2019 DOE Hydrogen and Fuel Cells Program
Annual Merit Review

Hydrogen Demand Analysis for H2@Scale

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Argonne National Laboratory

April 30, 2019

SA172

Overview

Timeline

- Start: October 2018
- End: Determined by DOE
- % complete (FY19): 80%

Budget

- Funding for FY19: $200K

Barriers to Address

A: Future Market Behavior

  - ➢ Potential market for low value energy and potential hydrogen markets beyond transportation

D: Insufficient Suite of Models & Tools

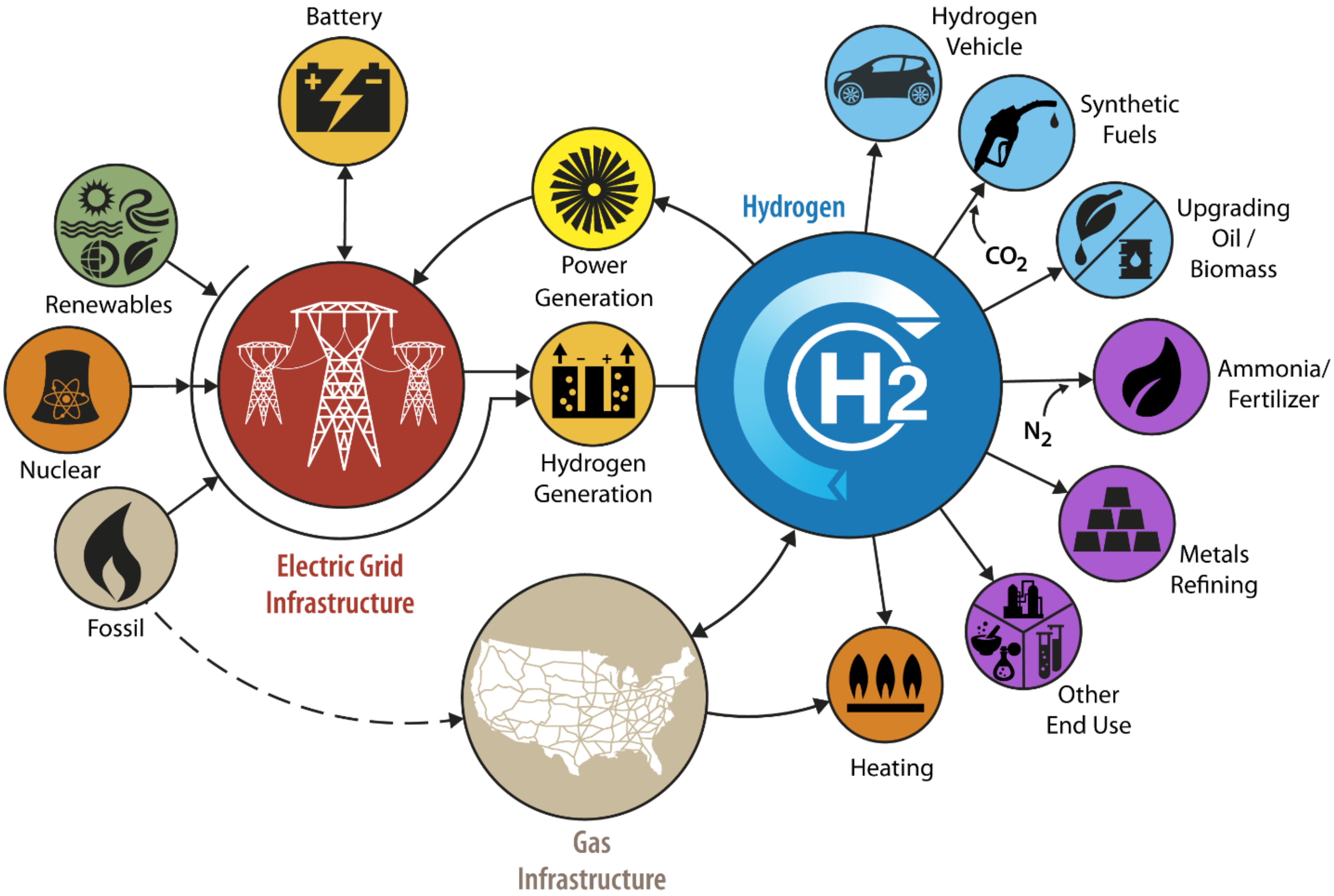
E: Unplanned Studies and Analysis

  - ➢ H2@Scale is a new concept and requires analysis of its potential impacts

Partners/Collaborators

- NREL, INL, PNNL, SNL, LLNL, LBNL
- DOE NE Office
- Industry partners (utilities, energy companies and OEMs)

H2@SCALE ENERGY SYSTEM* – *Relevance/Impact*

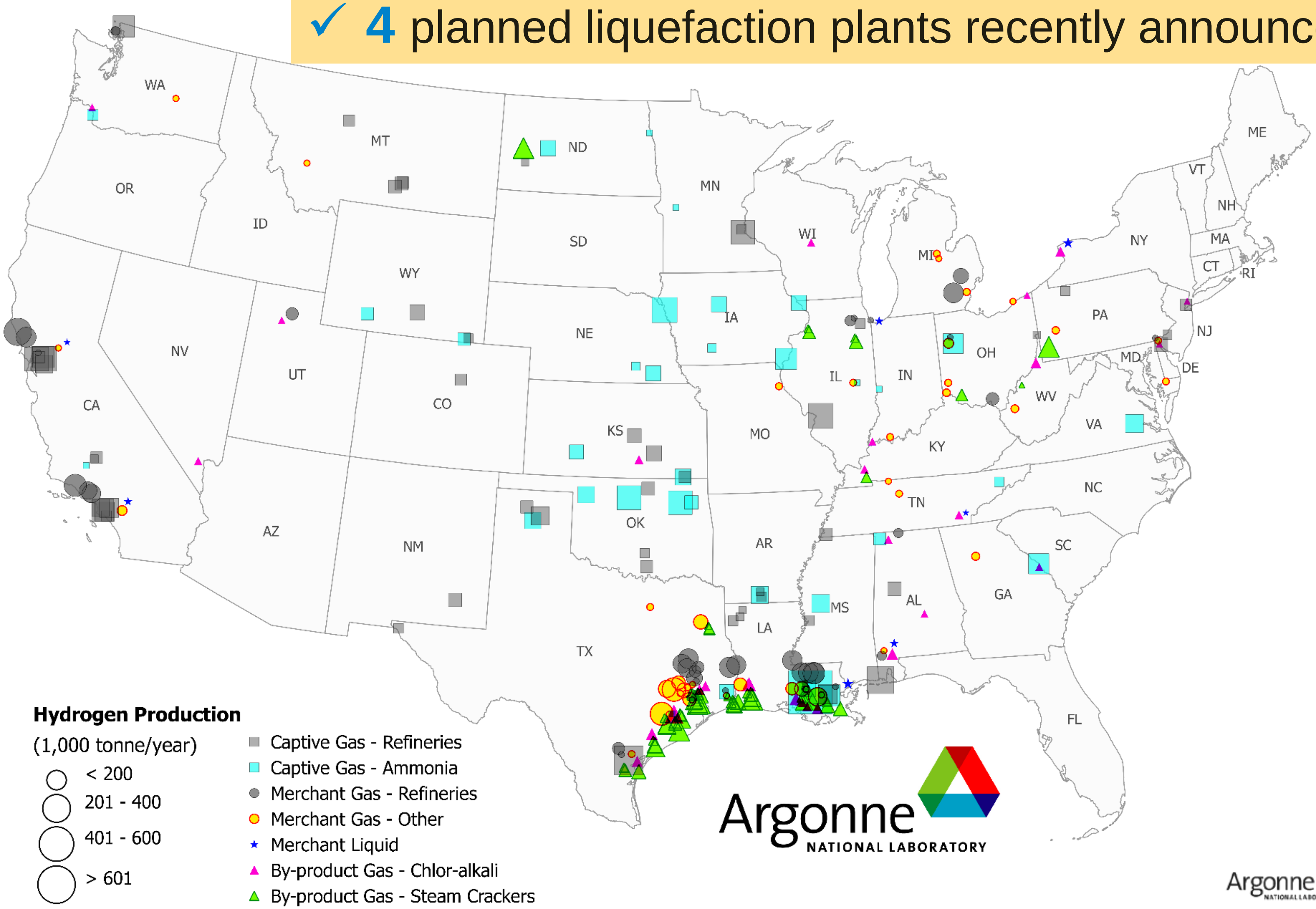


*Illustrative examples, not comprehensive

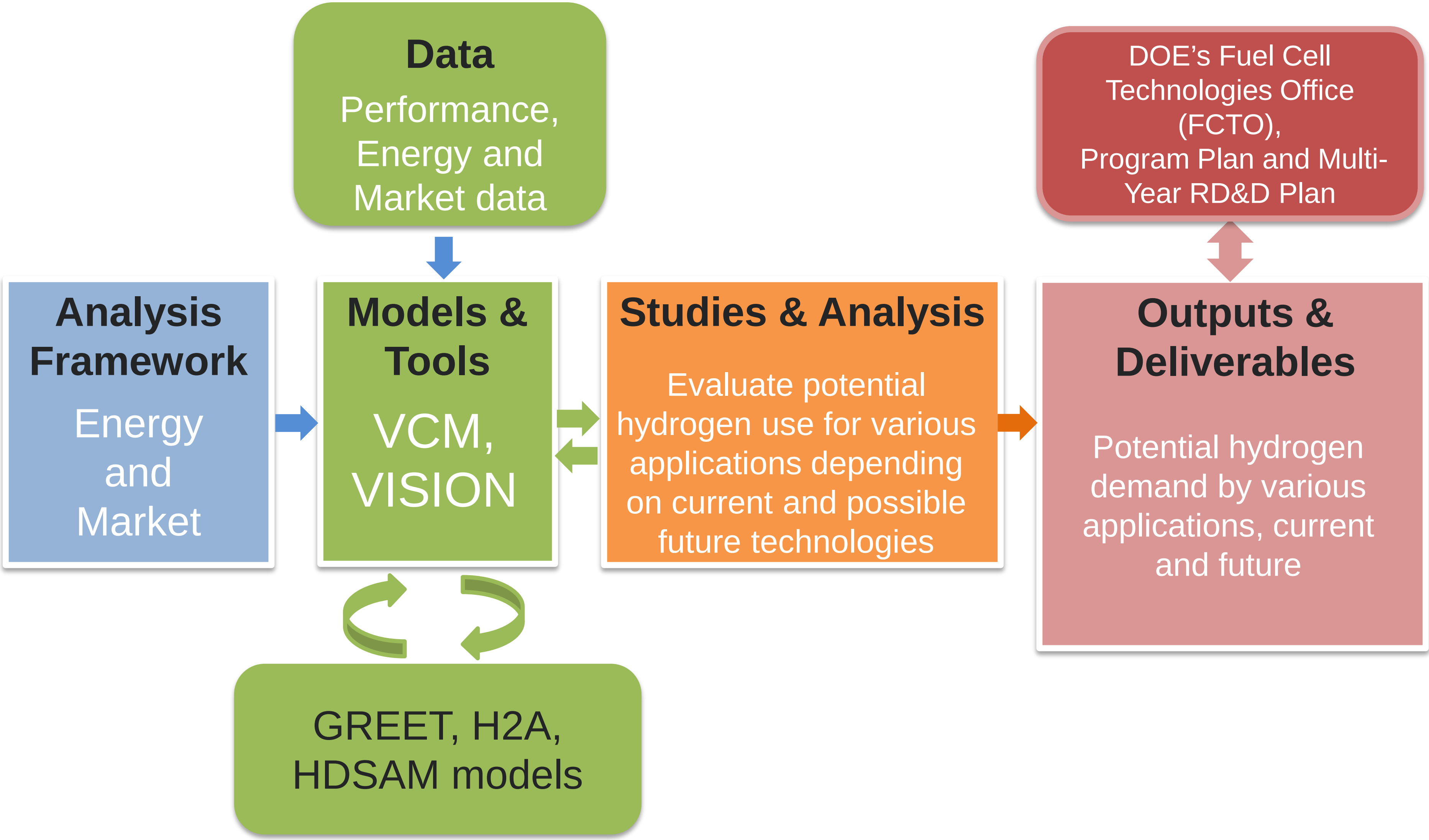
TODAY, MORE THAN 10M METRIC TONS OF HYDROGEN ARE PRODUCED IN THE U.S. ANNUALLY – Relevance/Impact

1600 mi. of H_2 pipeline; **10** Liquefaction plants in North America

✓ **4** planned liquefaction plants recently announced



COLLECT PERFORMANCE, ENERGY, MARKET DATA FOR CURRENT AND POTENTIAL FUTURE MARKETS – *Approach*



Data

Performance, Energy and Market data

DOE’s Fuel Cell Technologies Office (FCTO),
Program Plan and Multi-Year RD&D Plan

Analysis Framework

Energy and Market

Models & Tools

VCM, VISION

Studies & Analysis

Evaluate potential hydrogen use for various applications depending on current and possible future technologies

