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Techno-Economic Analysis of Solar-Thermal Ammonia Production

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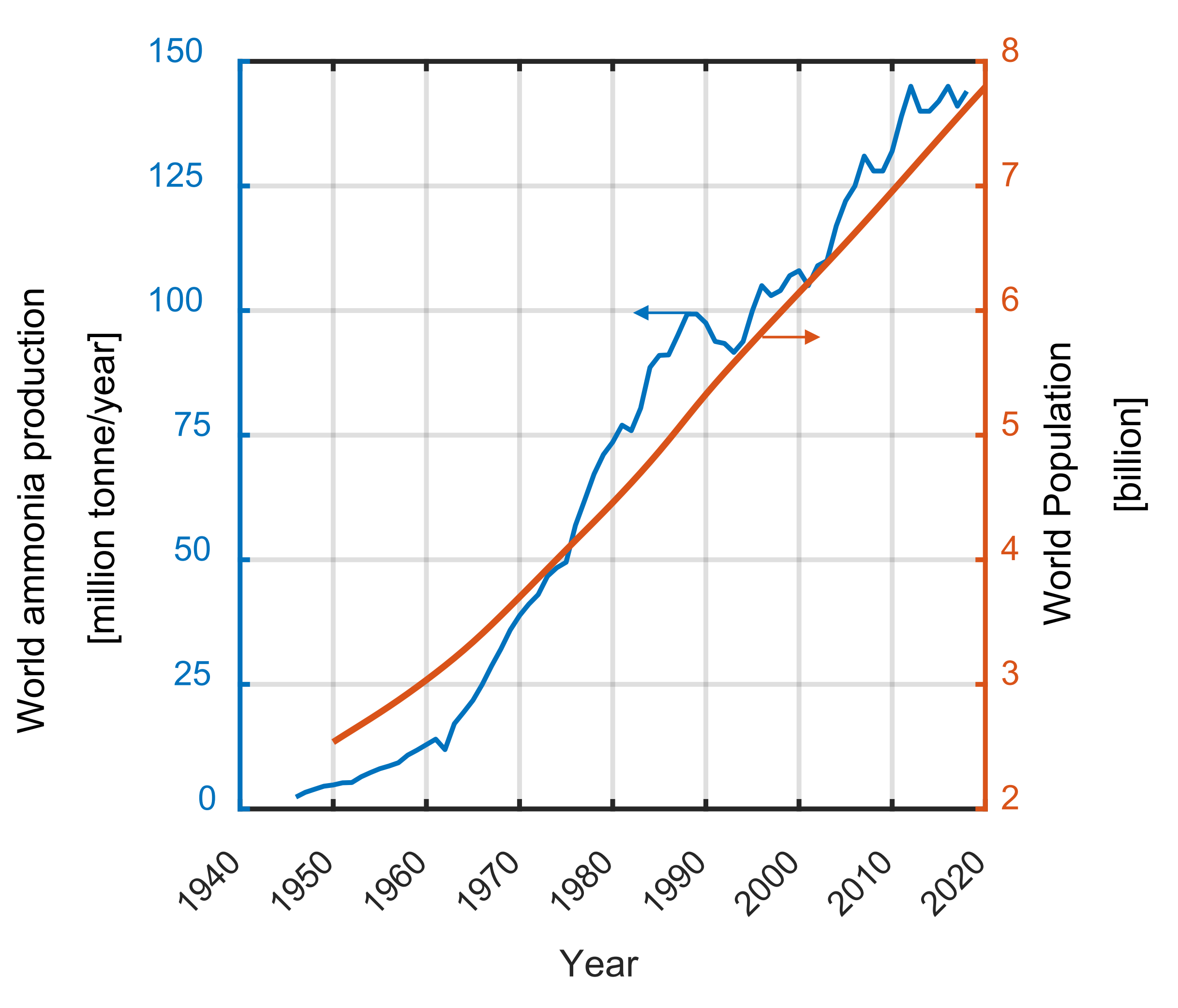
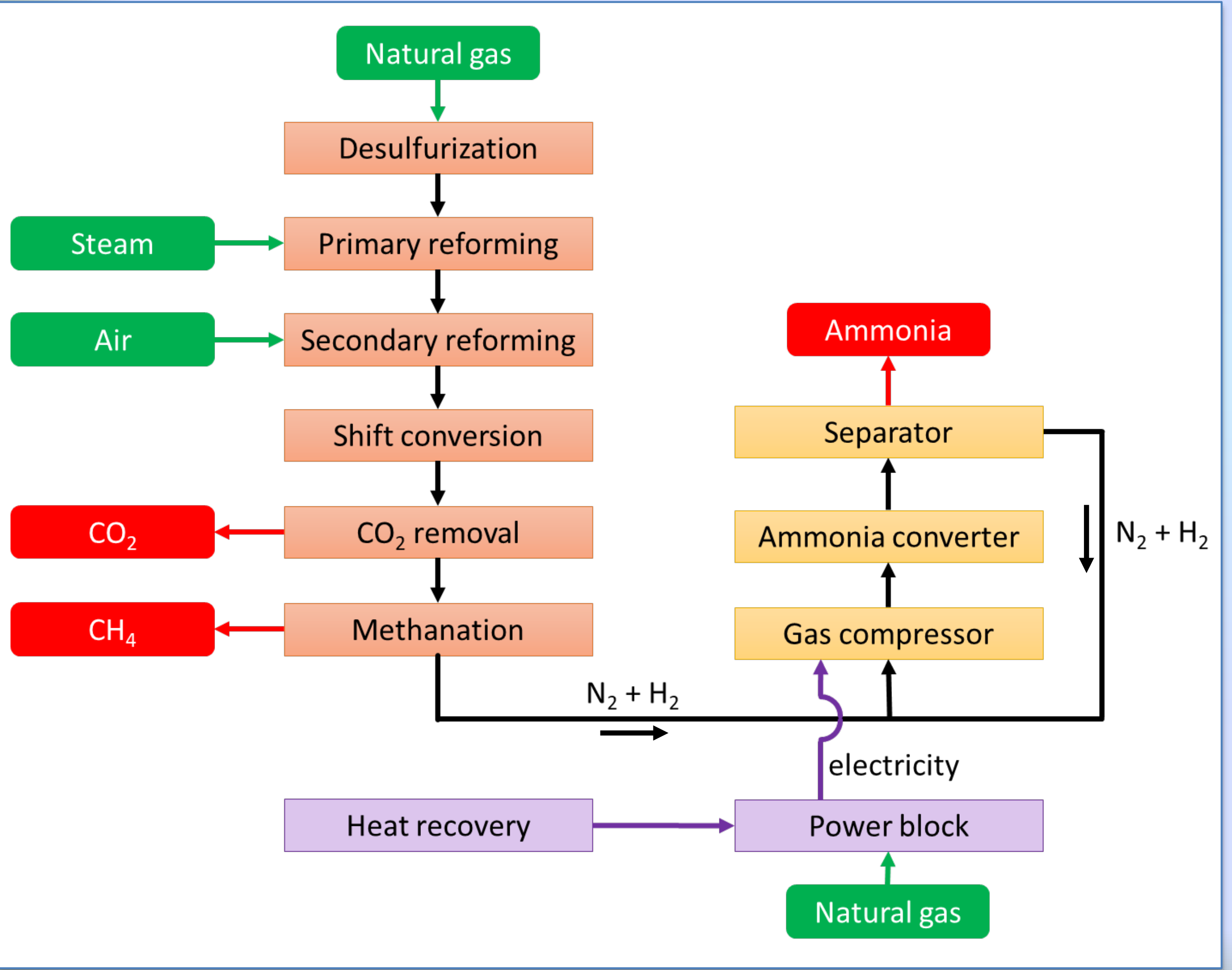
Ammonia Production



