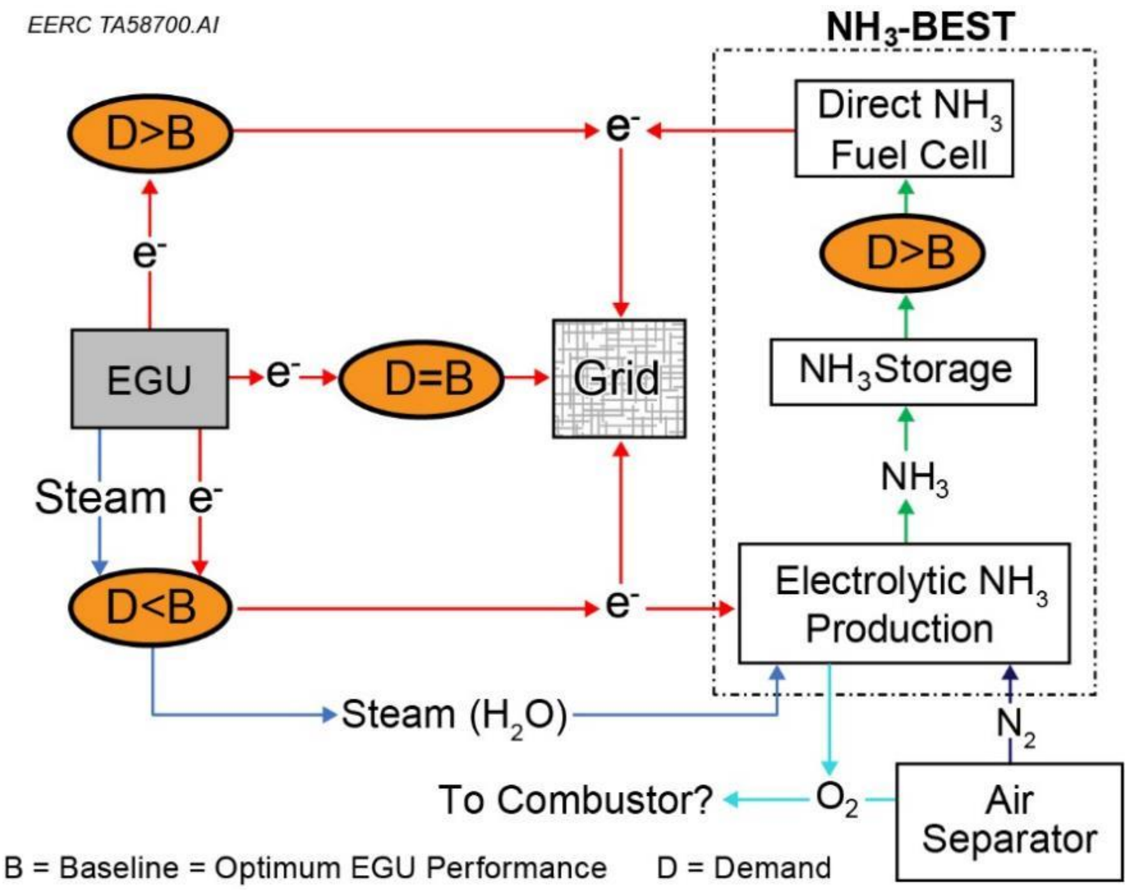
Ammonia-Based Energy Storage (NH_3-BEST)

Critical Challenges. **Practical Solutions.**

+ Project Utility Partners/Sponsors:
Basin Electric
Minnkota Power
Ottertail Power
Major Sponsors:
U.S. Department of Energy
North Dakota Lignite Research Program