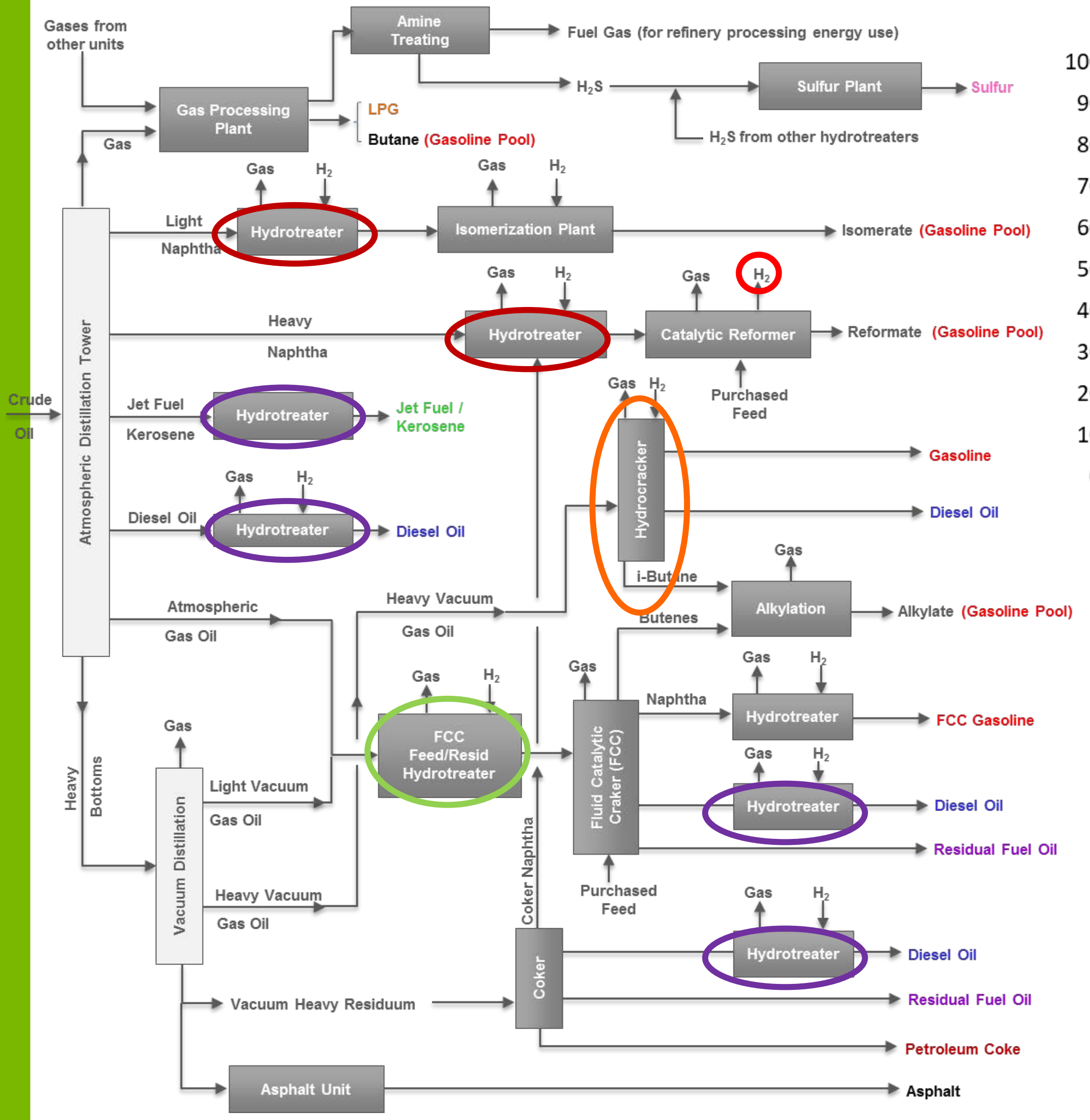
Outputs & Deliverables

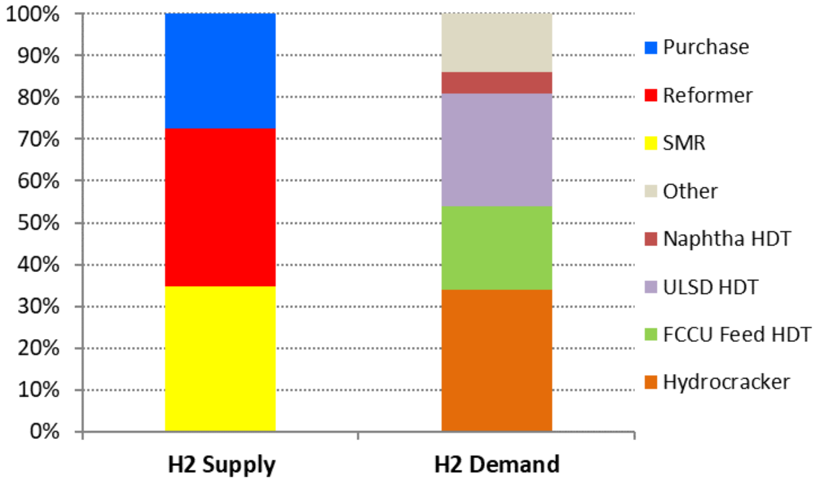
Potential hydrogen demand by various applications, current and future

GREET, H2A, HDSAM models

POTENTIAL HYDROGEN DEMAND BY REFINERIES

HYDROGEN CONSUMERS IN PETROLEUM REFINING – *Relevance/Impact*



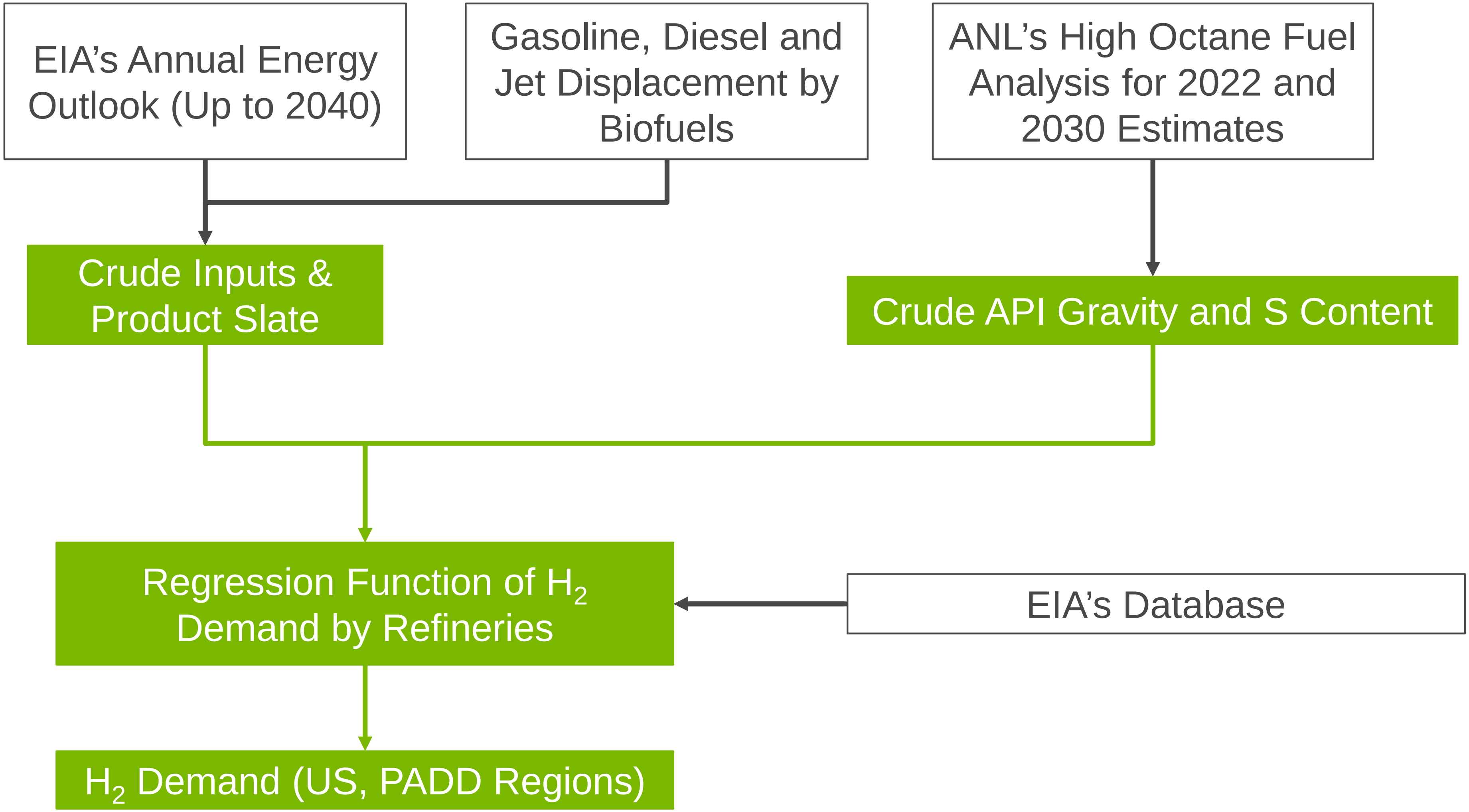


Major consumers

- Hydrocracker → Diesel from Heavy Crude
- ULSD Hydrotreater → Diesel
- FCCU Feed Hydrotreater → Heavy Crude and S removal
- Hydrotreater → S removal

✓ Elgowainy et al. *Environmental Science and Technology*, 2014

HYDROGEN DEMAND ASSESSMENT FOR PETROLEUM REFINING – *Approach*



EIA's Annual Energy Outlook (Up to 2040)

Gasoline, Diesel and Jet Displacement by Biofuels

ANL's High Octane Fuel Analysis for 2022 and 2030 Estimates

Crude Inputs & Product Slate

Crude API Gravity and S Content

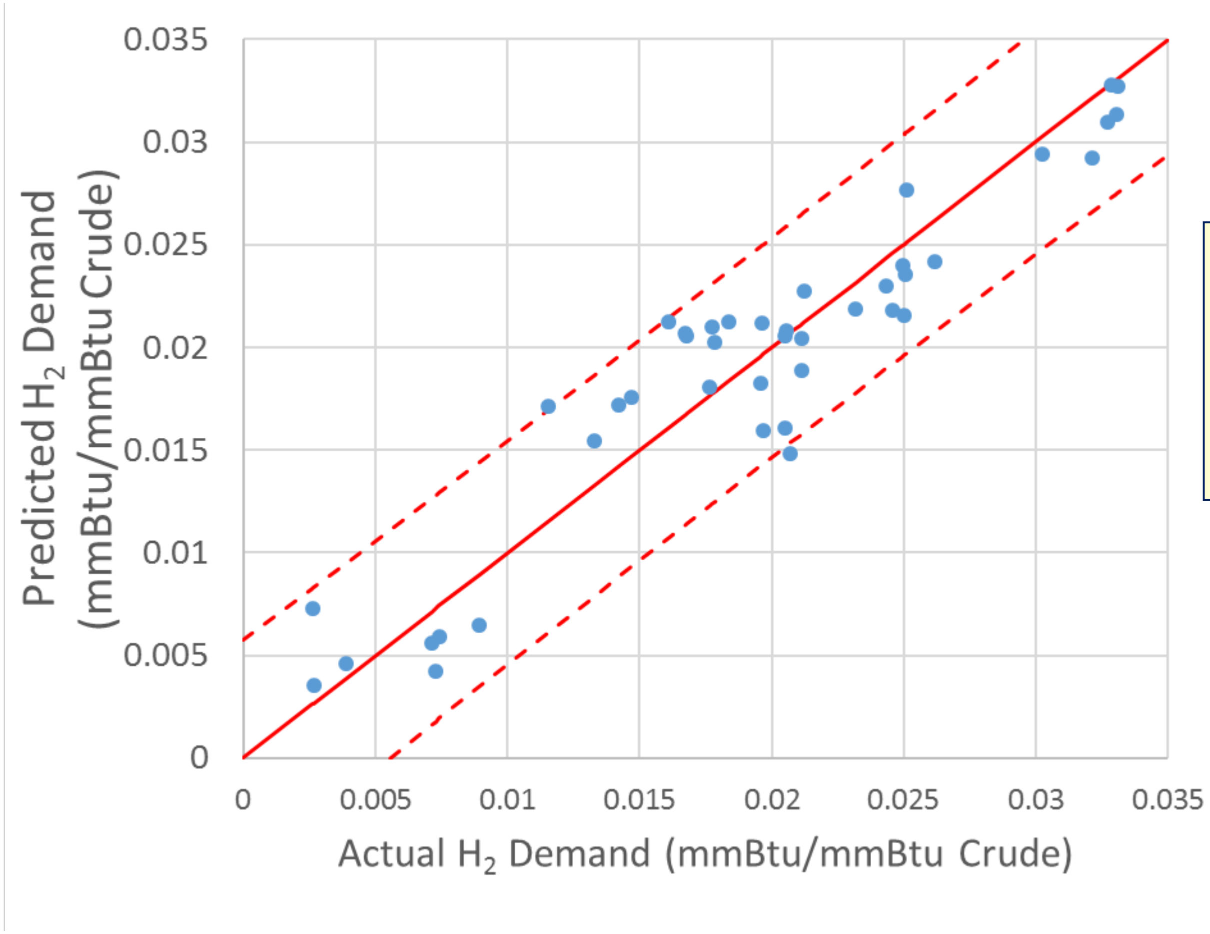
Regression Function of H_2 Demand by Refineries

EIA's Database

H_2 Demand (US, PADD Regions)

DEVELOPMENT OF REGRESSION FUNCTION OF H_2 DEMAND BY REFINERIES USING EIA'S DATABASE – *Accomplishment*

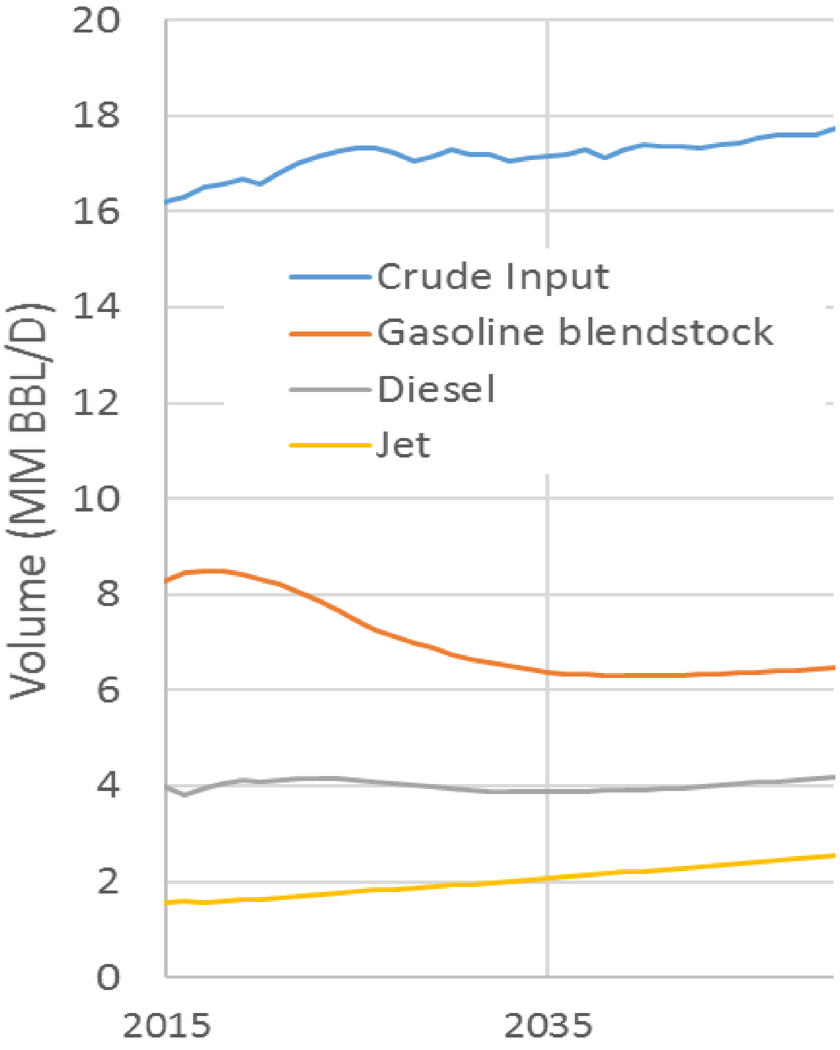
- H_2 (mmBtu/mmBtu Crude) = 0.059-0.00175 x (Crude API)+0.02218 x (Sulfur Ratio)-0.00139 x (G/D Ratio)-0.59416 x (LPG/Total)