- Ammonia is the second most produced industrial chemical in the world
- About 80% of the nitrogen in our body comes from synthetic nitrogen fertilizer
- Responsible for over **1.4%** of global CO_2 emissions

Data from:
[1] U.S. Geological Survey, National Minerals Information Center
[2] United Nations, Department of Economic and Social Affairs

The Haber-Bosch Process



Ammonia synthesis:

$$\frac{3}{2}\,\mathrm{H_2} + \frac{1}{2}\mathrm{N_2} \rightarrow \mathrm{NH_3}$$

Exothermic reaction: ΔH_{298K}=-45 kJ/mol

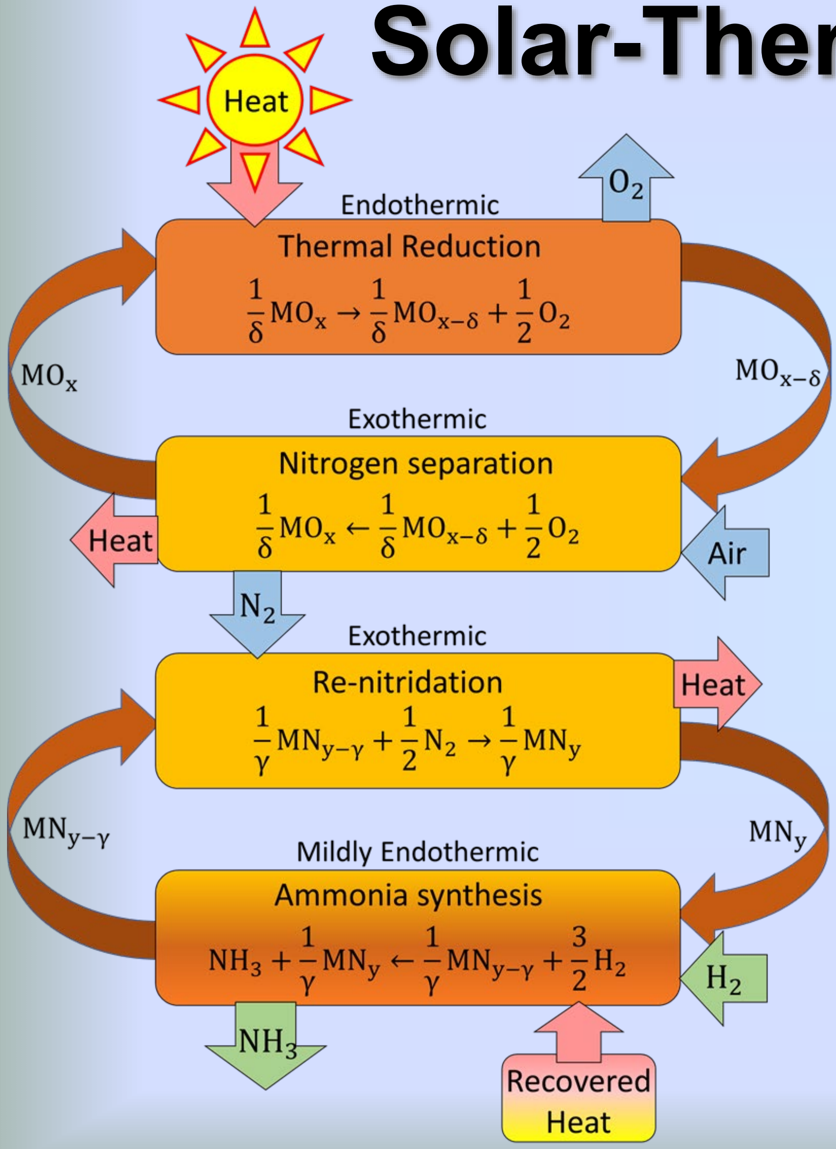
High pressure: 150-300 bar

Moderately elevated temperature: 350-500 °C

Low conversion: ~10-20%

- H_2 is produced via steam methane reforming
- N_2 is produced via methane combustion in air