NH_3-BEST–Power Plant Integration
Project Overview and Status
20 April 2023

Integrated Energy Storage via NH_3-BEST



NH_3-BEST integrated with EGU

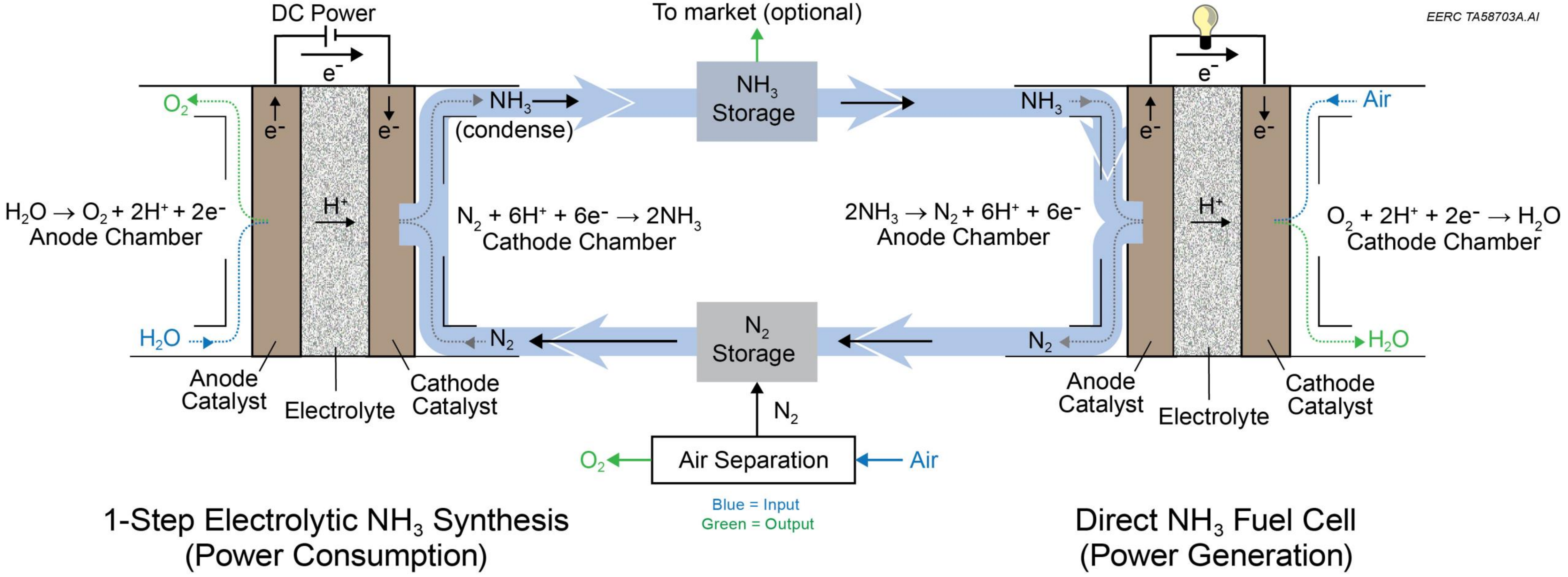
Ammonia assets as energy storage medium

- High hydrogen/energy content
- Low storage cost
- Near-zero explosivity hazard
- Carbon-free composition means no CO_2 emitted when converted to electricity, via fuel cell or combustion
- Long-established globally fungible commodity, offers economic flexibility via selling and/or buying to capitalize on market conditions or address production/supply challenges

Major project outcomes

- Preliminary design of NH_3-BEST subsystem and associated EGU integration requirements
- Modeled demonstration of NH_3-BEST performance, including estimated round-trip efficiency and preliminary economics when integrated with an EGU
- Road map for bringing ammonia energy storage to commercial deployment