<u>Good for</u>
Crude API: 28.5 – 34.3
Sulfur Ratio: 0.65 – 1.6
G/D Ratio: 0.5 – 5.8

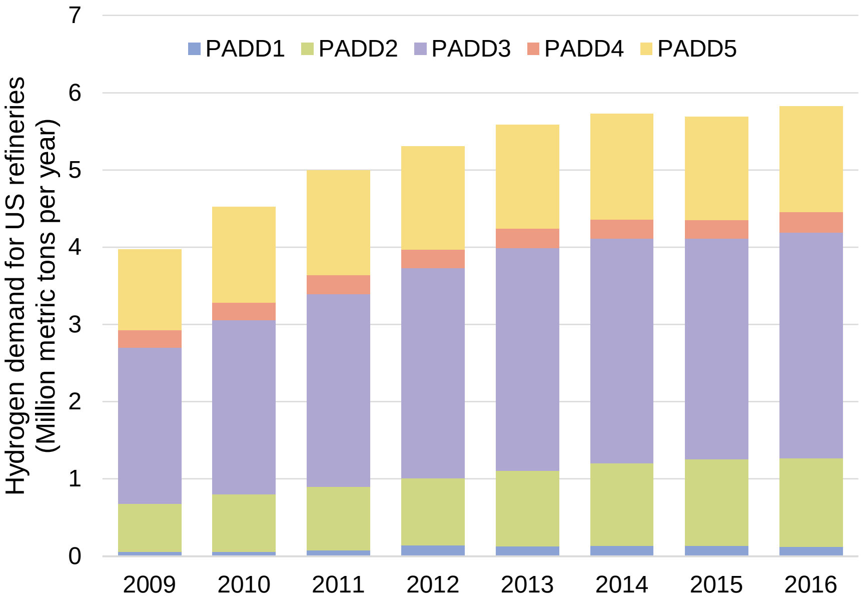
BACKGROUND DATA FOR ESTIMATING H_2 CONSUMPTION RATE – *Accomplishment*

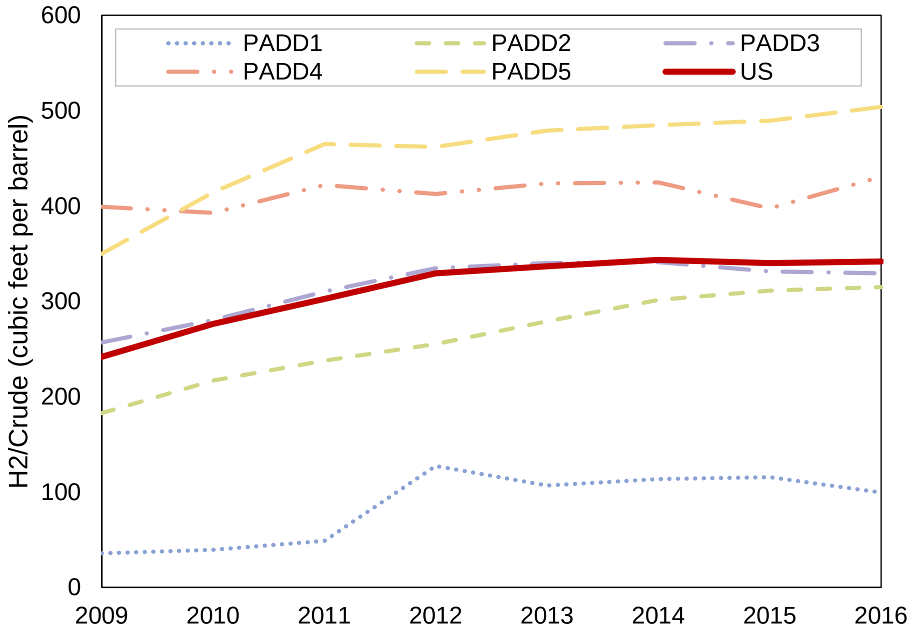
- EIA Database
  - Crude Input
  - Product Slate → G/D Ratio
- ANL's High Octane Fuel Analysis for 2022 and 2030 Estimates
  - Crude API
  - Crude S Contents



RECENTLY, H_2 DEMAND FOR US REFINERIES HAS INCREASED SIGNIFICANTLY – *Accomplishment*

- H_2 demand has been increased due to increased diesel demand and more stringent regulations.
- H_2/Crude ratio shows regional variation; H_2/Crude increases over time.





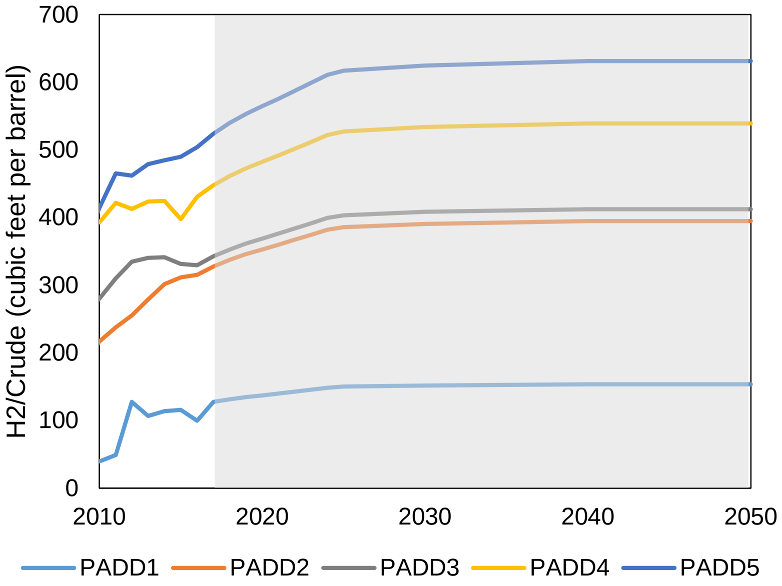
Source: EIA

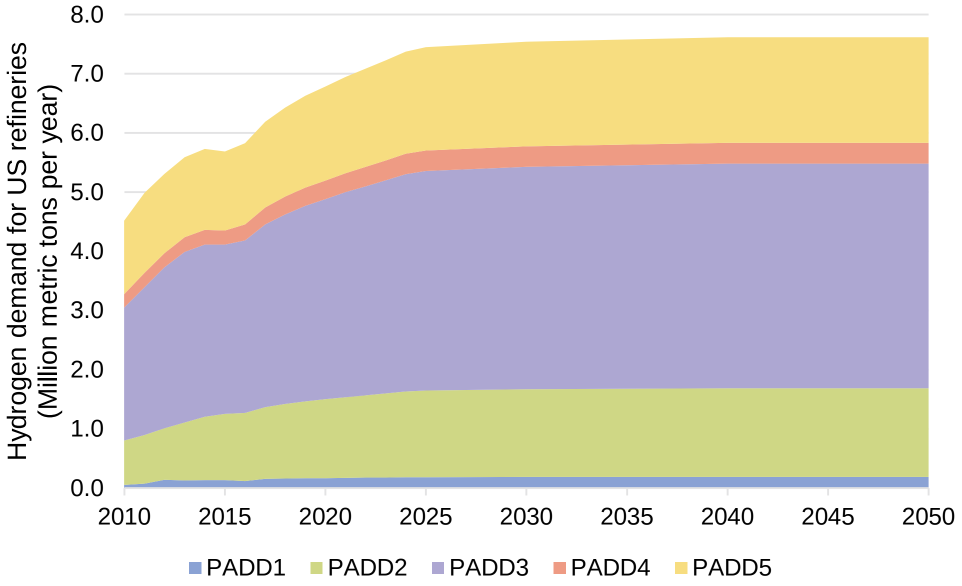
ESTIMATION OF FUTURE H_2 DEMAND FOR US REFINERIES – *Accomplishment*

Preliminary

- H_2/Crude will increase through 2030
- Crude capacity would increase 9% from 2015 to 2021 (EIA AEO)

	PADD1	PADD2	PADD3	PADD4	PADD5	US
H_2 demand in 2030 (MMT)	0.2	1.5	3.8	0.4	1.8	7.5

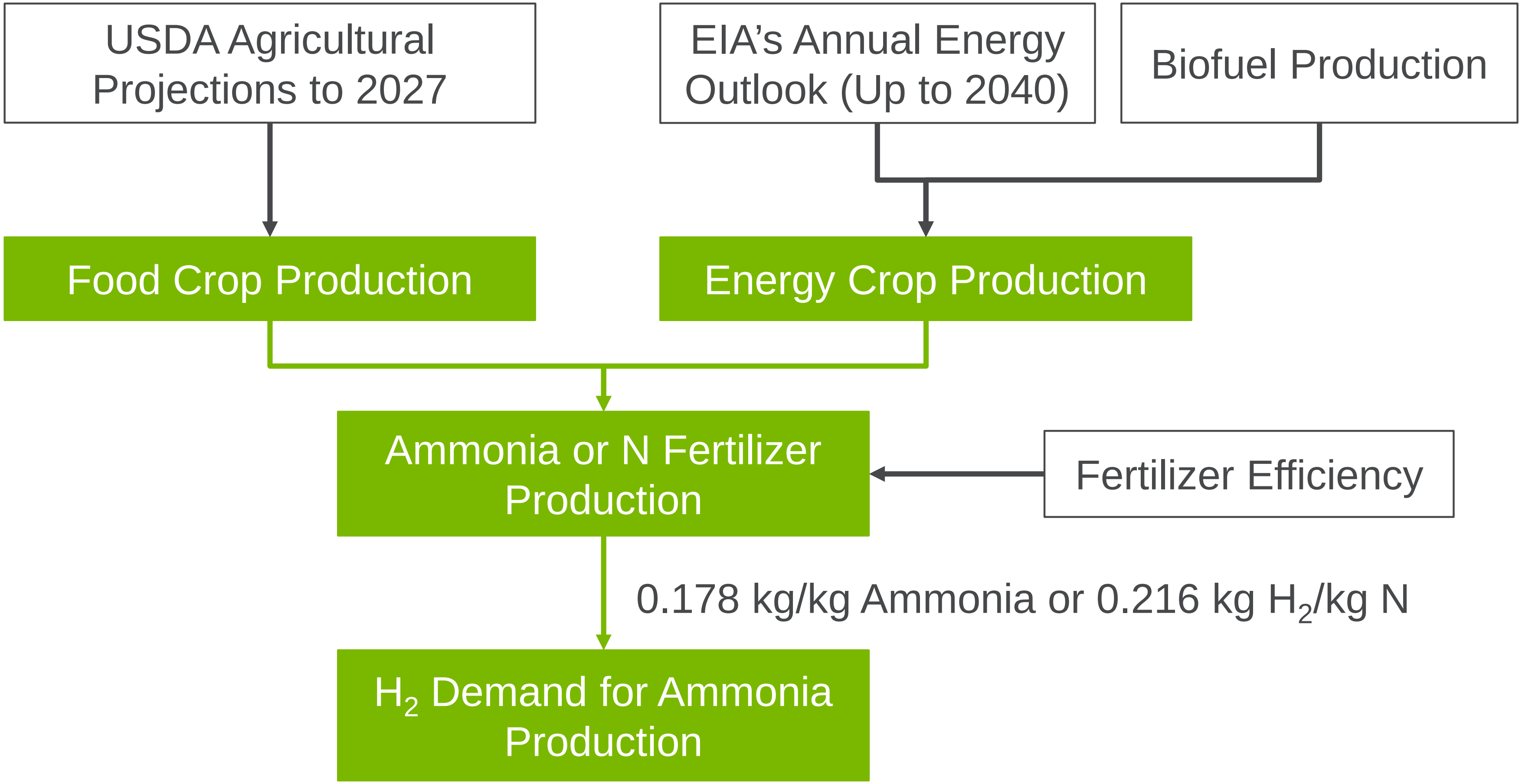




- Generally increasing H_2 consumption by refineries
  - Increasing H_2 consumption rate due to heavier and more sour crude
  - Increasing D/G ratio
  - Increasing crude inputs

POTENTIAL HYDROGEN DEMAND FOR AMMONIA PRODUCTION

HYDROGEN DEMAND ASSESSMENT FOR AMMONIA PRODUCTION – *Accomplishment*



USDA Agricultural Projections to 2027

EIA's Annual Energy Outlook (Up to 2040)