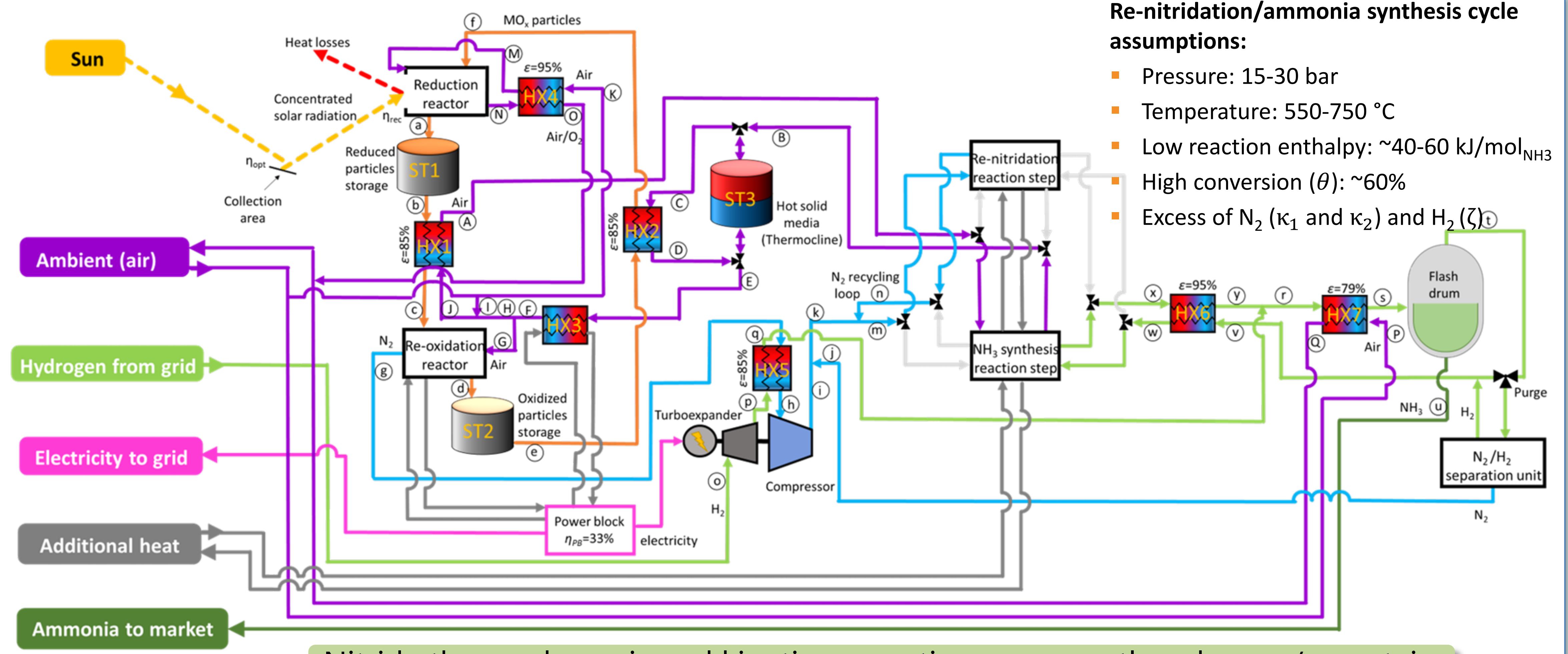
Solar-Thermal Ammonia Production



Goal: CO_2-neutral ammonia production with concentrated solar technology

- **First stage:** nitrogen production from air using concentrated solar heat
- **Second stage:** ammonia production targeting pressures lower than HB by an order of magnitude

System Description: Assumptions



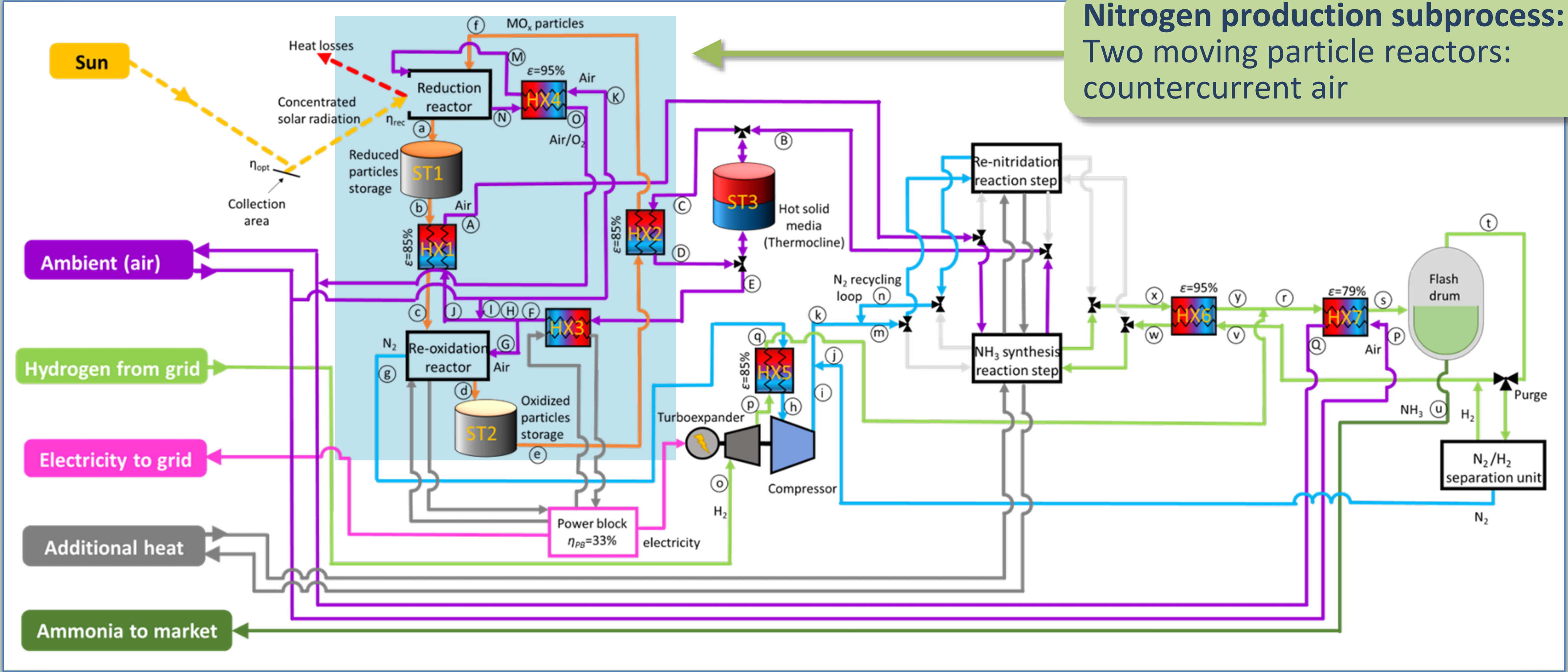
Re-nitridation/ammonia synthesis cycle assumptions:

- Pressure: 15-30 bar
- Temperature: 550-750 °C
- Low reaction enthalpy: ~40-60 kJ/mol$_{NH3}$
- High conversion (θ): ~60%
- Excess of N_2 (κ_1 and κ_2) and H_2 (ζ)

