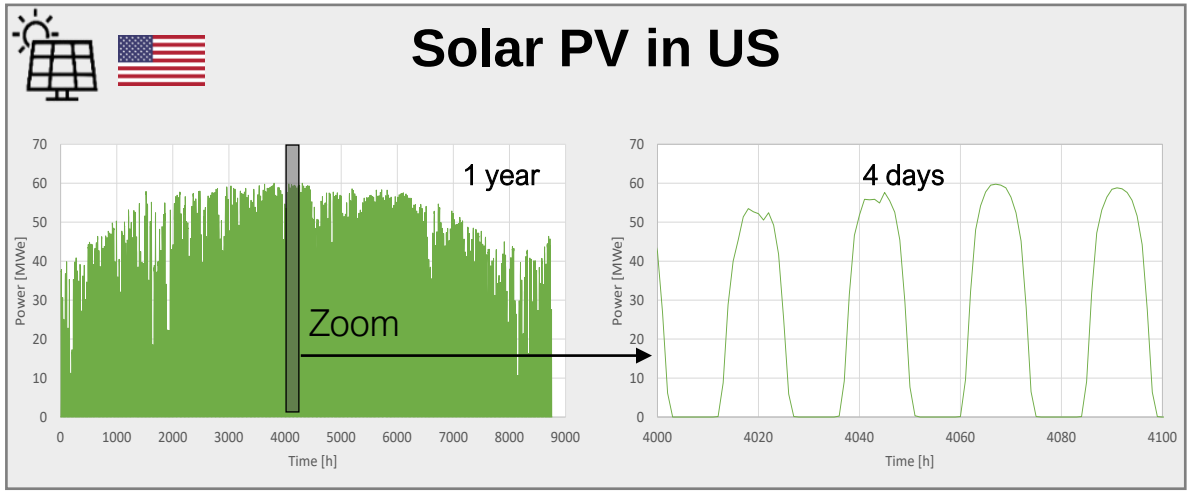
Valorisation of renewable energy & incentivised by emission credits
Chemical feedstock, green fertilizer, energy vector, low carbon fuel
Value chain in centralised and distributed production

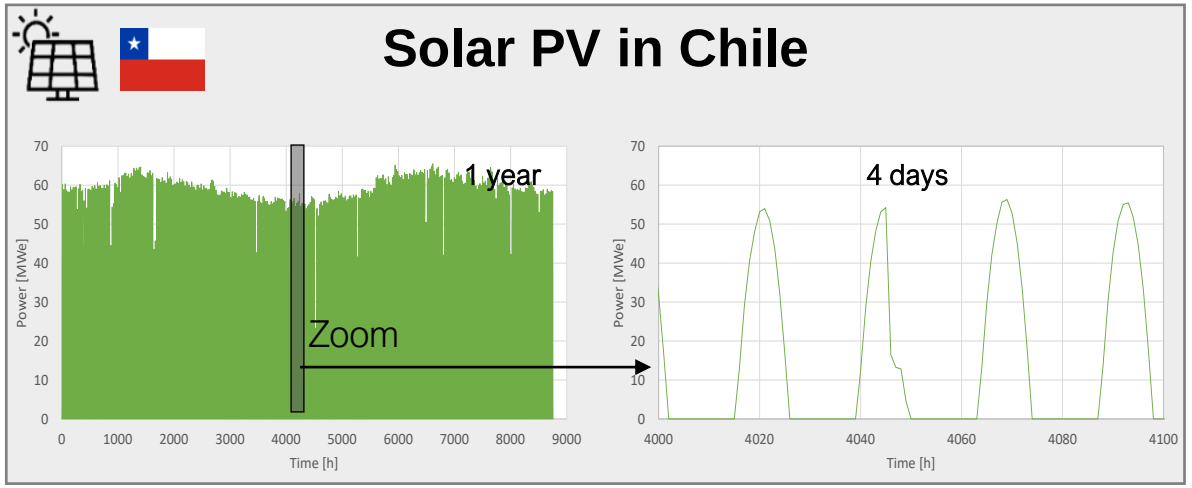
Plantwide control system embraces conventional elements & newcomers