Biofuel Production

Food Crop Production

Energy Crop Production

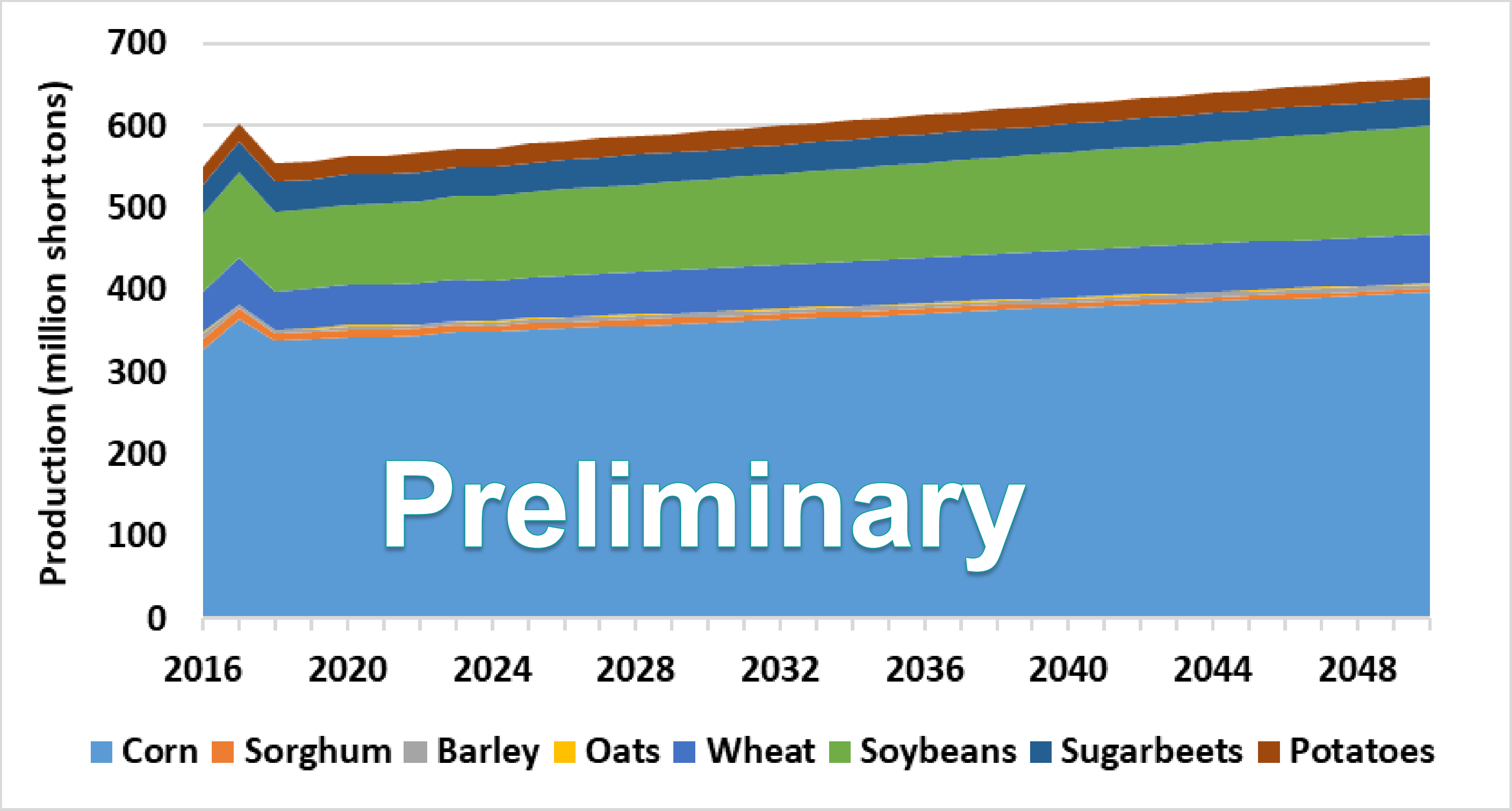
Ammonia or N Fertilizer Production

Fertilizer Efficiency

0.178 kg/kg Ammonia or 0.216 kg H_2/kg N

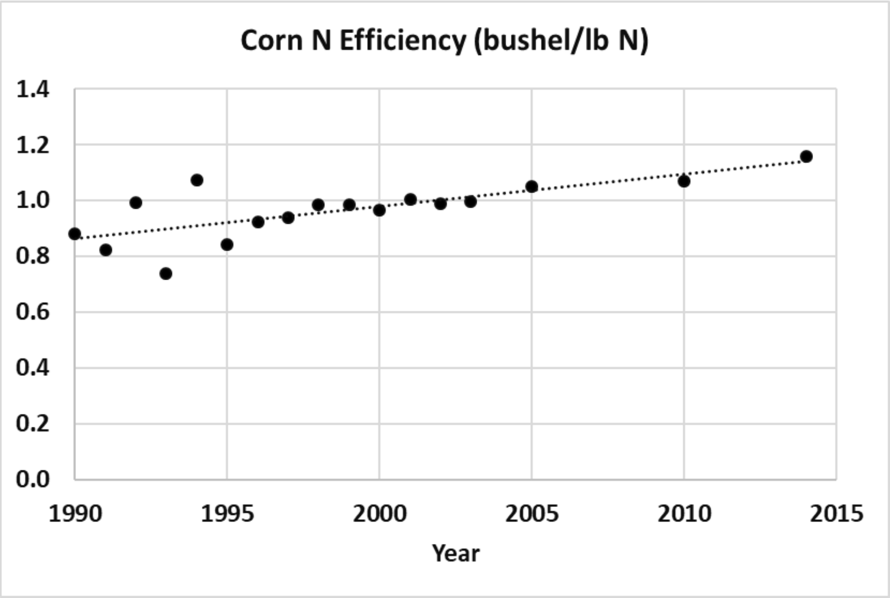
H_2 Demand for Ammonia Production

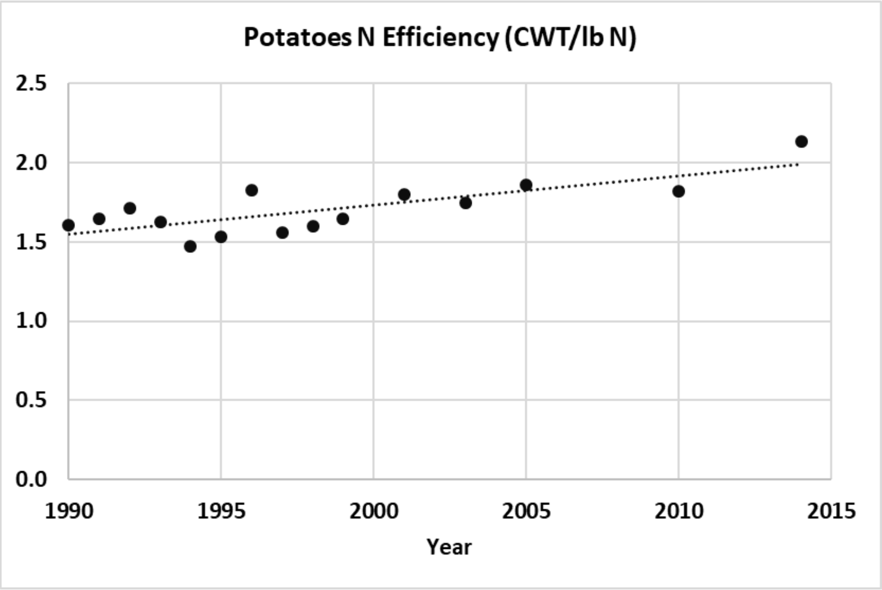
AGRICULTURE PRODUCTS PRODUCTION – *Accomplishment*



- Dominated by corn, wheat and soybean
- USDA projection up to 2027
- Extended average rates of 2020 to 2027 through 2050

N FERTILIZER EFFICIENCY – *Accomplishment*





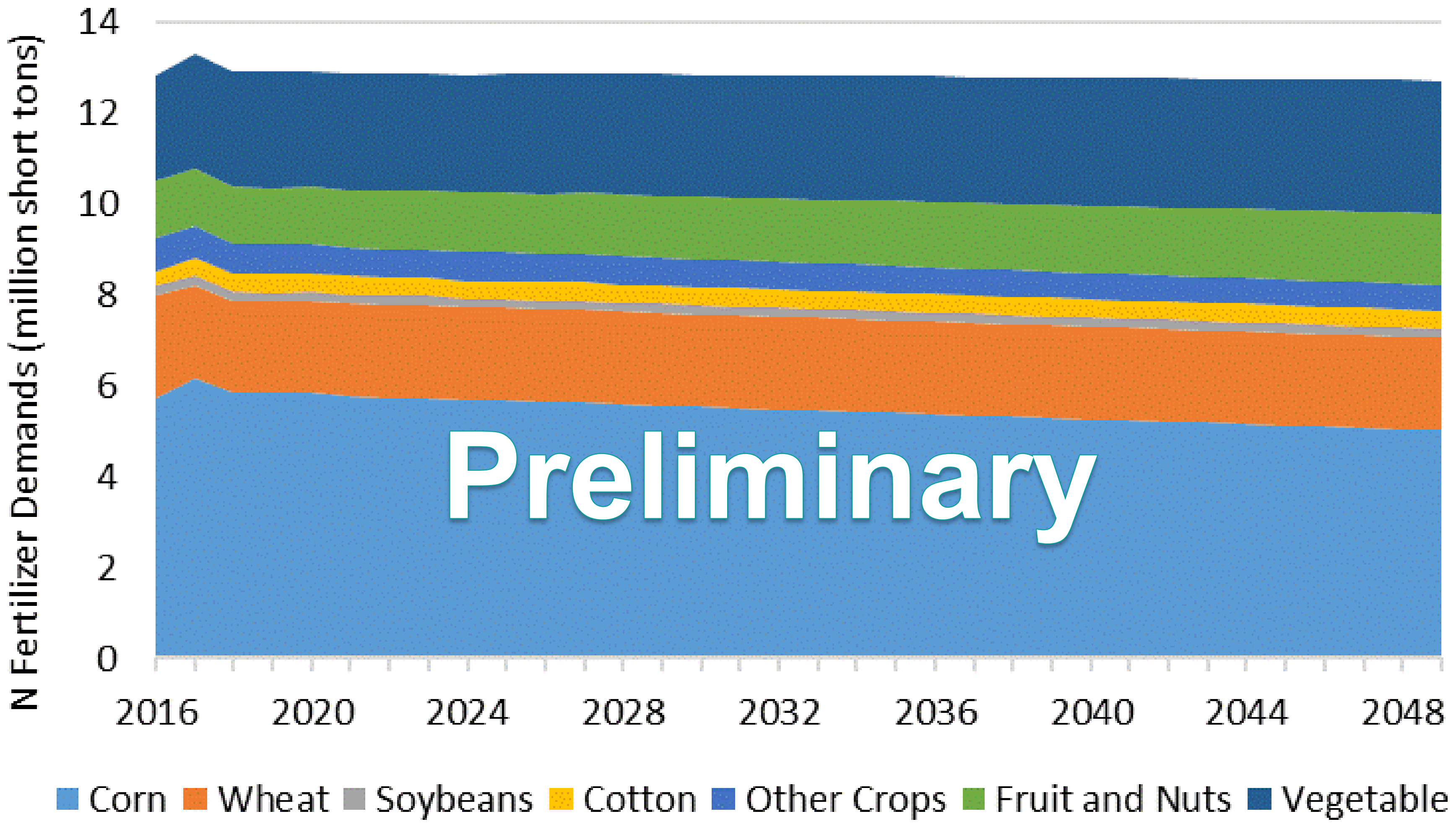
- Based on USDA NASS Database
  - Corn, soybeans, wheat, potatoes have enough samples for regression
  - Soybeans and wheat does not show strong trends over year

Crop	Unit	N Efficiency
Sorghum[1]	bushel/lb N	0.69
Barley[1]	bushel/lb N	0.99
Oats[1]	bushel/lb N	0.81
Wheat[1]	bushel/lb N	0.63
Soybeans[1]	bushel/lb N	9.27
Rice[1]	CWT/lb N	0.45
Cotton[1]	bale/lb N	0.02
Sugarbeets[2]	short ton/lb N	0.02

[1] Average from 2010 to 2015

[2] Only one data point

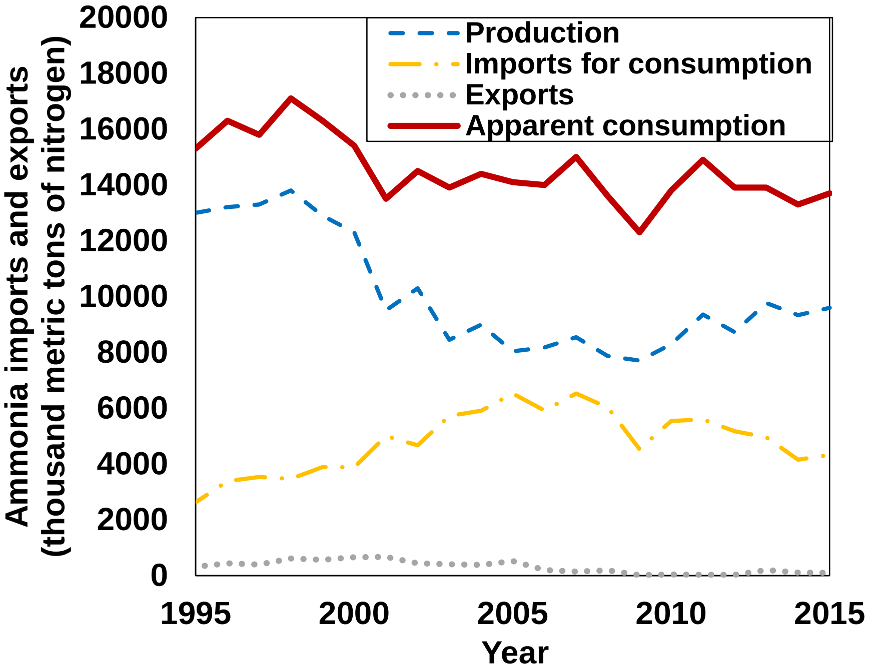
NEAR STEADY DEMAND OF N FERTILIZER – *Accomplishment*



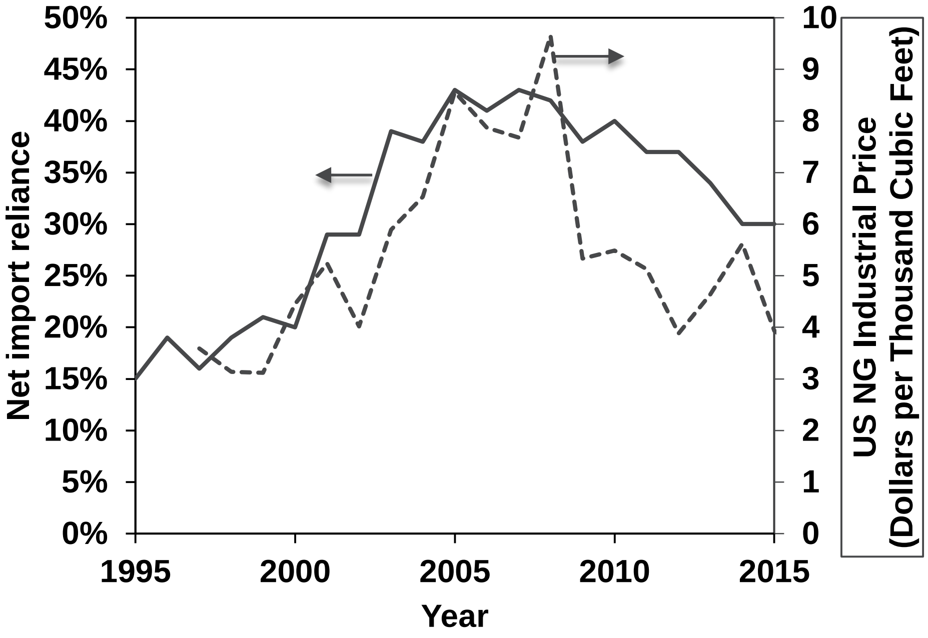
- Mainly for corn, wheat, fruit and nuts, and others

US DOMESTIC AMMONIA PRODUCTION AND IMPORTS VARIED OVER TIME WHILE CONSUMPTION REMAINS STABLE – Accomplishment

- If the amount of current imported ammonia is produced in the US, domestic production can be increased by 43% without increment in ammonia demand.