Nitride thermodynamic and kinetic properties are currently unknown/uncertain

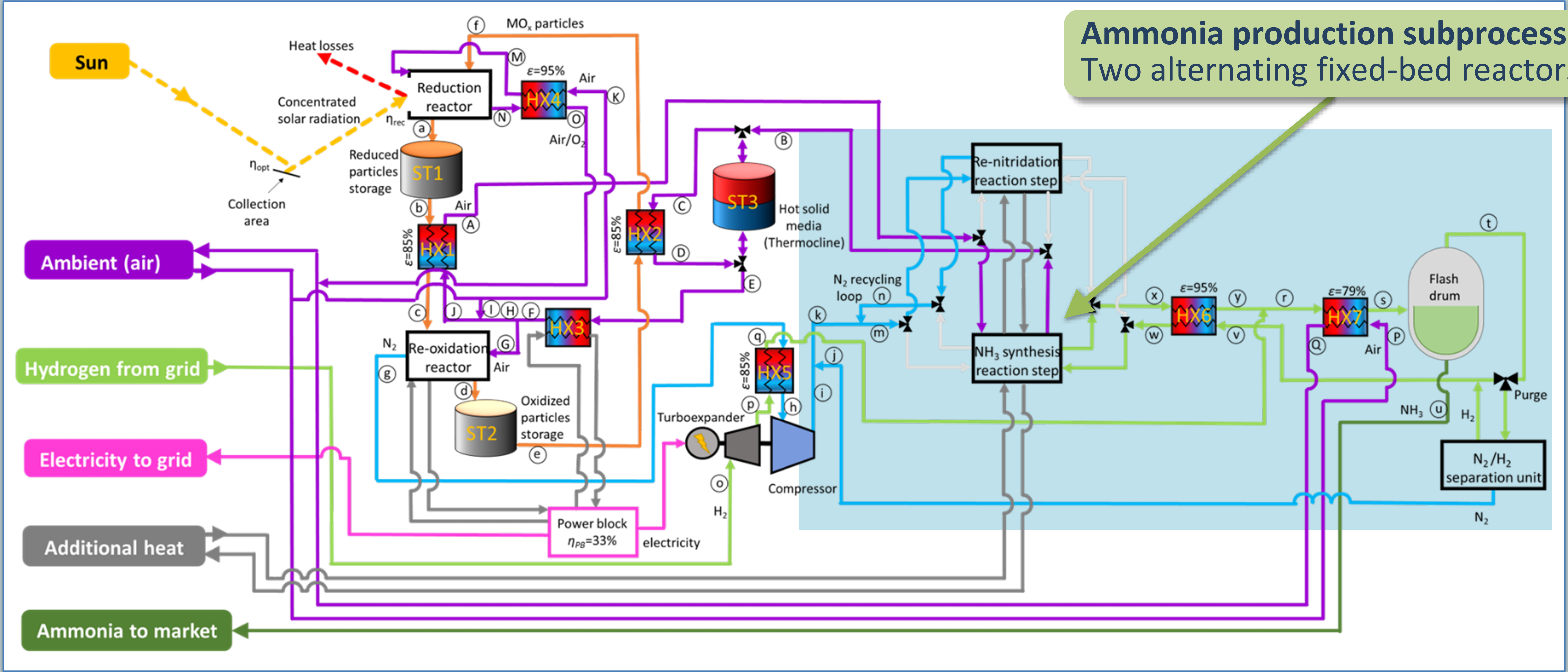
System Description: Thermal Reduction and Air Separation