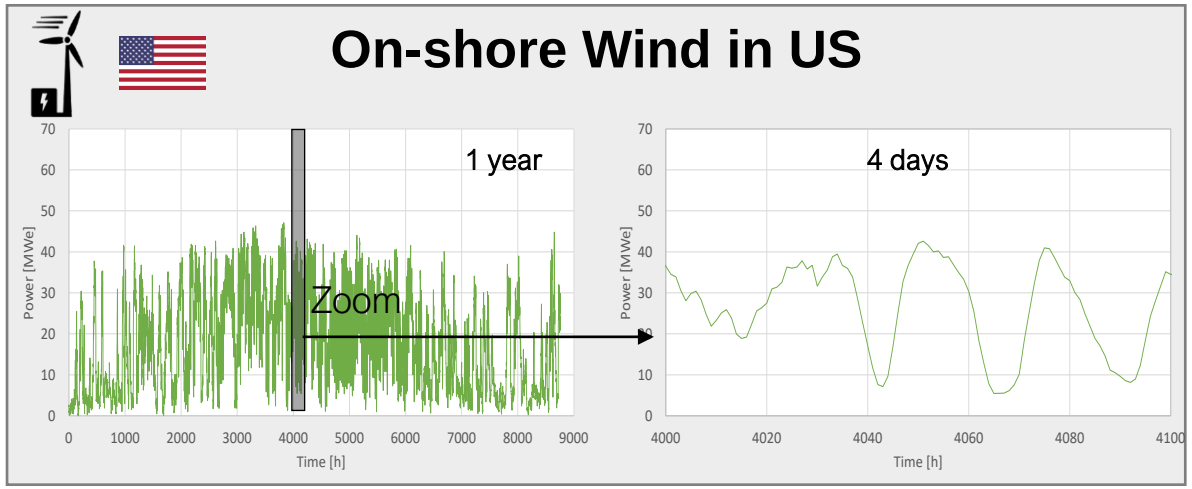


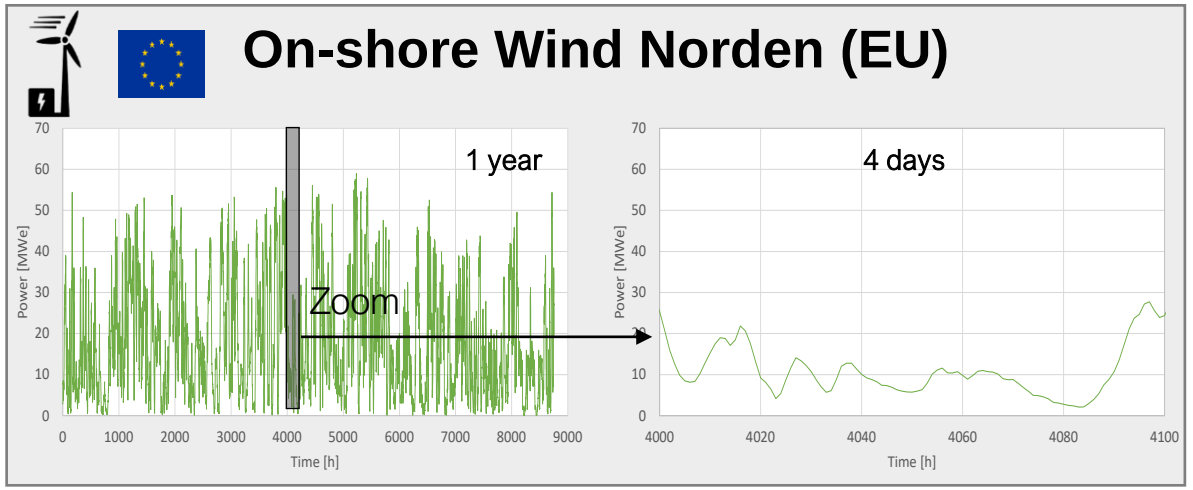
The intermittency of renewables demands the ammonia loop to be more flexible, it imposes operational discontinuities on the process, and it increases the Levelized Cost of Ammonia (LCOgA).