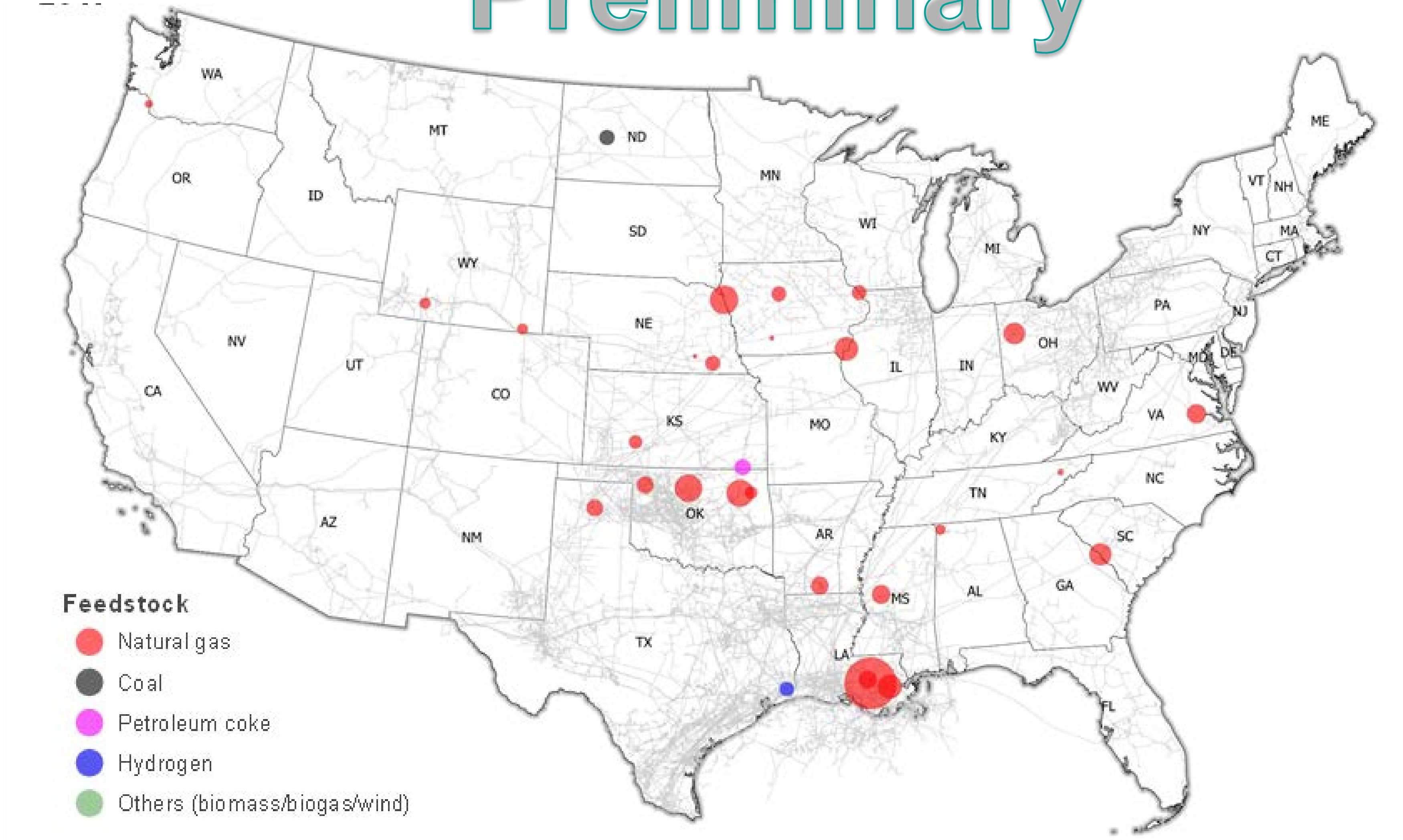
Data: USGS nitrogen (fixed)-ammonia (USGS 2016)



Data: USGS 2016; EIA 2017

U.S. AMMONIA PRODUCTION 2017 – *Accomplishment*

Preliminary

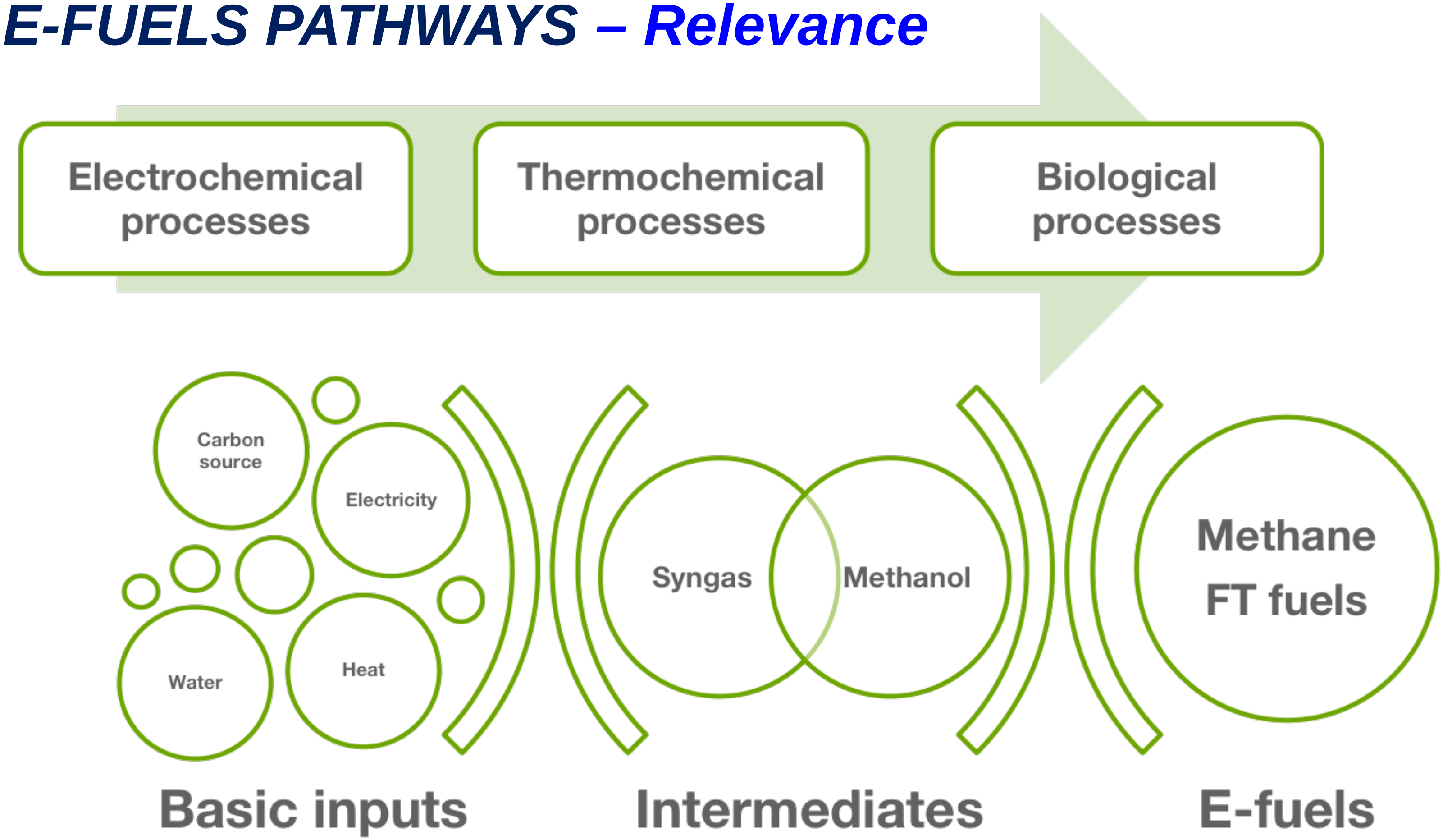


Assumption: capacity factor 90%

H_2 demand: 2.6 MMT
NH_3 production: 16.2 MMT

E-FUEL (SYNFUEL) PRODUCTION
(H_2 +CO_2 → LIQUID HC)

E-FUELS PATHWAYS – *Relevance*



Electrochemical processes

Thermochemical processes

Biological processes

Carbon source

Electricity

Water

Heat

Syngas

Methanol

Methane

FT fuels

Basic inputs

Intermediates

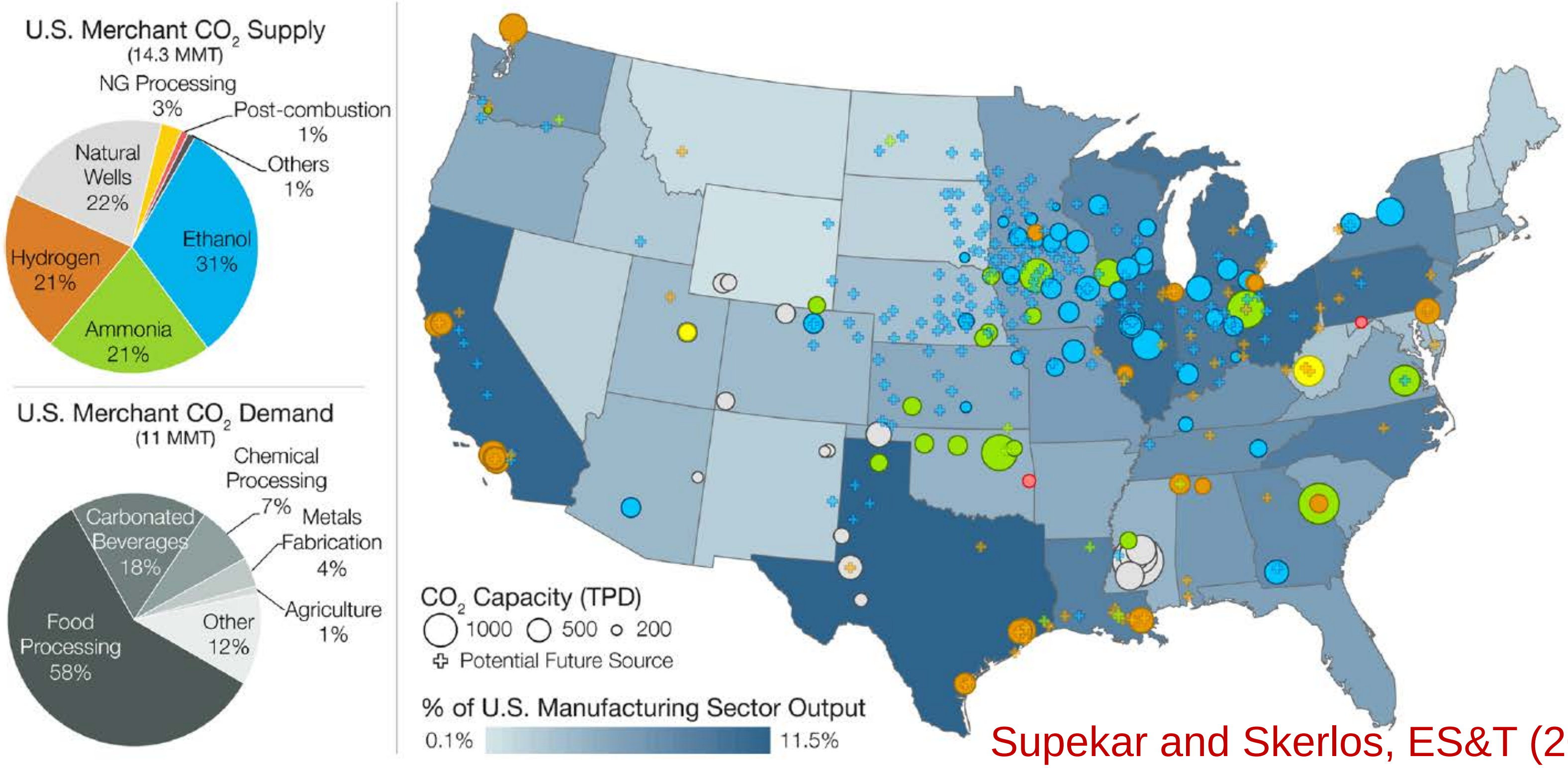
E-fuels

WHAT ARE ELECTROFUELS?

Electrofuels or “e-fuels” encompass **energy carriers** and their **intermediates** synthesized primarily using a carbon source and electricity.