NH_3-BEST Unit Operations

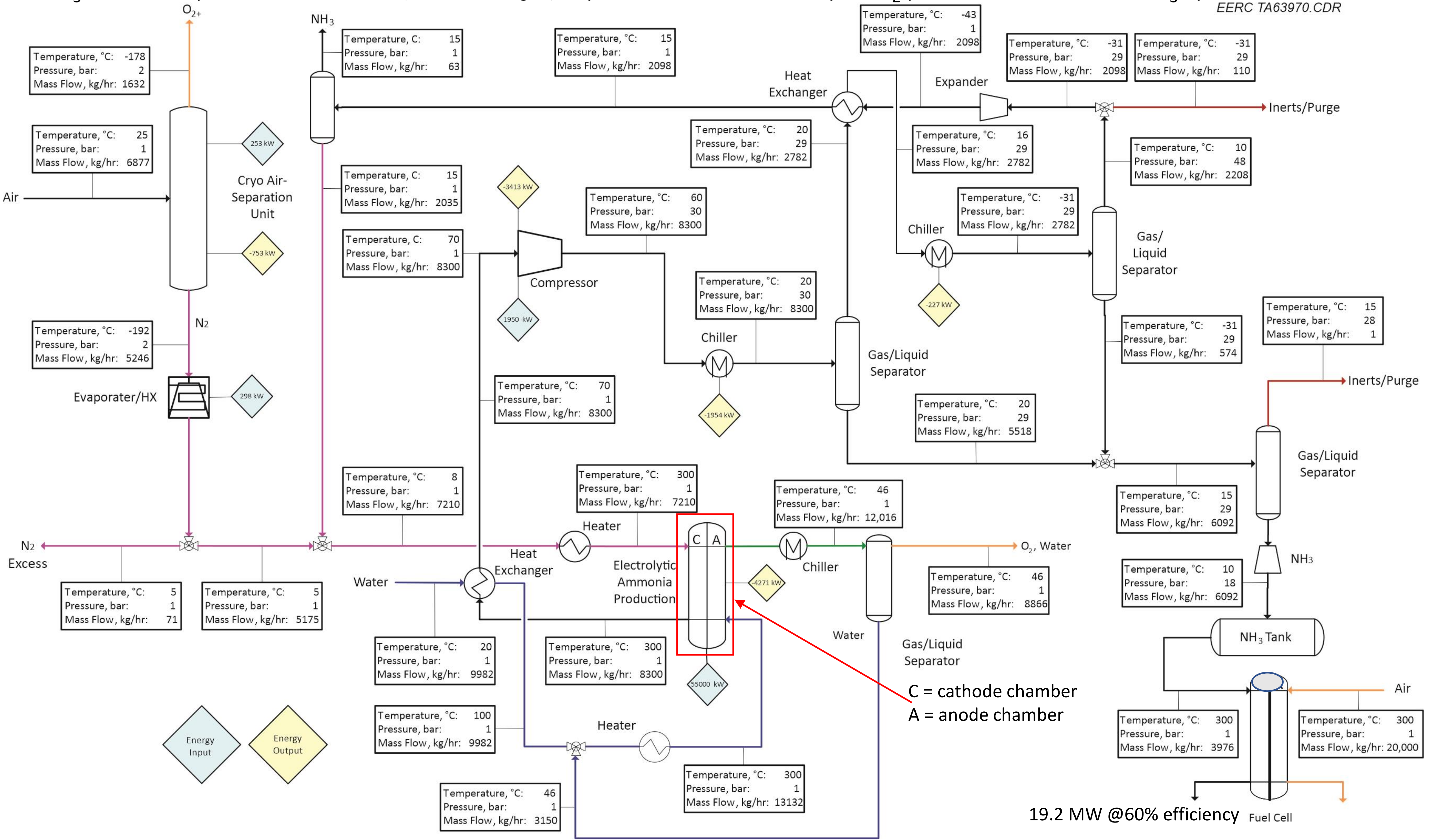


Under development at EERC

Commercially available

Under development around the world

58-MW NH_3-BEST subsystem with reactor (red rectangle) capable of water electrolysis/H_2 production at anode, NH_3 synthesis at cathode



55-Megawatt[1] Integrated Electrolysis/NH_3 Synthesis Reactor (proton generation at anode, NH_3 synthesis at cathode) Performance Parameters	Estimated Values	
	Ultimate Target	Current Target
Efficiency (based on NH_3 HH value of 5.2 kWh/kg)	64%	55%
Voltage, V	1.6	1.9
Current density, amps/cm^2	0.406	0.342
Power consumption, watts/cm^2	0.65	0.65
Water consumption, kilograms/hour	11,543	9982
O_2 generation, kg/hr	12,419	10,498
NH_3 production, kg/hr	7281	6155
Electricity consumption, kilowatt-hours/kilogram NH_3	7.6	9.0
Balance of plant[1] electricity consumption, kWh/kg NH_3	0.5	0.5
Total electricity consumption, kWh/kg NH_3	8.1	9.5
NH_3 to power via fuel cell at 6155 kg NH_3/hr, 60% efficiency		19.2 MW
Round trip (electrical) efficiency[2]		33%

[1] Additional power for 1) N_2 separation from air and 2) NH_3 product condensation translates to 58 MW total system.

[2] Does not account for thermal energy recovery from NH_3 synthesis or fuel cell operations.