Casale employs real power profiles to capture their impact on green ammonia cost



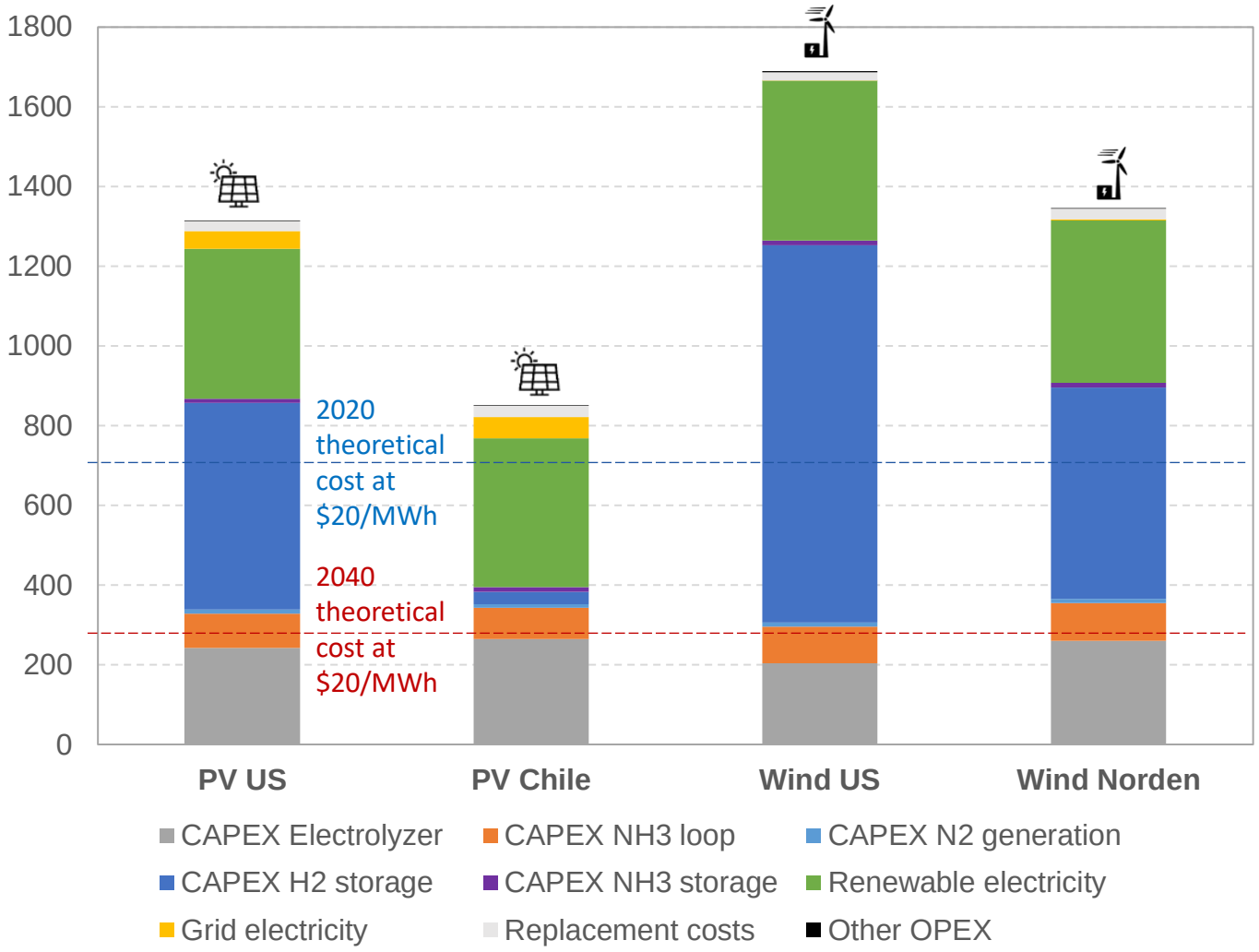






LCOgA ≈US$900-1650 per ton with the conventional «rigid» synthesis

Levelized Cost of Ammonia, $/MT for the different profiles