DEMAND FOR E-FUEL PRODUCTION→ CO$_2$ SOURCES – *Accomplishment*

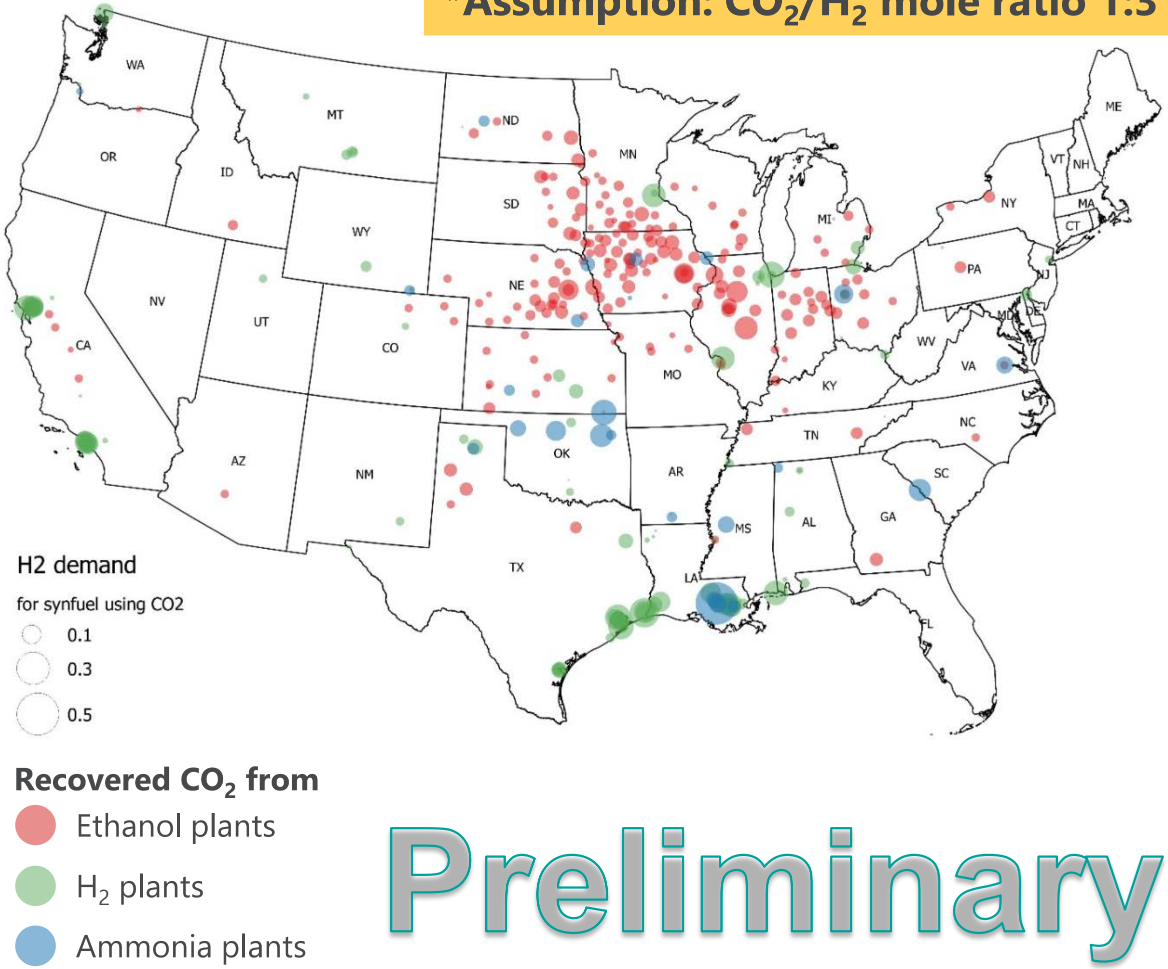
- 100 million MT of concentrated CO$_2$ produced annually (out of total 3 GT CO$_2$)
  - ➢ 44 million MT from ethanol plants
    - ✓ Current market supply capacity of 14 MMT, and demand of 11 MMT
  - ➢ Remainder from hydrogen SMR (refineries) and ammonia plants



Supekar and Skerlos, ES&T (2014)

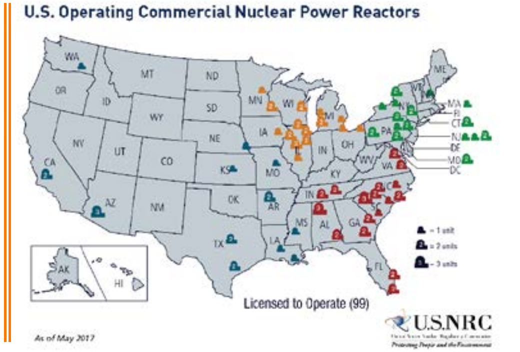
TOTAL E-FUEL H_2 DEMAND BY CO_2 SOURCE LOCATION COULD ADD UP TO 14 MMT PER YEAR – *Accomplishment*

***Assumption: CO_2/H_2 mole ratio 1:3**

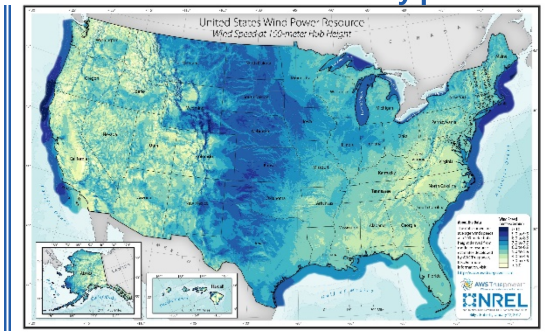


Preliminary

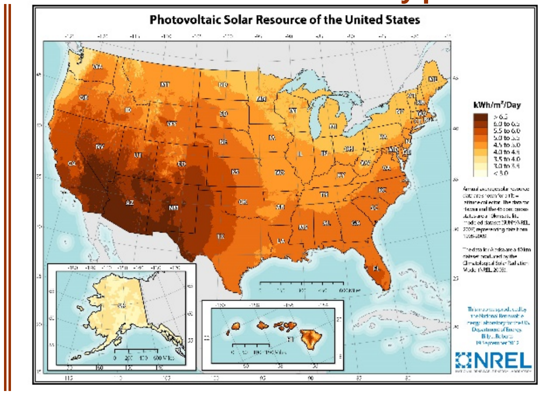
Installed nuclear plants



Wind electricity potential

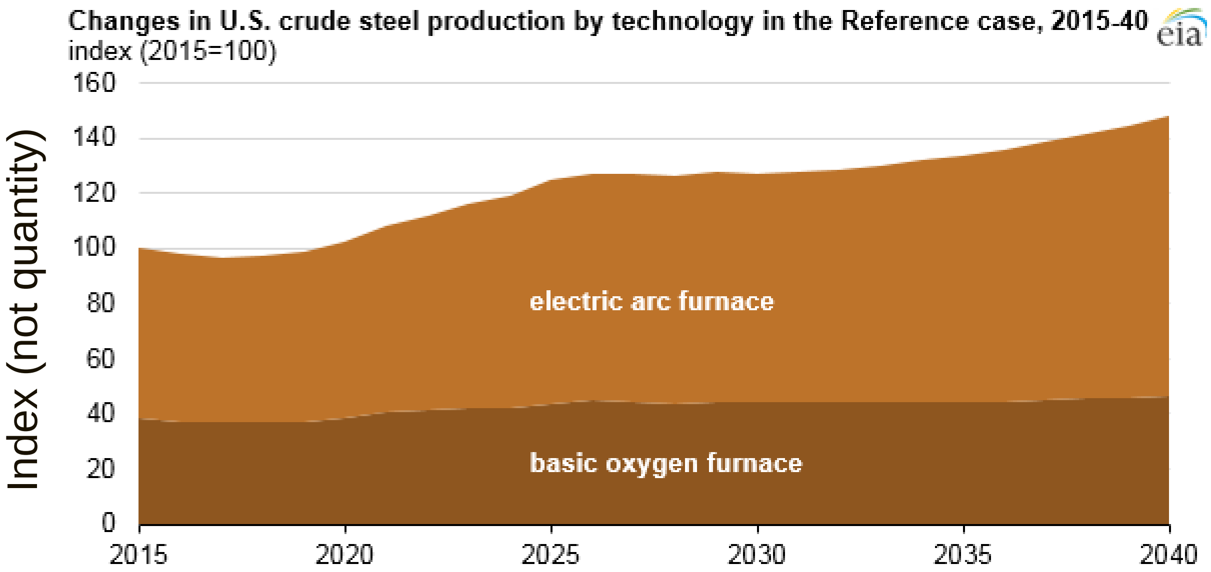


Solar electricity potential



POTENTIAL HYDROGEN DEMAND FOR STEEL REFINING

STEEL MAKING AND POTENTIAL HYDROGEN DEMAND – *Accomplishment*



Projected growth from 80 to 120 MMT (50%) by 2040

- 100 kg of hydrogen is estimated to produce 1 MT of hot iron with direct reduction iron (DRI) technology
  - 1 ton of H_2 can replace 5 ton of coke
  - If all imported steel (35 MMT steel) is replaced with U.S. production via DRI, demand would be 3.5 MMT H_2
  - If all steel is produced via DRI in U.S. in 2040 (120 MMT steel), demand would be 12 MMT H_2
    - ✓ In near-term, DRI in a mix of 30% H_2 by energy is feasible (Midrex)
  - H_2 price of ~$1.50 (2017 dollars)/kg would generate positive NPV for DRI[1]

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1. Sohn, H.Y., and Y. Mohassab, 2016. "Development of a Novel Flash Ironmaking Technology with Greatly Reduced Energy Consumption and CO_2 Emissions," *Journal of Sustainable Metallurgy*, Vol. 2(3):216–227. DOI 10.1007/s40831-016-0054-8.

POTENTIAL HYDROGEN DEMAND FOR OTHER APPLICATIONS – *Accomplishment*

Application	Target H_2 Price [$/kg]	Potential H_2 Demand [MMT]	Notes
Light-Duty FCEV (cars)	5	2.5	Vehicle choice model (VCM)
	2.7	3.3	Vehicle choice model
Light-Duty FCEV (trucks)	5	4	Vehicle choice model
	2.7	6.2	Vehicle choice model
Medium-Duty FCEV	5	1	Zero-emissions mandate
Heavy-Duty FCEV	5	0.5	Zero-emissions mandate
Petroleum Refining	inelastic demand	7.5	No substitute for H_2 in refining process
Biofuels	inelastic demand	4	Renewable Fuel Standard
NH_3	inelastic demand	2.6	Demand for current production of NH_3
	2	3.6	Competitive with SMR H_2
Synthetic MeOH	2	3.8	Competitive with SMR H_2
Synthetic FT Diesel	1.5	6	To compete with petroleum diesel
Injection to NG Infrastructure	0.8	10	Competitive with NG HHV
Iron Reduction and Steelmaking	1.7	3.5	Techno-economic analysis of DRI
	0.8	12	Competitive with NG HHV

✓ We note that the assessed scenarios for potential H_2 demand by various applications may be exclusive of one another (i.e., the H_2 demand by different scenarios may not be additive)

SUMMARY – Accomplishment

- Evaluated current and potential future annual hydrogen demand for various applications
  - Petroleum refining (7.5 MMT)
  - Ammonia production (3.6 MMT)
  - e-fuels (14 MMT)
  - Steel refining (12 MMT)

- Additional potential H_2 market demands were evaluated
  - Biofuels production
  - FCEVs (LDV and M/HDV)
  - Injection into NG pipelines

- Documented all data sources, modeling approach and analysis in a report
  - Report has been peer reviewed
  - Awaiting clearance for public release

Collaborations and Acknowledgments

- Mark Ruth, Paige Jadun and Bryan Pivovar: NREL
- Richard Boardman: INL
- Jamie Holliday: PNNL
- Troy Hawkins, Krishna Reddi, Sarang Supekar, Ted Krause and John Kopasz: ANL
- Elizabeth Connelly: DOE
- George Parks: FuelScience

Future Work

- Develop LCA for environmental analysis of new pathways
  - e.g., e-fuels and steel refining
- Conduct regional analysis considering proximity of supply and demand
  - Delivered H_2 vs. onsite production
  - Delivery mode / bulk storage requirement
    - As a function of volume, schedule, and pressure requirement
- Consider potential other markets (e.g., hythane for NG power generators)
- Consider non-physical materials for delivering and storing hydrogen (e.g., chemical carriers)
- Publish H2@Scale Demand Report

Project Summary

- **Relevance**: hydrogen from clean energy sources can enable renewable energy penetration and serve energy sectors beyond transportation
- **Approach**: evaluate potential growth in hydrogen demand for existing and emerging applications
- **Collaborations**: H2@Scale is a multi-national laboratory effort with collaboration across DOE national lab complex
- **Technical accomplishments and progress**:
  - Evaluated current and potential future hydrogen market demand for various applications
    - Petroleum refining, ammonia production, e-fuels, and steel refining
  - Additional potential H_2 market demands were evaluated
    - Biofuels production, FCEVs (LDV and M/HDV), Injection into NG pipelines
  - Documented all data sources, modeling approach and analysis in a report
    - Report was peer reviewed
    - Awaiting clearance for public release
- **Future Research**:
  - Develop LCA for environmental analysis of new pathways
  - Conduct regional analysis considering proximity of supply and demand
  - Consider potential other markets (e.g., hythane for NG power generators)
  - Consider non-physical materials for delivering and storing hydrogen (e.g., chemical carriers)
  - Publish H2@Scale Demand report