NH_3-BEST Island – Details and Considerations

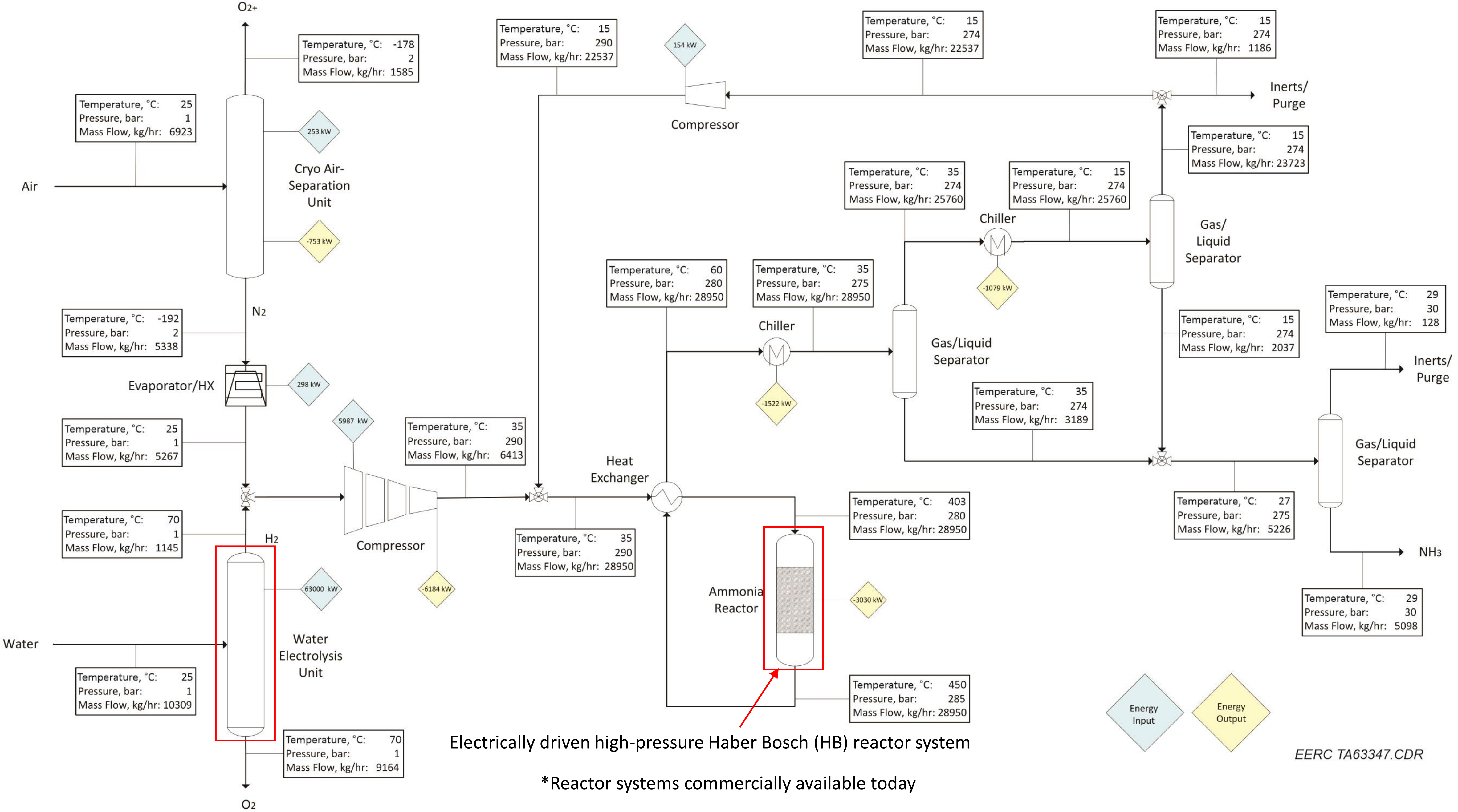
All below numbers based on 55% NH_3 production efficiency

- Total power input (for current design/layout): 58 Mwe – includes ammonia production, purification, storage
- Ammonia production capacity: 6155 kg/hour (148 tonnes/day)
- Water input: 9982 kg/hour (2634 gallons/hour or 63,211 gallons/day)
- Air input: 6877 kg/hour
- O_2 output: 8866 kg/hour (electrolyzer) + 1632 kg/hour (air separator) = 10,498 kg/hour
- Max pressure (for ammonia condensation/recovery as product): 17 bar (250 psi)
- Max temperature (for ammonia production): 300°C
- NH_3-BEST Island footprint: ??
- NH_3-BEST Island height requirement: ??
- Ammonia storage capacity: dependent on ammonia disposition (sales, energy storage, combination)
- Ammonia conversion-to-electricity capacity (via direct ammonia fuel cell or ammonia turbine): dependent on ammonia disposition