Results with Casale gNH_3 Optimizer

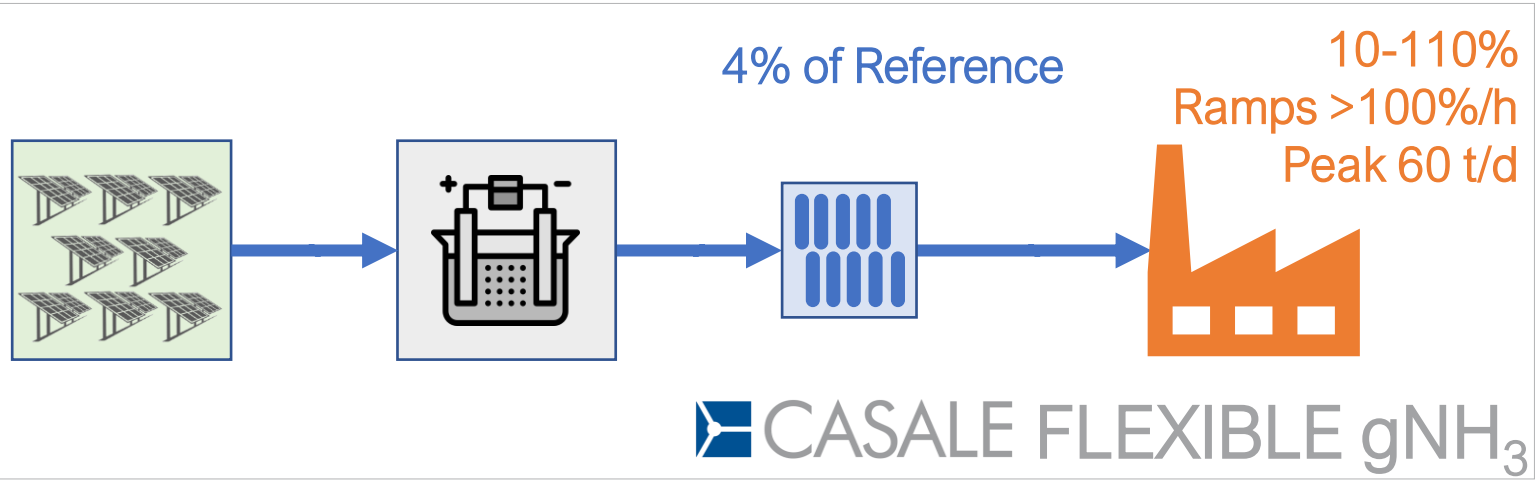
- All make 45MTD average NH_3
- H_2 buffer impacts 39-56% of LCOA, except PV Chile
- PV Chile favored by “moderately seasonal” power profile
- Optimal blend of grid & renewable electricity for PV