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Backup Slides

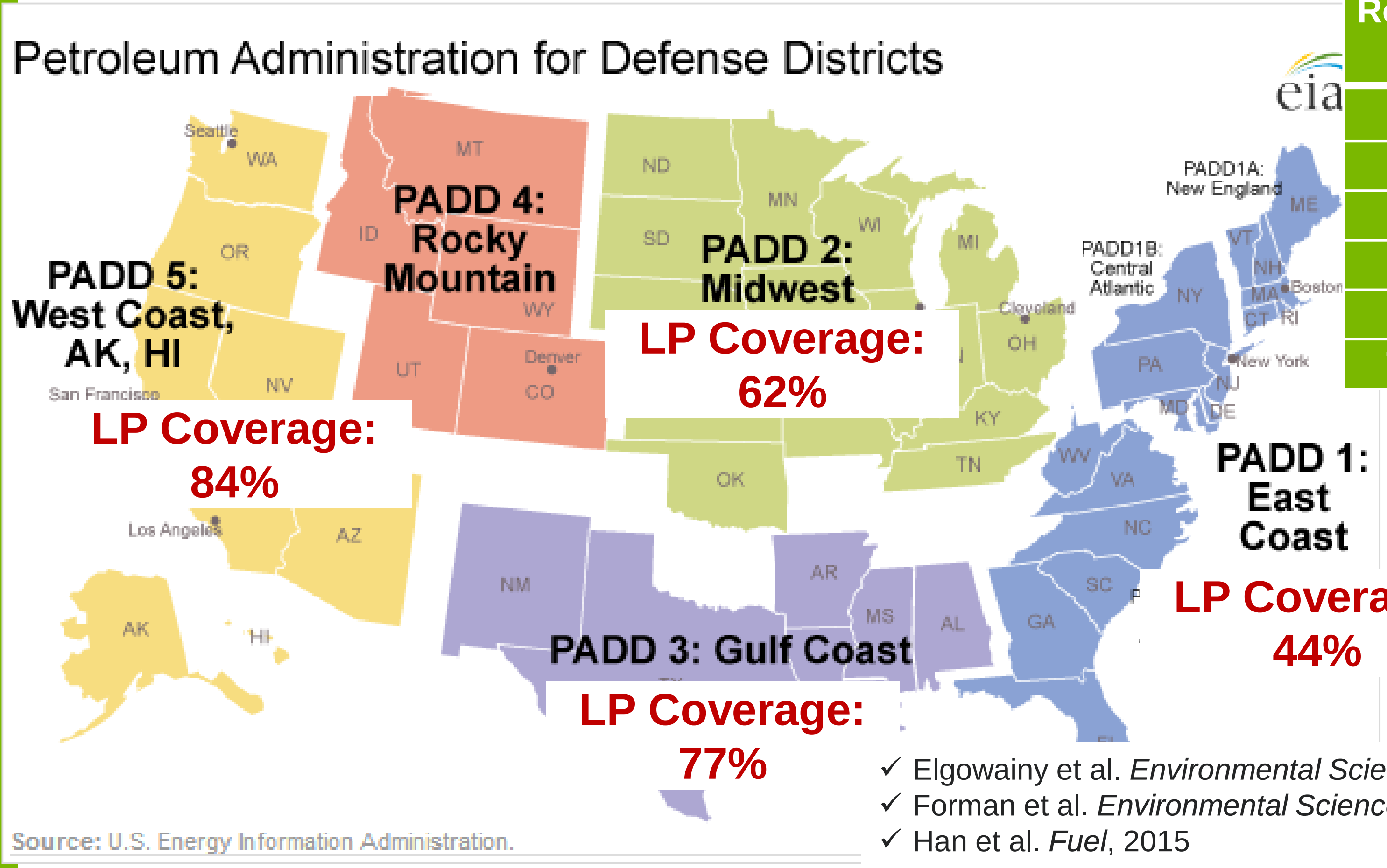
Acronyms

- AEO: Annual Energy Outlook
- AMR: Annual Merit Review
- API: American Petroleum Institute
- ANL: Argonne National Laboratory
- BBL: Barrel
- CI: Complexity Index
- CWT: hundredweight (=100 lb)
- D: Diesel
- DME: Di-Methyl Ether
- DOE: Department of Energy
- DRI: Direct Iron Reduction
- EIA: Energy Information Administration
- FCCU: Fluid Catalytic Cracker Unit
- FCEV: Fuel Cell Electric Vehicle
- FCTO: Fuel Cell Technologies Office
- FT: Fischer-Tropsch
- FY: Fiscal Year
- G/D: Gasoline/Diesel ratio
- GH_2: Gaseous Hydrogen
- GREET: Greenhouse gases, Regulated Emissions, and Energy use in Transportation
- GT: Giga Ton
- H_2: Hydrogen
- H2A: Hydrogen Analysis
- HC: Hydrocarbon
- HDSAM: Hydrogen Delivery Scenario Analysis Model
- HDT: Hydrotreater
- HHV: Higher Heating Value
- HP: Heavy Products
- INL: Idaho National Laboratory
- LBNL: Lawrence Berkeley National Lab.
- LCA: Life Cycle Analysis
- LDV: Light Duty Vehicle
- LHV: Lower Heating Value
- LLNL: Lawrence Livermore National Lab.
- LP: Linear Programming
- LPG: Liquefied Petroleum Gas
- M/HDV: Mediun- and Heavy-Duty Vehicle
- MeOH: Methanol
- MT: Metric Ton
- MMT: Million Metric Ton
- N: Nitrogen
- NASS: National Agricultural Statistics Service
- NE: Nuclear Energy
- NG: Natural Gas
- NH_3: Ammonia
- NPV: Net Present Value
- NREL: National Renewable Energy Lab.
- PADD: Petroleum Administration for Defense Districts
- PNNL: Pacific Northwest National Laboratory
- RD&D: Research, Development, and Demonstration
- S: Sulfur
- SMR: Steam Methane Reformer
- SNL: Sandia National Laboratory
- ULSD: Ultra Low Sulfur Diesel
- U.S.: United States
- USDA: United States Department of Agriculture
- VCM: Vehicle Choice Model
- η: Efficiency

ANL STUDY COVERED 70% OF U.S. REFINING CAPACITY – *Approach*

- LP modeling of 43 large (>100k bbl/d) refineries in four PADD regions

PADD Region	Crude Input to Refineries (1000 bbl/day)[a]
I	
II	
III	
IV	
V	
Total	



LP Coverage: 84%

LP Coverage: 62%

LP Coverage: 77%

LP Coverage: 44%

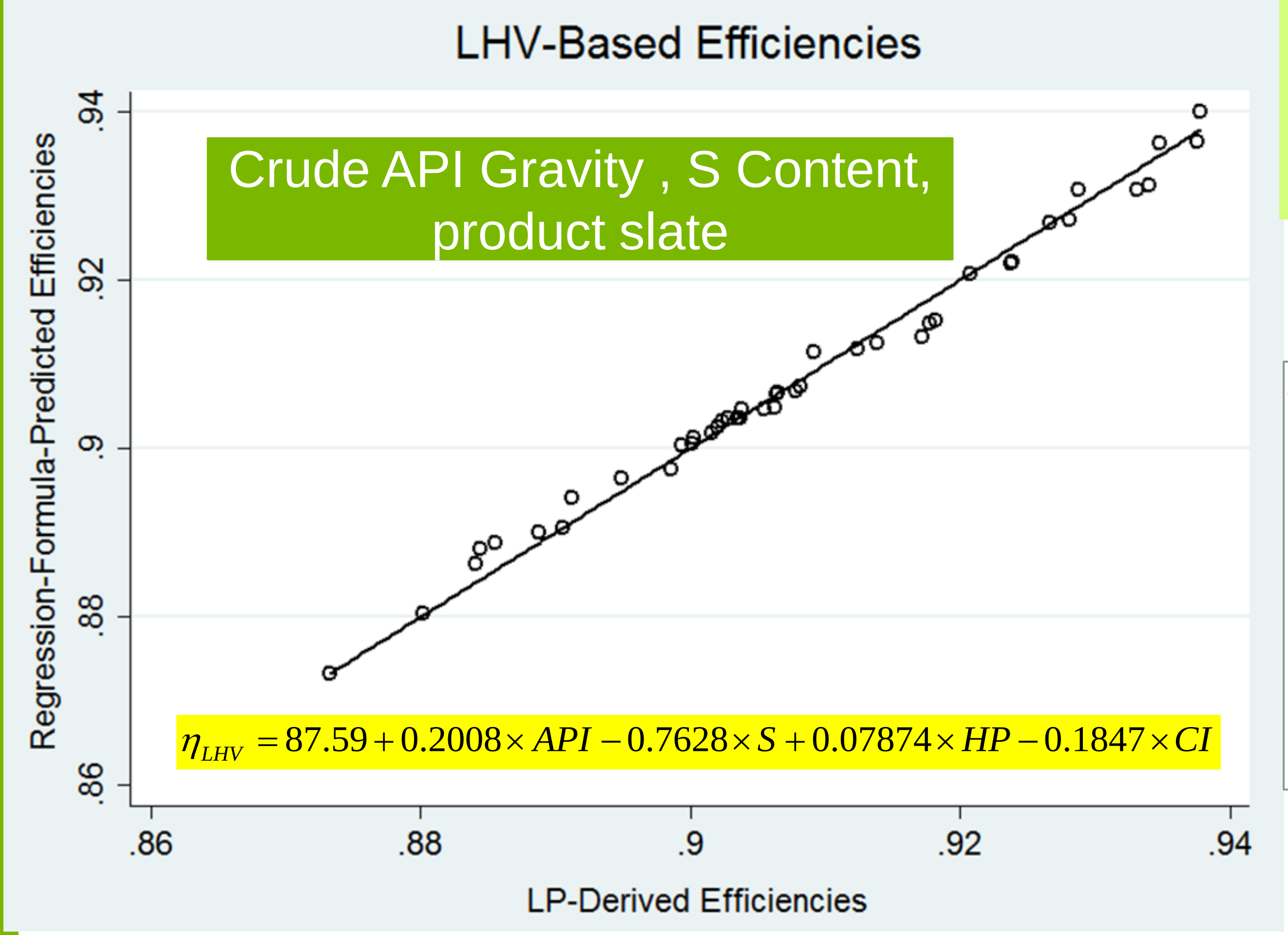
Source: U.S. Energy Information Administration.

- ✓ Elgowainy et al. *Environmental Science and Technology*, 2014
- ✓ Forman et al. *Environmental Science and Technology*, 2014
- ✓ Han et al. *Fuel*, 2015

LP=Linear programming

CORRELATED REFINERY OVERALL EFFICIENCY WITH KEY REFINERY PARAMETERS – *Relevance/Impact*

Efficiency=f(API, sulfur%, heavy product yield, refinery complexity index)



Crude API Gravity , S Content, product slate

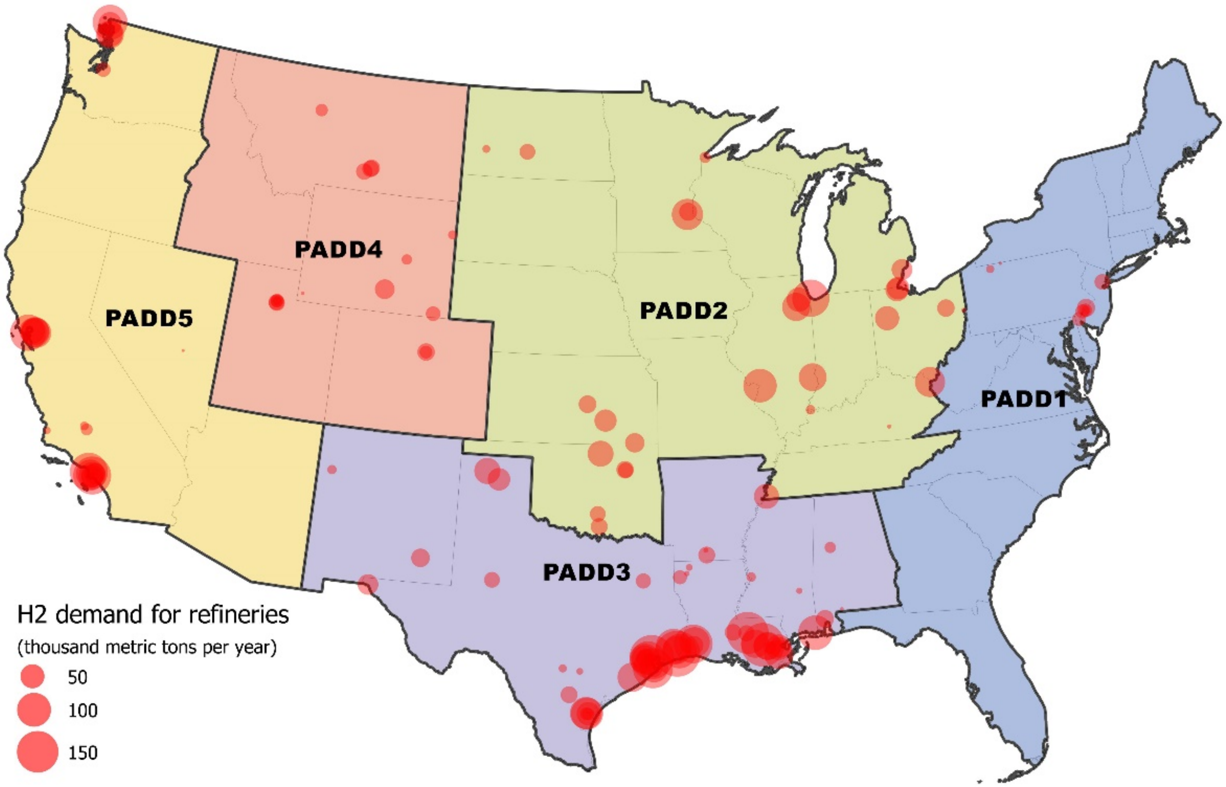
$$\eta_{LHV} = 87.59 + 0.2008 \times API - 0.7628 \times S + 0.07874 \times HP - 0.1847 \times CI$$

70% of US refining capacity, covering 43 large (>100K bbl/d) refineries in four PADD regions

η_{LHV}	is the refinery's overall efficiency (on an LHV basis) in %;
API	is the API gravity of crude oil;
S	is the sulfur content of crude oil in % by weight;
HP	is the heavy products yield in % by energy;
CI	is the actual utilized Complexity Index of the refinery.

FACILITY-LEVEL H_2 DEMAND FOR US REFINERIES (2017) – Accomplishment

	PADD1	PADD2	PADD3	PADD4	PADD5	US
H_2 demand (MMT)	0.12	1.2	3.0	0.3	1.4	5.9
H_2/Crude (ft^3/bbl)	100	315	329	430	504	342

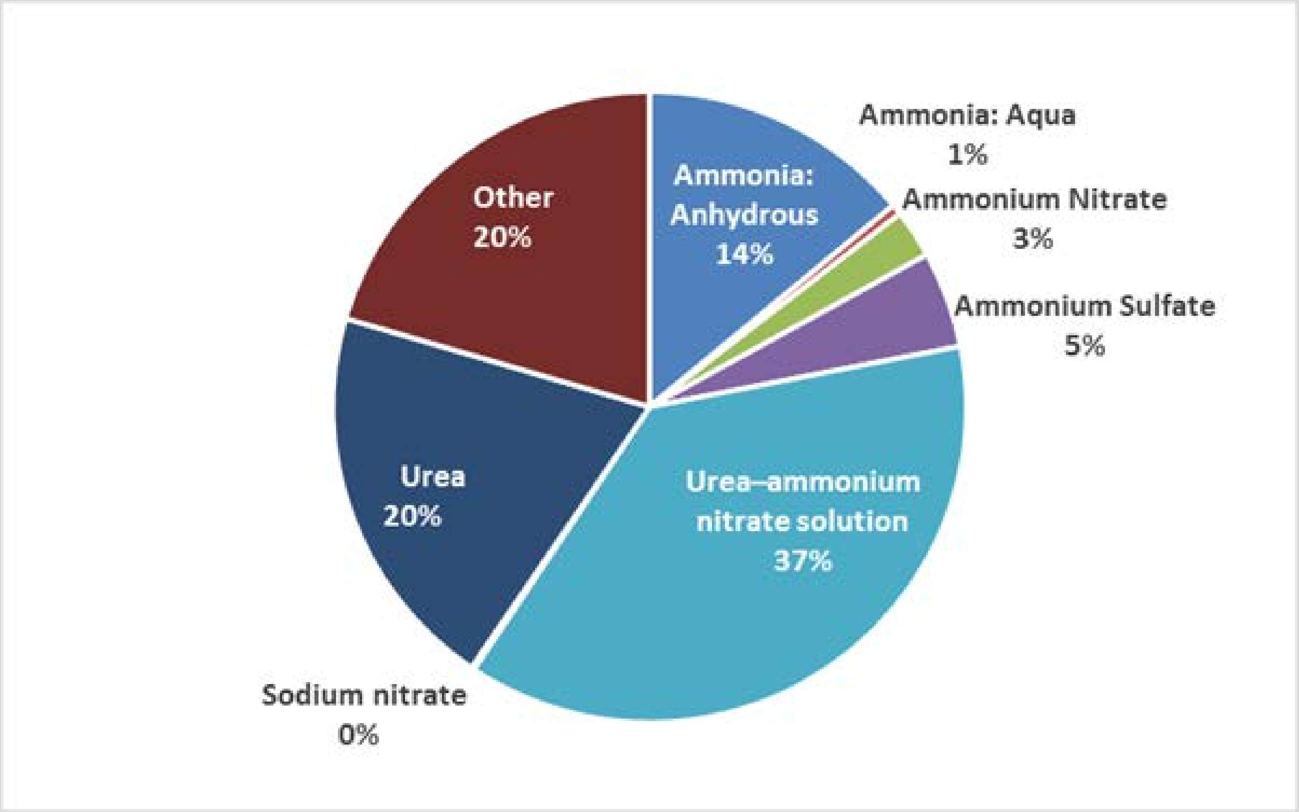


- Estimated based on facilities' crude distillation capacity and PADD H_2/crude ratios