Nitrogen production subprocess:
Two moving particle reactors: countercurrent air

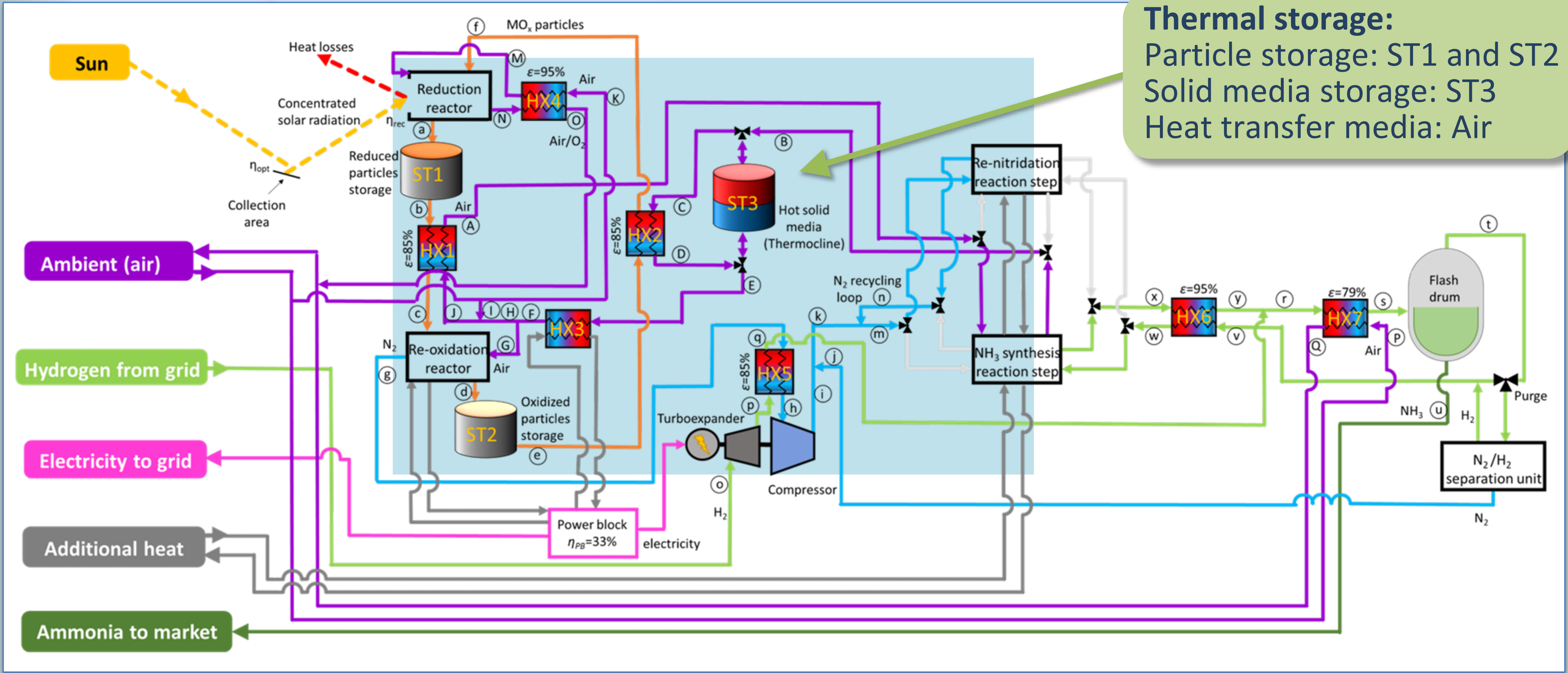


System Description: Ammonia Synthesis and Re-nitridation

Ammonia production subprocess:
Two alternating fixed-bed reactors

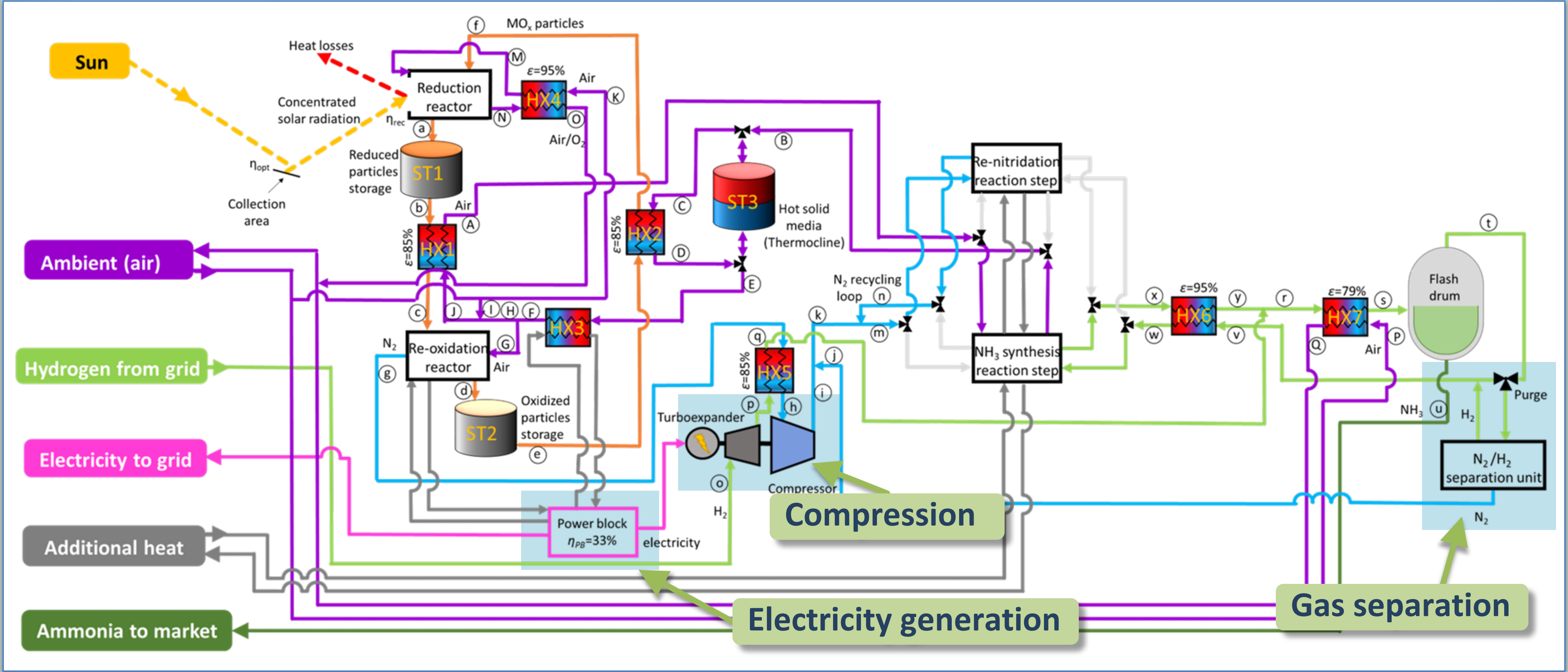


System Description: Thermal storage

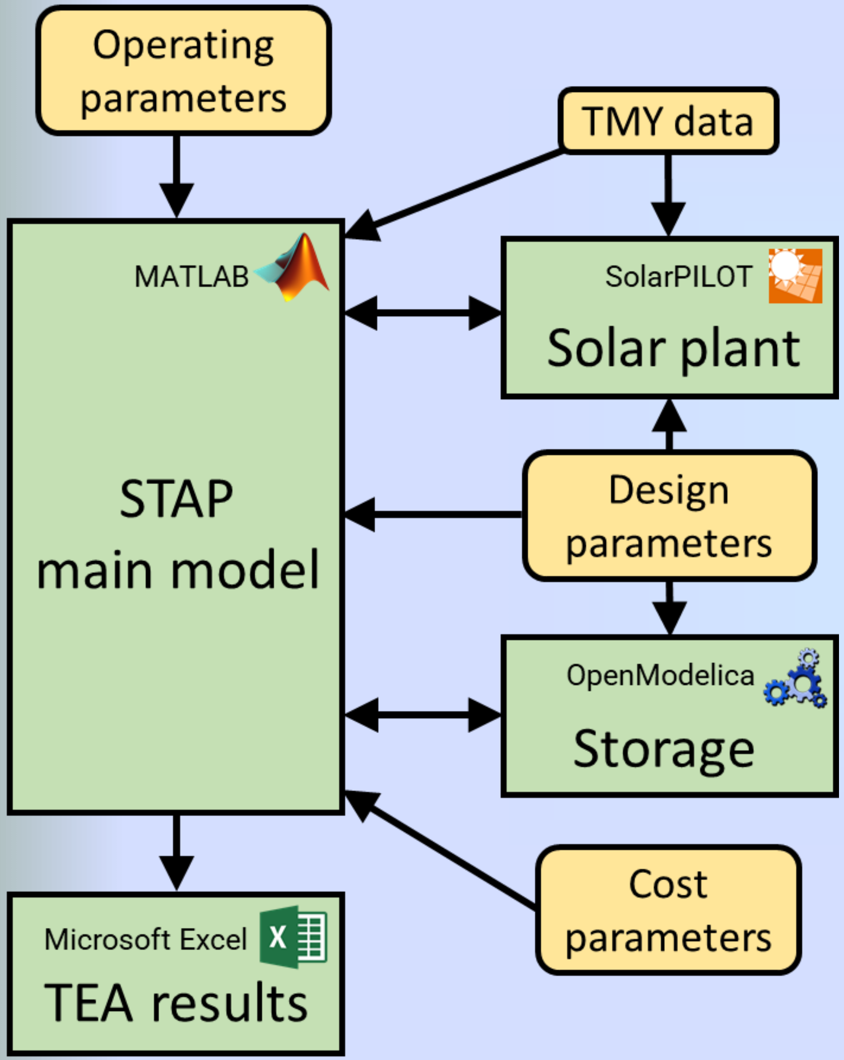


Thermal storage:
Particle storage: ST1 and ST2
Solid media storage: ST3
Heat transfer media: Air

System Description: Balance of plant



Model design



Integration completed in a single Matlab script that communicates with other support software to perform the simulation.