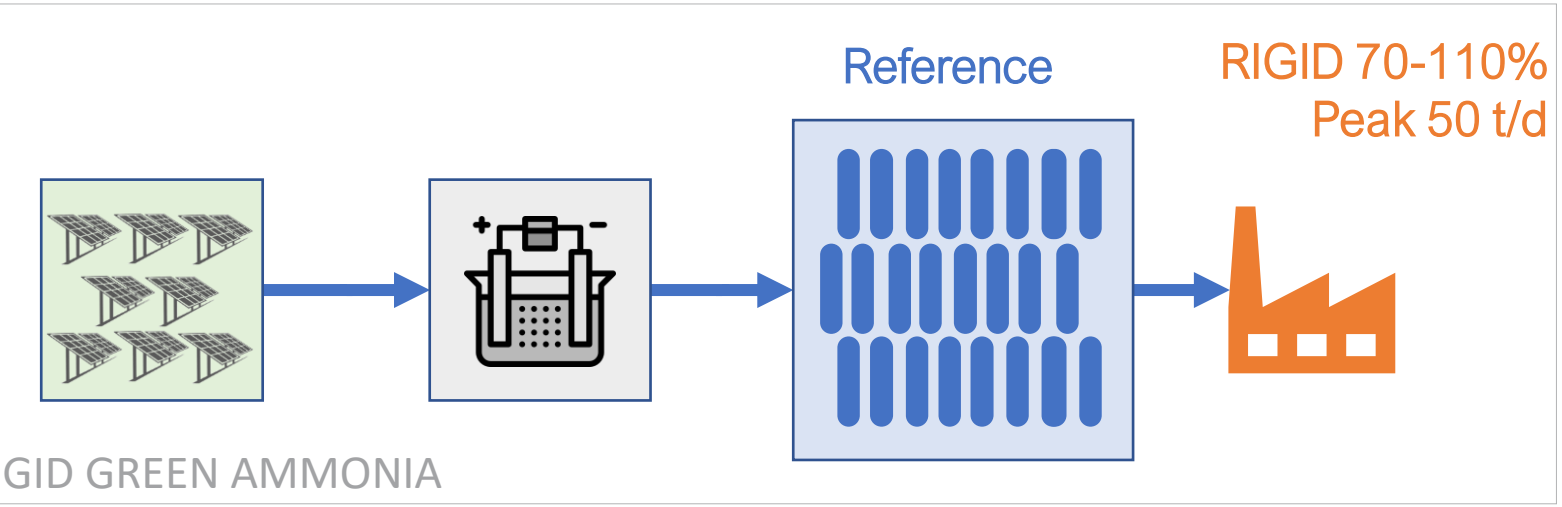
Key Assumptions

- Energy input 156GWh/y, 95% utilization
- Rigid synthesis 70-110% load change
- “Renewable” electricity 40$/MWh
  “Grid” electricity 100$/MWh

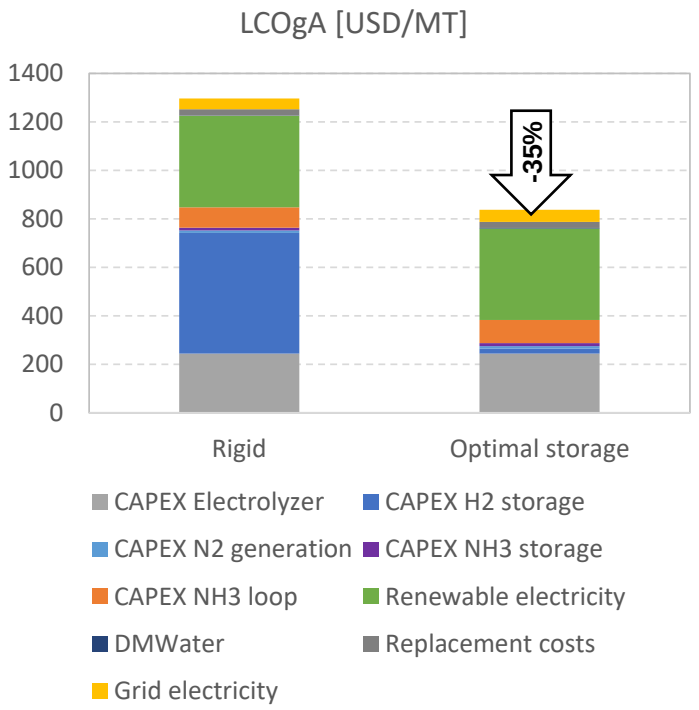
Casale Flexible Green Ammonia delivers 35% lower LCOgA from PV US than a «rigid» synthesis

PV US | $N_2 + H_2$ Generation | H_2 Storage | gNH_3 Synloop





Benefits of Casale Flexible gNH_3



-421 $/MT For Wind Norden
-40 $/MT For PV Chile
"No storage" results in 40-95$/t higher LCOgA for PV & Wind US

How Casale Flexible Green Ammonia tackles key challenges of fluctuating profiles

Challenges

1. System flexibility needed to cope with fluctuation of renewables
2. Plant suffers from operational discontinuities of power: e.g. reactor shutoff, overpressure
3. Negative impact of fluctuations on LCOA
4. Site specific profiles impacting differently on gNH_3 concept
5. Novel nexus of ammonia synthesis to input electric power via H_2 &N_2 generation & storage

CASALE *Focus*

1. Adopt **AmoMax™-Casale** catalyst to new synthesis conditions and minimise poisoning
2. Own **Casale Dynamic model** of gNH_3 process to assess impact of fluctuations
3. **gNH_3 Optimizer**: lowest Levelized Cost of Green Ammonia by Casale gNH_3 plant
4. Analysis and Optimization of **Real, Project Specific Input Profiles**
5. Casale Embracing **the Full Scope** from Power input to Ammonia Storage