Water Input for NH_3 Electrolyzer Must Meet ASTM D1193 Type II Specification

Parameter	Value
Electrical conductivity, max, microsiemens/cm at 25°C	1.0
Electrical resistivity, min, megaohms-cm at 25°C	1.0
Total organic carbon (TOC), max, micrograms/liter	50
Sodium, max, µg/L	5
Chlorides, max, µg/L	5
Total silica, max, µg/L	3

70-MW NH_3 synthesis unit with separate reactors* (red rectangles) for water electrolysis/H_2 production and NH_3 synthesis



*Reactor systems commercially available today

Per Tonne Ammonia Production Energy Consumption and Cost*

Process/Reactor Type	Energy Consumption, MWh/tonne	Energy Cost, $/ton
PEM electrolyzer + electrically driven HB reactor	12.0	720
Intgrated electrolyzer/NH_3 synthesis reactor	9.5	570

*All energy costs based on electricity cost of $60/MWh (current ND large industrial rate is $30/MWh)

Energy Storage Round-Trip Efficiency (RTE)*

Process/Reactor Type	RTE
PEM electrolyzer + electrically driven HB reactor	28%
Integrated electrolyzer/NH_3 synthesis reactor	33%

*Based on NH_3 higher heating value of 5.2 MWh/tonne, NH_3 conversion to electricity in NH_3 fuel cell @60% efficiency

Considerations

PEM or alkaline electrolyzer + electrically driven HB reactor available today
Integrated electrolyzer/NH_3 synthesis unit, NH_3 fuel cell, NH_3 turbine available 2025–2030
Diverting power to producing NH_3 (even if only for sale) could eliminate deep cycling
NH_3 is global commodity with expanding demand as hydrogen carrier
NH_3 price ($1000–$1500 for last 18 months) unlikely to drop in near future

Deploying Energy Storage at Existing Power Plant – Considerations

Interconnection limitations: Existing power plants have interconnection rights that limit the amount of energy allowed onto the grid through the interconnection point at any given time. Adding an ammonia fuel cell behind the same interconnection point would require applying for Surplus Interconnection Service, which requires:

- A system impact study to evaluate reliability impacts of the added generator.
- A Monitoring and Consent Agreement outlining how and when the existing interconnection rights will be made available to the new resource.

Resiliency: Pairing energy storage at an existing coal-fired power plant may be challenged by the fact that a coal-plant is designed to run at a high capacity factor, possibly limiting availability to add energy storage as a surplus interconnection.

Economics: Ultimately, as a regulated utility, adding energy storage will need to be proven as a cost-effective addition.