- **SolarPILOT:** Design and simulation of solar field + receiver optical efficiency
- **Matlab:** System design, annual simulation, TEA, data processing and modeling integration
- **OpenModelica:** Fast annual simulation of the dynamic model (storage)
- **Microsoft Excel:** TEA result display

Cost parameters

Key parameters

- 30 MW_{th} solar tower
- Three receivers
- Solar multiple 3
- 14 h storage
- Metal oxide: $SrFeO_3$
- N_2 purity: 10 Pa, T_{OX}= 500 °C
- Metal nitride: Co_3Mo_3N
- T_{AS}=T_{RN}=700 °C
- NH_3 yield: 60%
- RN/AS cycle time: 120 min

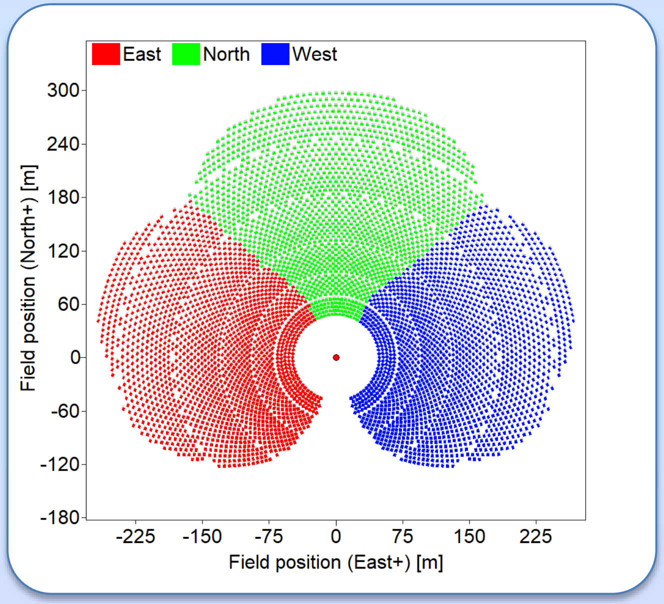


Table 1. Cost parameters

Parameter	Units	Value
Heliostat cost	\$/m²	75
Site preparation	\$/m²	10
Land cost	\$/m²	2.47
Power block	\$/kW_e	1000
Additional heat	\$/MWh	15
Electricity	\$/MWh	50
MOx particle loss	%/y	10
EPC and owner cost	%	11
Contingency	%	7
O&M	%/y	2
Real discount rate	%	7
Lifetime	y	30

Techno-economic analysis

Costs Calculation	Units	Value
Heliostat field	$	3,975,900.50
Tower	$	6,251,716.68
Receiver	$	1,009,800.00
OX reactor	$	336,600.00
Lift	$	259,740.16
Storage tanks ST1 & ST2	$	1,344,389.90
MO particles	$	3,551,288.54
Storage tank ST3 and material	$	834,750.51
Heat Exchangers	$	1,550,681.99
Turboexpander	$	283,220.00
Power Block	$	2,758,295.81
Separation NH3	$	107,307.00
Separation N2/H2	$	-
AS & RN Reactors	$	3,326,583.31
MN particles	$	91,336,698.62
Subtotal direct cost	**$**	**116,926,973.02**
Contingency	$	8,184,888.11
Total direct cost	**$**	**125,111,861.14**
Land cost	$	1,007,571.02
EPC and owner cost	$	13,762,304.72
Total indirect cost	**$**	**14,769,875.74**
Total CapEx	**$**	**139,881,736.88**
OpEx (fixed)	$/y	2,797,634.74
Particle loss	$/y	355,128.85
Additional heat	$/y	-
OpEx (variable)	$/y	355,128.85
Total OpEx	**$/y**	**3,507,892.45**
Total revenue	**$/y**	**474,058.12**
LCOA w/o H2	**$/tonne**	**213.11**

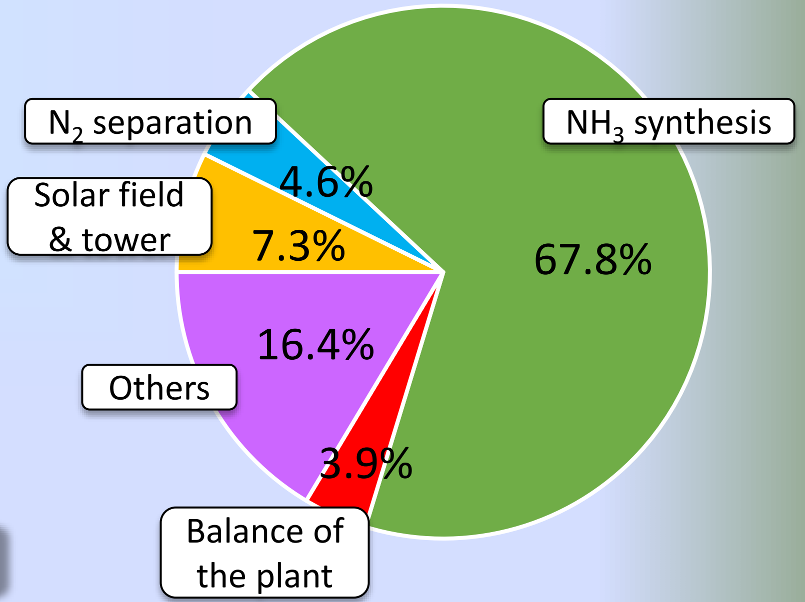
NH_3 yield and cycle time have a high impact on the total cost of the plant

The nitride cost is the most significant system expense, accounting for more than the 50% of the total CapEx