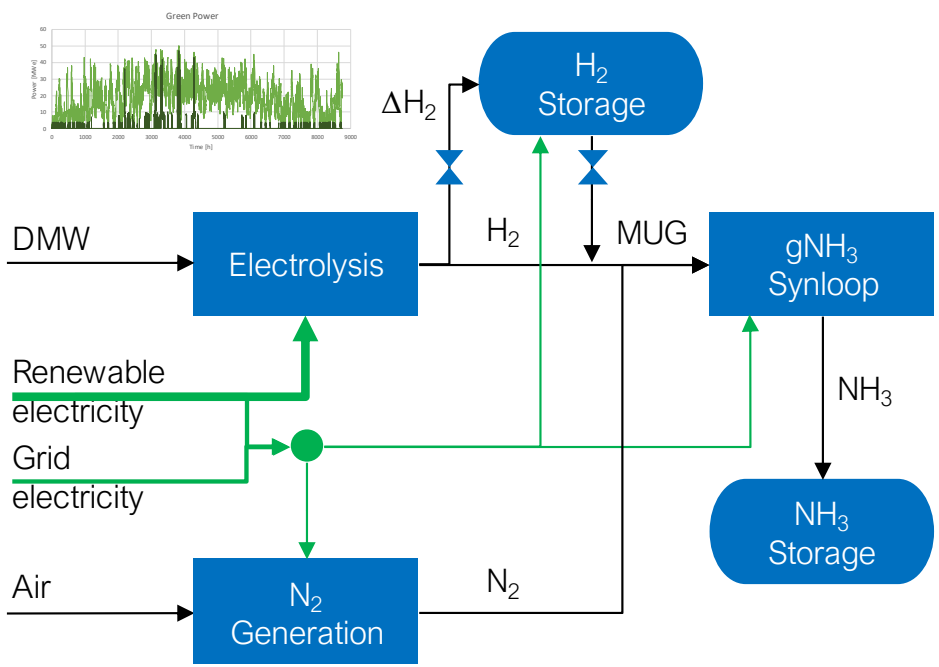
Deep understanding of dynamics is a stepping stone of Casale's Flexible Green Ammonia

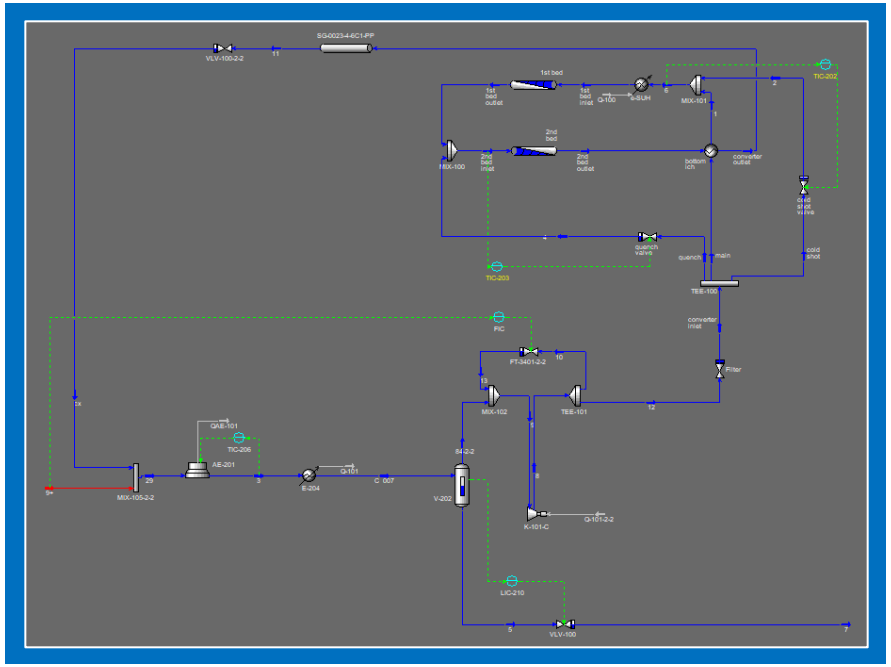
gNH_3 Optimizer

- Optimal component pre-sizing and energy utilization, to the target LCOgA
- Based on actual power profiles
- Leverage Casale design features of 10-110% load flexibility with > 100%/h load change