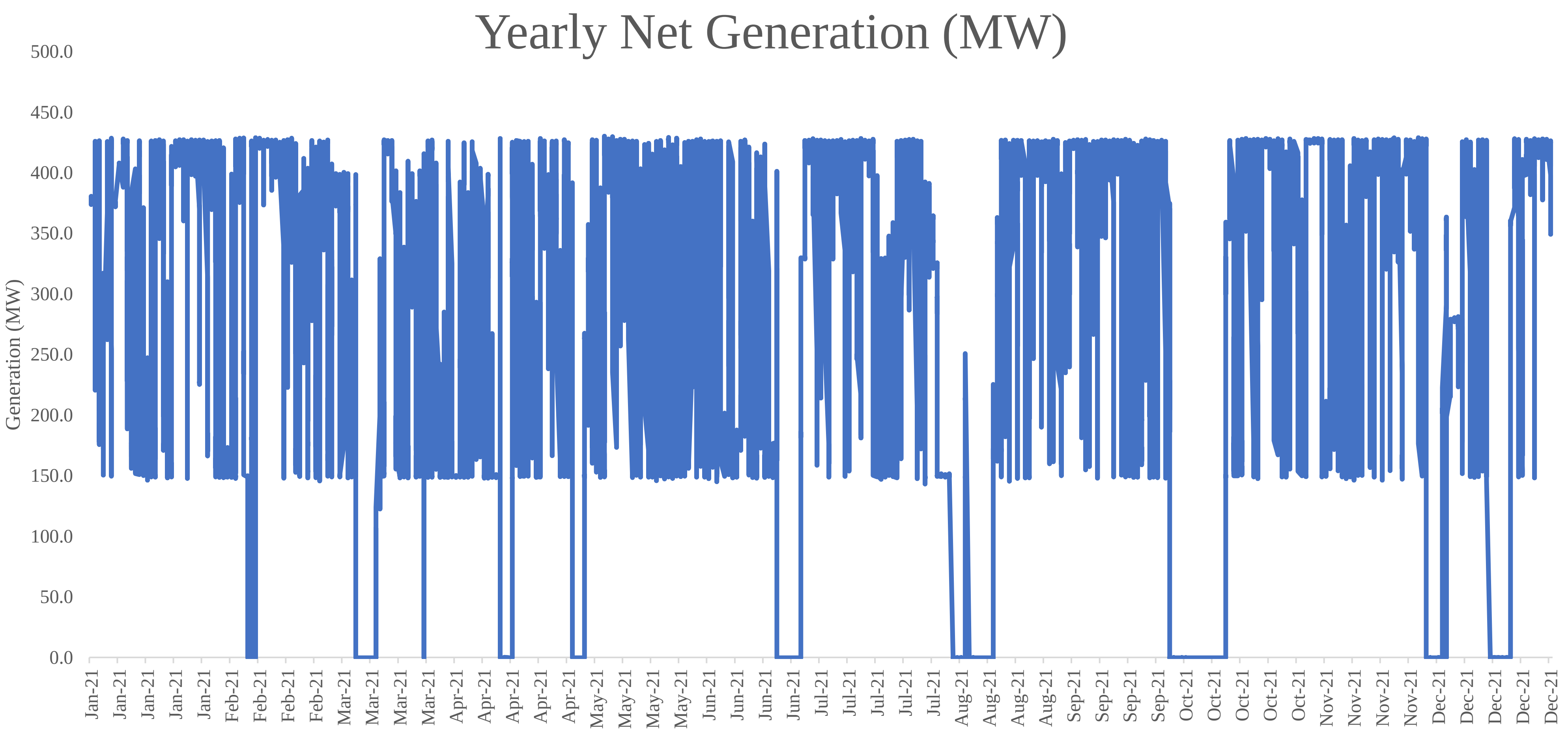
Permitting and approvals: Any new resource addition will require approval from state environmental agency and (for all regulated utilities) state public service commission.

Ranking of Generation Resources Based on Resiliency Factors

Generation Resource	Dispatchable	Reliable Fuel Supply	Energy Price Protection	Ranking Factors
1) Coal Generation	Yes	Yes	Yes	Fuel storage capability and low volatility in fuel price
Ammonia Fuel Cell	Yes	Yes	Yes	Fuel storage capability, made with coal-fired power
2) Dual Fuel Simple Cycle	Yes	Yes	Yes	Fuel oil storage capabilities, multiple fuel sources, fuel oil storage protects from volatility in natural gas market
3) Fuel Oil Simple Cycle	Yes	Yes	Yes	Fuel oil storage capability protects from volatility in natural gas market
1) Natural Gas Simple Cycle	Yes	No	No	No dual fuel capability means dependence on single natural gas supply pipeline, no fuel storage, close gas–electricity market correlation means subject to gas price volatility
1) Battery Storage*	Yes	No	No	Fuel supply cannot be considered reliable only covering 17% of one day, limited fuel supply also diminishes ability to protect customers in volatile events
1) Solar	No	No	No	Ranked higher than wind due to generation occurring during peak loads, and while not dispatchable, no significant correlation to energy and natural gas markets
1) Wind	No	No	No	No fuel storage and relatively close inverse correlation between wind generation operating and energy and gas market prices

*Batteries are not technically generation

If an energy storage system can deliver these attributes, we will use our resource planning software to help determine if it makes cost-effective sense for our customers. In our resource plan filed on March 31, 2023, we evaluated battery storage resource alternatives as purchased power agreements (PPA) with a 30-year term and fixed pricing over that term.