…but, it is also the most uncertain variable

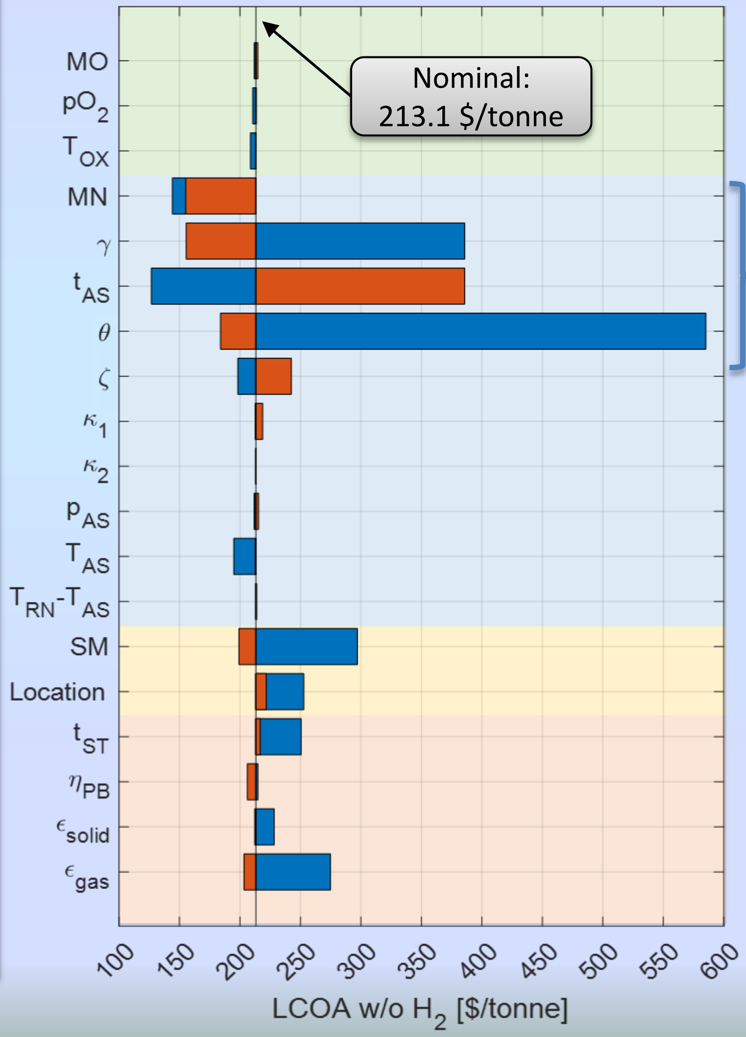
LCOA without including the H_2

Capital expenses distribution



Sensitivity analysis

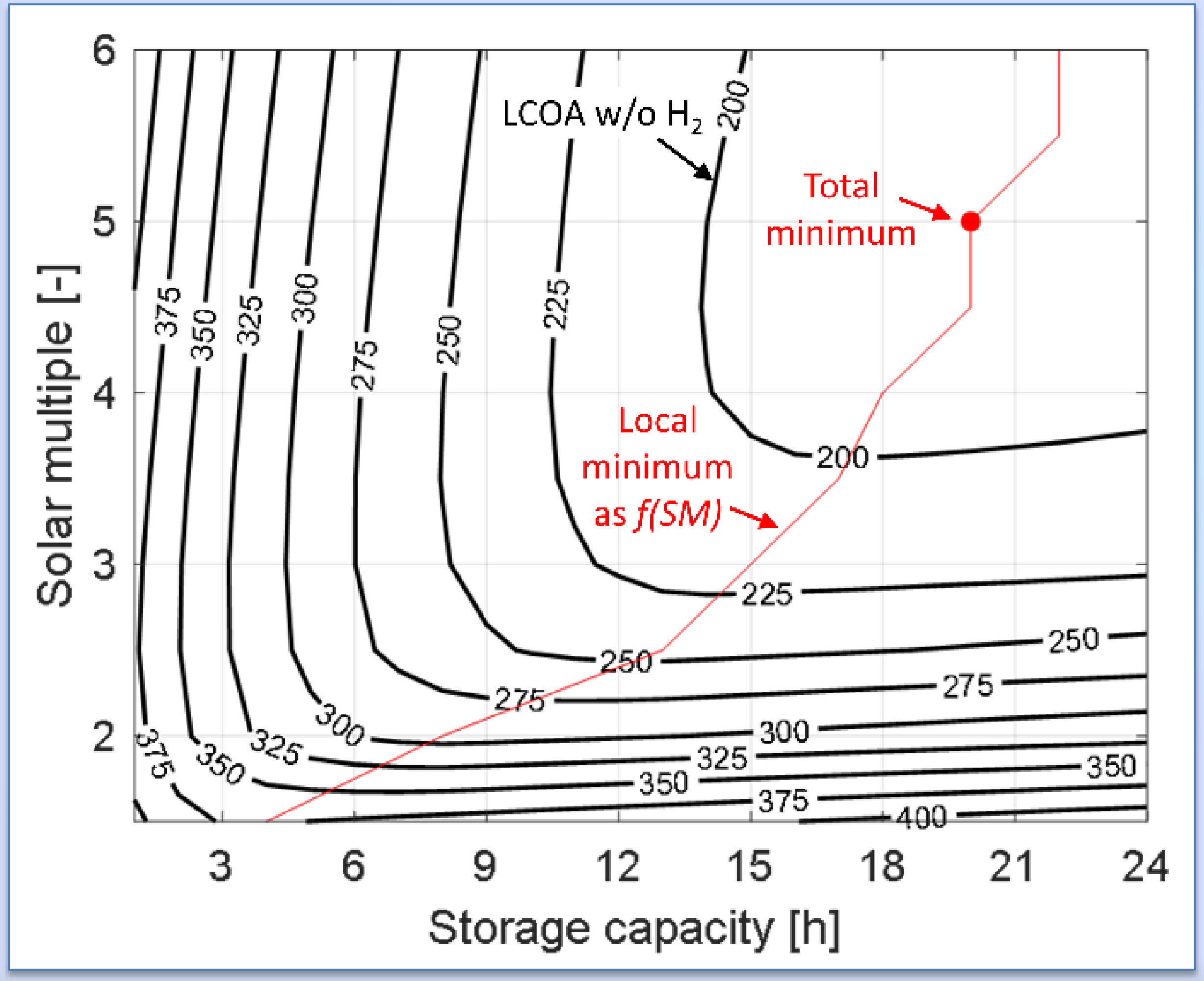
	Variable	Nominal	Range (low)	Range (high)
N_2 separation sub-system	MO	SF	LSF15	BSF15
	pO_2 [Pa]	10	1	100
	T_{OX} [°C]	500	450	600
NH_3 synthesis sub-system	MN	Co_3Mo_3N	Fe_3Mo_3N	Ni_2Mo_3N
	γ [-]	0.5	0.25	0.75
	t_{AS} [h]	2	1	4
	θ [%]	60	20	70
	ζ [-]	10	0	50
	$κ_1$ [-]	1	0	20
	$κ_2$ [-]	5	0	20
	p_{AS} [bar]	20	15	30
	T_{AS} [°C]	700	550	750
	T_{RN} -T_{AS} [°C]	0	0	150
Solar capture sub-system	SM [-]	3	2	4
	Location	Daggett CA	Tonopah NV	Tucson AZ
Auxiliary sub-system	t_{ST} [h]	14	8	24
	$η_{PB}$ [%]	33	25	65
	$ε_{solid}$ [%]	85	50	99
	$ε_{gas}$ [%]	95	50	99