gNH_3 Dynamic Model

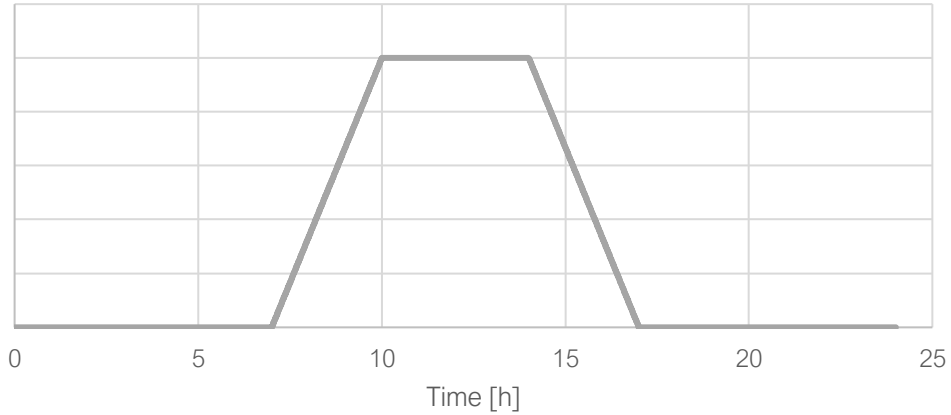
- Dynamic process model of the plant run in scenarios from real fluctuations of power profile
- <1 sec resolution, 1 day horizon with focus on e.g. reactor shut-off, over-pressurization
- Design verification for techno-economic targets