Nameplate Capacity: 427 MW

Major Deep Cycle: 150 MW (277 MW spread)

Output at 95% Nameplate Capacity: 406 MW

Looking for buyer of 70 MWs

55-Megawatt NH_3-Based Energy Storage Subsystem 65/35 Power/Sales NH_3 Allocation	Values
NH3 production, tonnes/year @100% capacity	54,000
NH3 to power via fuel cell, tonnes/year	35,000
MWh power @60% efficiency	109,200
Power value @$105/MWh (ND residential rate)	11,466,000
NH3 to sales, tonnes/year	19,000
Sales value @$1200/tonne	22,800,000
NH3 value with 100% (54,000 tonnes) to power	17,690,000
NH3 value with 100% (54,000 tonnes) to sales	64,800,000

Recent Texas A&M study shows natural gas price only accounts for 15% of run-up in anhydrous ammonia price, as reported by *Drovers,* 12 January 2022

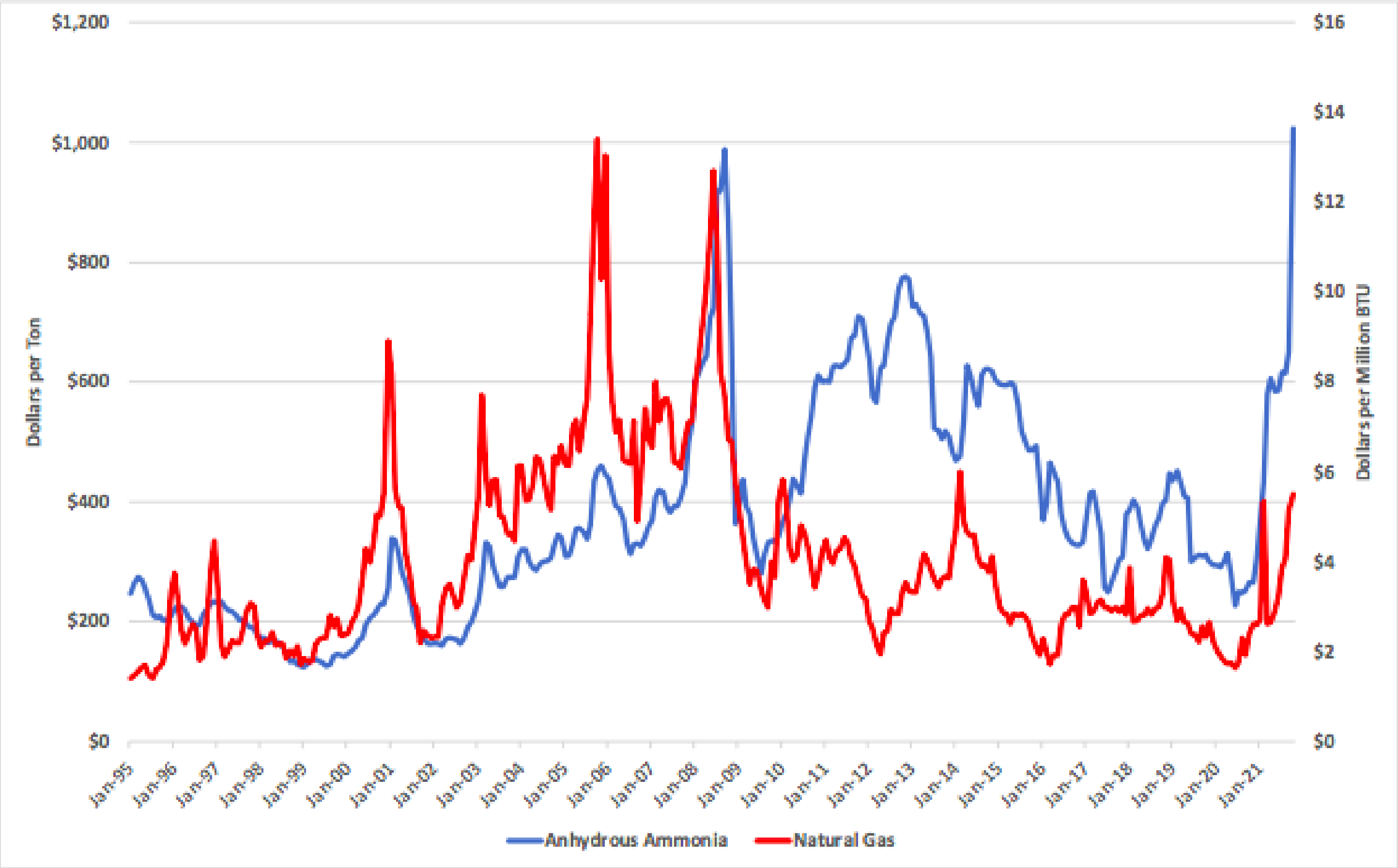
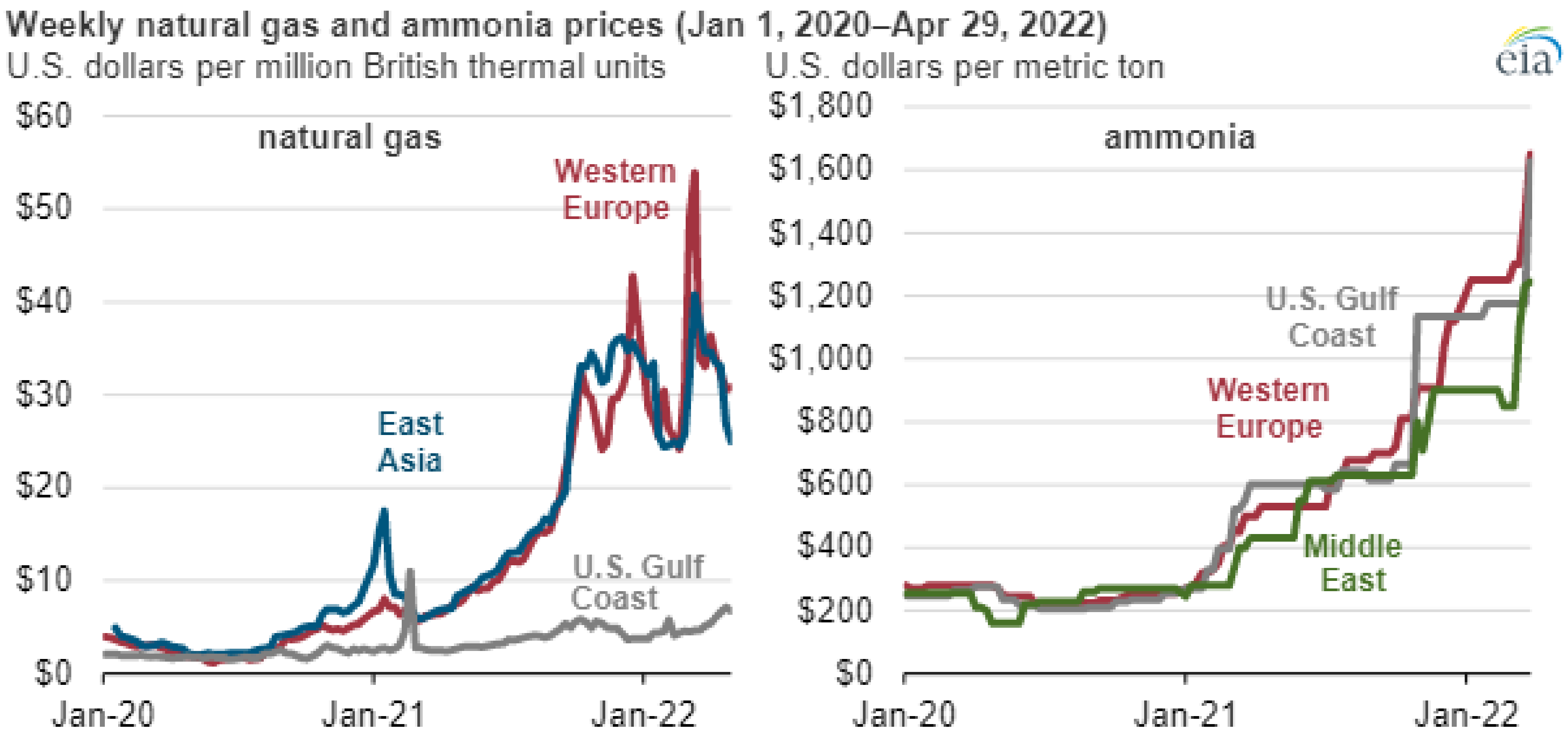


Figure 7. Anhydrous Ammonia and Natural Gas Prices, January 1995 to October 2021.

Graphic Courtesy of Lindsey Benne; Data Provided by AFPC Texas A&M Fertilizer Price Study for Corn Growers


Weekly natural gas and ammonia prices (Jan 1, 2020–Apr 29, 2022)
U.S. dollars per million British thermal units
U.S. dollars per metric ton
eia
natural gas
$60
$50
$40
$30
$20
$10
$0
Western Europe
East Asia
U.S. Gulf Coast
Jan-20
Jan-21
Jan-22
ammonia
$1,800
$1,600
$1,400
$1,200
$1,000
$800
$600
$400
$200
$0
U.S. Gulf Coast
Western Europe
Middle East
Jan-20
Jan-21
Jan-22