Quantity of metal nitride and its price dominate the variability in LCOA

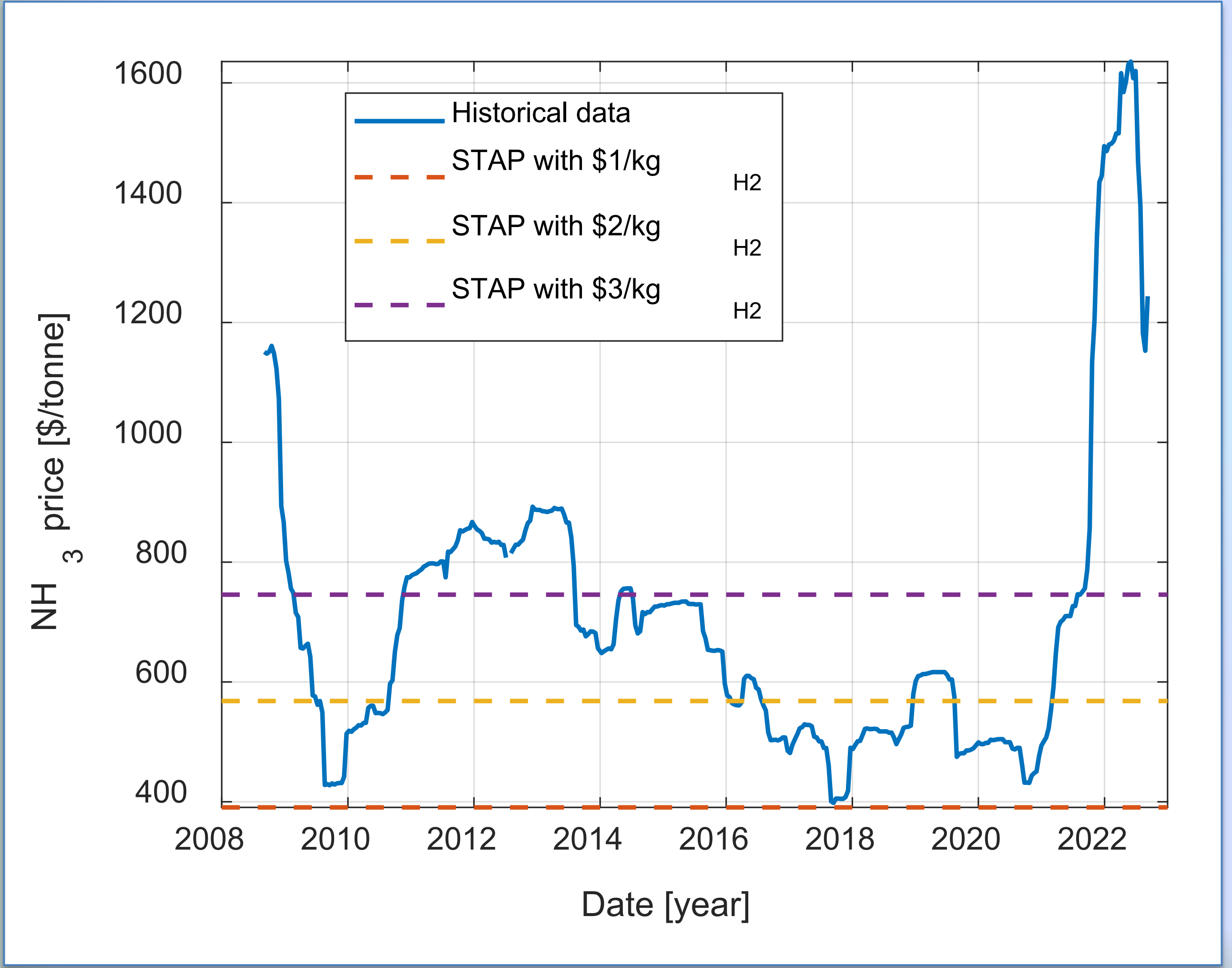
Little room for improvement in other parts of the plant

Solar multiple and storage capacity



STAP plant benefits from a large solar multiple and large storage capacity

Ammonia price context



Natural gas costs comprise ~ 70%–80% of HB production cost

Main drivers in the ammonia price in the US:

- record natural gas output
- a decline in domestic fertilizer production
- an increase in global demand for fertilizers
- an increase in the demand for fertilizers by

STAP can offer price stability

Data from:
[3] U.S. Department od Agriculture, Agricultural Marketing Service, Illinois Production Cost Report (Bi-weekly)

Summary

- CO_2-neutral ammonia production with concentrated solar technology is theoretically possible based on advanced solar thermochemical looping technology
- STAP offers price stability achieving a target price <250 \$/tonne NH_3 without including the H_2
- The nitride cost is the most significant expense, accounting for more than the 50% of the total CapEx

Thank you for your attention!!

We would like to acknowledge the team and institutions involved in this work

SOLAR ENERGY TECHNOLOGIES OFFICE U.S. Department Of Energy | Sandia National Laboratories | ASU Arizona State University | Georgia Tech

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If you like this work…

…there is more STAP in SolarPACES 2022:

- *Wednesday 28 – 17:40:* **Demonstration of a Solar Air Separation Process to Produce High-Purity N_2 via $Ba_{0.15}Sr_{0.85}FeO_{3-\delta}$ Reduction/Oxidation Cycles.** Evan Bush, Matthew Kury, Kevin Albrecht, and Andrea Ambrosini
- *Wednesday 28 – 17:00:* **Solar-Thermal Ammonia Production: A Renewable, Carbon-Neutral Route to Ammonia via Concentrating Solar Thermochemistry.** Andrea Ambrosini, H. Evan Bush, Xiang Gao, Nhu "Ty" Nguyen, Alberto de la Calle, Ivan Ermanoski, Tyler Farr, Kevin Albrecht, Matthew W. Kury, Peter Loutzenhiser, and Ellen B. Stechel
- *Friday 30 - 9:10:* **Investigation of Co_3Mo_3N reduction/re-nitridation extents as a function of temperature and N_2 partial pressure for solar thermochemical NH_3 production.** Nhu Pailes Nguyen, Shaspreet Kaur, H. Evan Bush, Xiang Gao, James E. Miller, Andrea Ambrosini , Peter G. Loutzenhiser
- *Friday 30 - 9:50:* **Solar Ammonia Production via Novel Two-step Thermochemical Looping of a Co_3Mo_3N/Co_6Mo_6N pair.** Xiang Gao, Ivan Ermanoski, Alberto de la Calle, Andrea Ambrosini, and Ellen B. Stechel