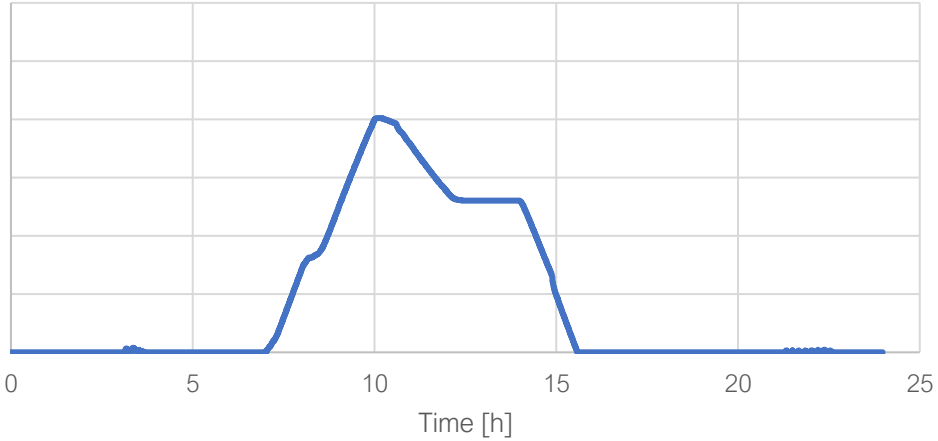


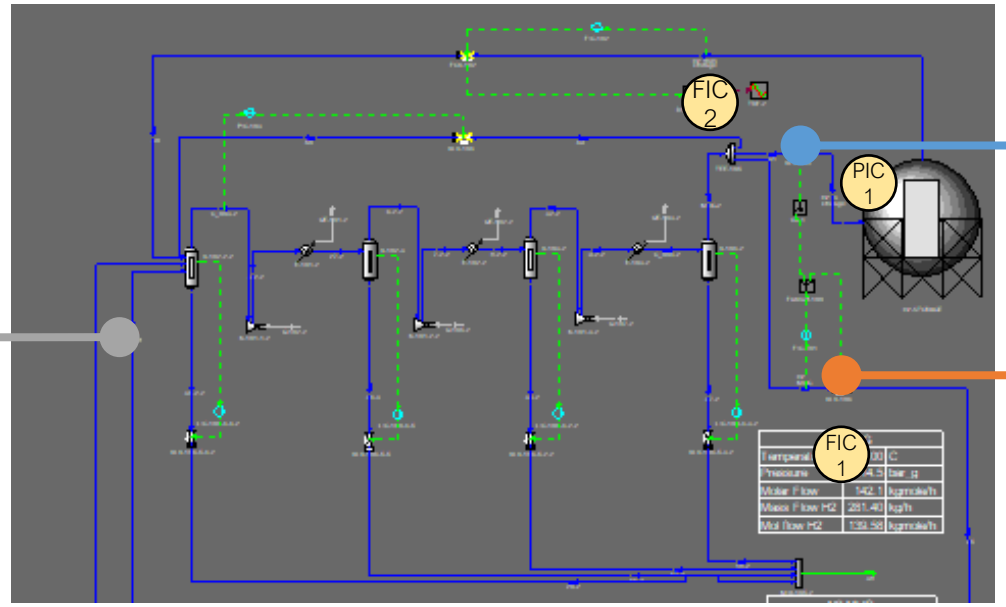
Dynamic Modeling of Casale H_2 + N_2 section under exemplary load changing ramp +/-50%/h confirms storage filling pressure and H_2 flows of Casale flexible gNH_3 control method

Flow Rate of H_2 from electrolysis

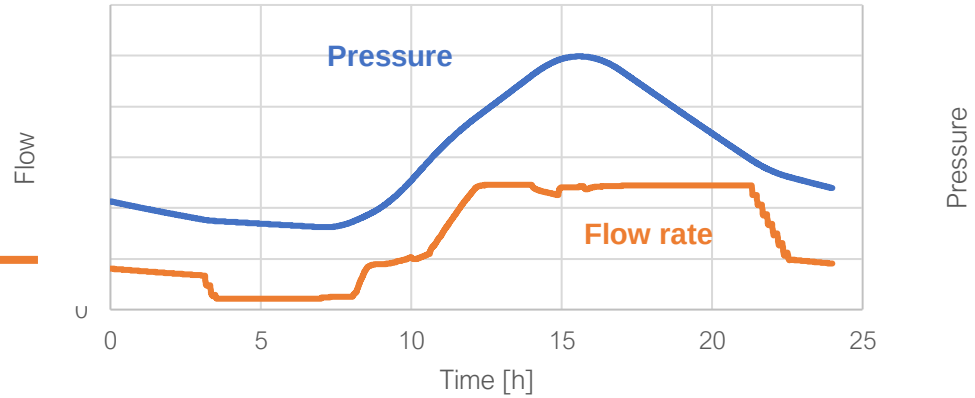


Flow Rate of H_2 to Storage





Flow Rate of H_2 to Synloop & Storage pressure



Journey of Further Product Refinement and Process Improvement

gNH3 optimizer + A-family

Casale Flexible Green Ammonia available in scales from 3-6000 tonnes per day

- Leveraging experience of proven designs of A60 A600 A6000 and flexibility needed by green ammonia
- Superior controls and loop flexibility enables Casale to offer a green product line - newbuilds & retrofits
- Achieving lowest ammonia cost is where we engage with specific customer needs
- Serving customer with full or specific plant scope

Durable AmoMax™

Continuous Development Effort to further maximise Casale Flexible Green Ammonia

- ARPA-E REFUEL and the REFUEL+IT pilot projects with RTI to further excel green ammonia technology
- Ongoing Casale's-Clariant efforts to maximize the use of AmoMax™-Casale iron based catalyst for dynamic conditions of green ammonia
- … and others.

Casale Flexible Green Ammonia delivers the lowest LCOgA from fluctuating profile

Dynamic behaviour of the plant is a key enabler for deployment of Green Ammonia. Loop flexibility contributes in Green Ammonia cost.

Casale flexible gNH_3 combines control and process technology to convert real fluctuating power profiles into ammonia which is validated by Casale dynamic tools

Casale gNH_3 Optimiser and gNH_3 Dynamic Model serve customers with a tailored plant, resulting in lowest LCOgA embracing the full scope operating on real profiles.

Flexible gNH_3 technology is the backbone of a green line of products of Casale, using proven solutions and AmoMax™-Casale catalyst. Continuously refined to excel the green ammonia technology.

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