U.S. CONSUMPTION OF SELECTED NITROGEN MATERIALS (SHORT TON) – *Relevance*

- Ammonia production in various forms

Ammonia: Anhydrous	Ammonia: Aqua	Ammonium Nitrate	Ammonium Sulfate	Urea–ammonium nitrate solution	Sodium nitrate	Urea	Other	Total
4,248,383	166,300	753,356	1,501,547	11,399,279	46,171	6,093,222	6,230,048	30,438,306



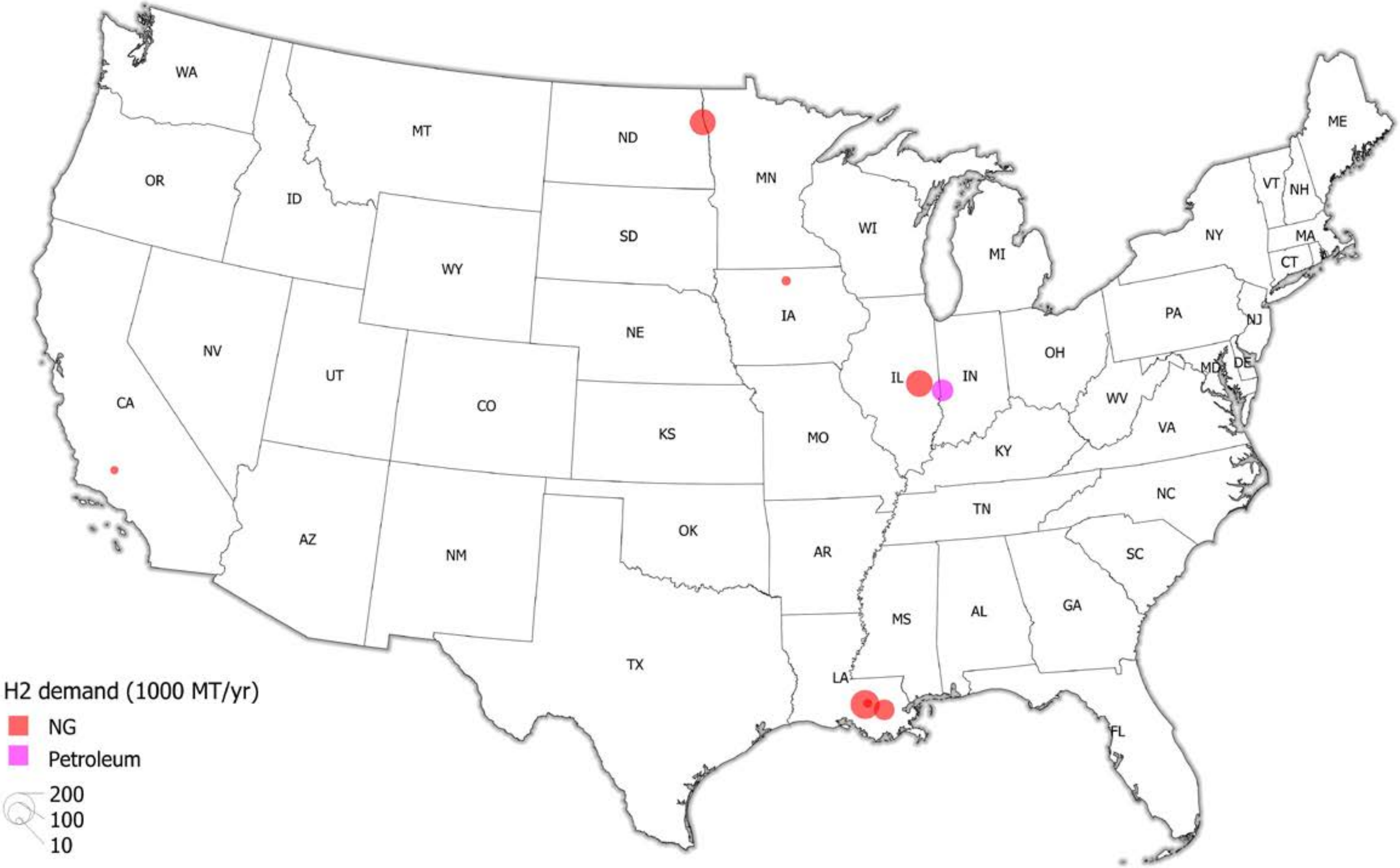
Source: USDA

***U.S. IMPORTS AND EXPORTS OF SELECTED N FERTILIZERS** – Relevance*

	2012		
	Export (short ton)	Import (short ton)	Net Import (short ton)
Ammonium Nitrate (Solid)	400,000	900,000	**500,000**
Urea (Solid)	400,000	7,700,000	**7,300,000**
Urea–ammonium nitrate solution	160,000	3,300,000	**3,140,000**
Ammonium Sulfate	1,400,000	300,000	**-1,100,000**
Anhydrous Ammonia	40,000	6,900,000	**6,860,000**
Aqua Ammonia	7,000	97,000	**90,000**
Calcium Nitrate	0	43,000	**43,000**
Diammonium Phosphate (DAP)	4,000,000	100,000	**-3,900,000**
Monammonium Phosphate (MAP)	2,700,000	600,000	**-2,100,000**
Other Nitrogen Fertilizers	30,000	460,000	**430,000**
Potassium Nitrate	17,000	175,000	**158,000**
Potassium-Sodium Nitrate	0	600	**600**
Sodium Nitrate	4,000	164,000	**160,000**
Total	~9,000,000	~21,000,000	**~12,000,000**

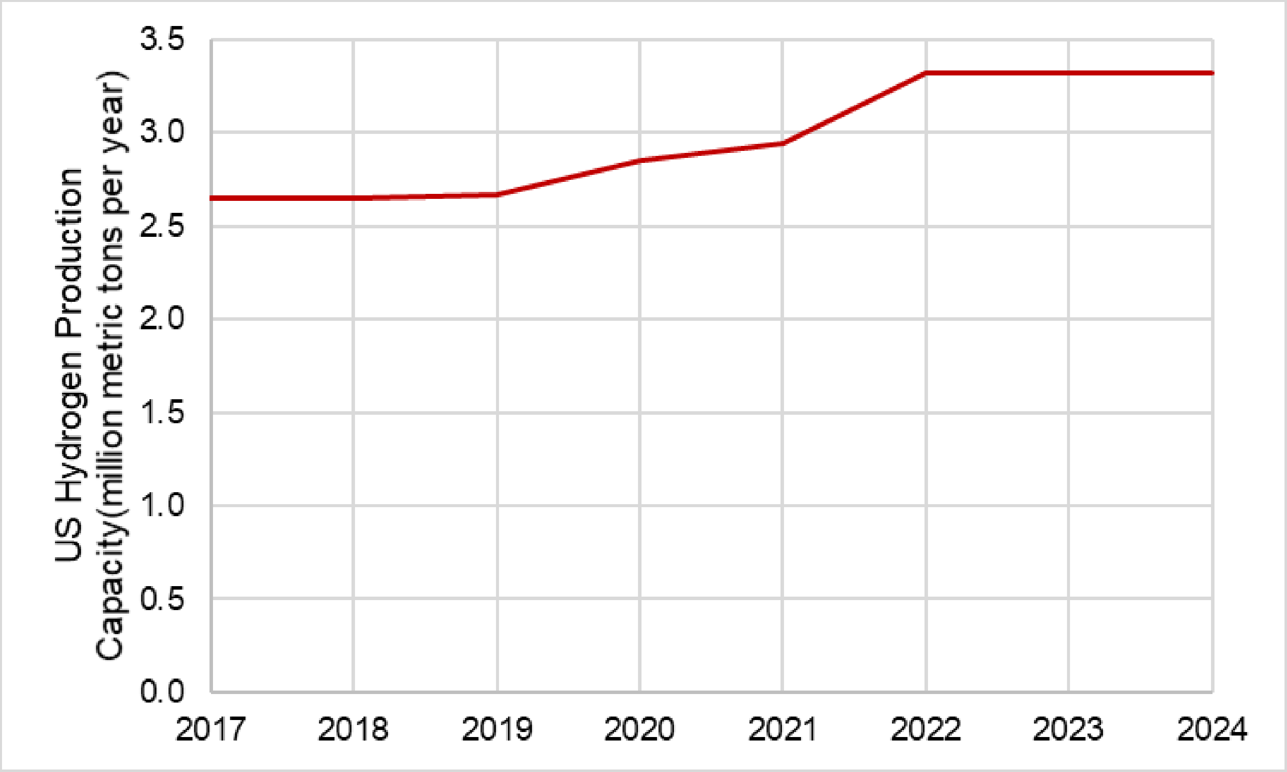
Source: USDA (estimates rounded)

“POSSIBLE” INCREASE IN U.S. AMMONIA PRODUCTION CAPACITY 2017-2022 – *Accomplishment*



AMMONIA PRODUCTION HYDROGEN DEMAND: KEY FINDINGS – *Accomplishment*

- Replacing imports with domestic would mean a 40% increase in production (while U.S. consumption could remain constant).
- Possible/likely increase in U.S. ammonia production based on planned capacity expansion at existing & new facilities



Ammonia production capacity data: AmmoniaIndustry.com (as of Nov. 2018) (only possible/likely plans are included)

MAJOR CARBON AND ELECTRICITY SOURCES TO CONSIDER – *Relevance*

Carbon Sources

High purity sources of CO_2

- **Ethanol plants**
- **Refineries**
- **Ammonia plants**
- Cement plants
- Iron & steel plants

Other sources of CO_2/CO

- **Natural gas combined cycle power plants**
- **Biomass power/gasification plants**
- Coal power/gasification plants
- Ambient air

Electricity Sources

Wind

Solar

Nuclear

NG combined cycle

DEMAND FOR E-FUEL PRODUCTION – H_2 DEMAND – Accomplishment

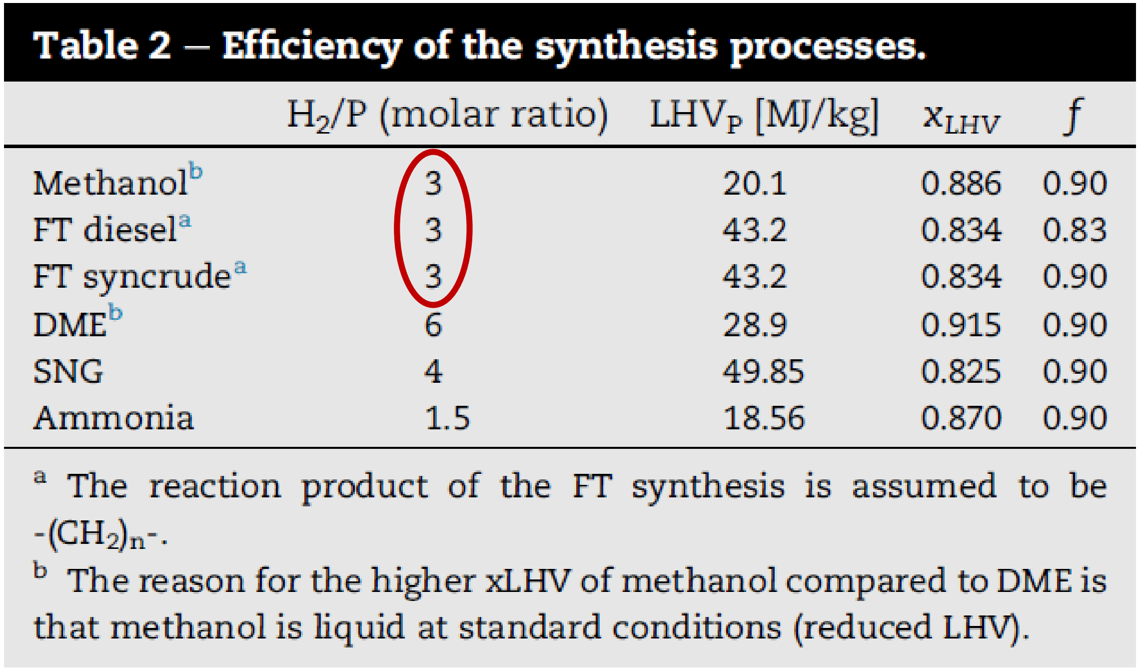


Table 2 – Efficiency of the synthesis processes.

	H_2/P (molar ratio)	LHV_P [MJ/kg]	x_{LHV}	f
Methanol[b]	3	20.1	0.886	0.90
FT diesel[a]	3	43.2	0.834	0.83
FT syncrude[a]	3	43.2	0.834	0.90
DME[b]	6	28.9	0.915	0.90
SNG	4	49.85	0.825	0.90
Ammonia	1.5	18.56	0.870	0.90

[a] The reaction product of the FT synthesis is assumed to be $\text{-}(CH_2)_n\text{-}$.

[b] The reason for the higher xLHV of methanol compared to DME is that methanol is liquid at standard conditions (reduced LHV).

Tremel et al.,
Int. J. H2 Energy (2015)

- For 44 million MT of concentrated CO_2 annually
  - 6 MMT of H_2 will be needed to produce FTD or DME via synthesis
    - ✓ CO_2/H_2 mole ratio = 1:3 (two H_2 moles to take out O_2)
  - 1 MMT of H_2 will be needed to produce FTD via electrochemical reduction of CO_2
    - ✓ CO_2/H_2 mole ratio = 2:1

STEEL MAKING AND POTENTIAL HYDROGEN DEMAND – *Accomplishment*

- 106 million MT of steel consumed in the U.S. in 2017[1]
  - ✓ 81 MMT produced (68% electric arc [EA], 32% BF) [1]
    - ➢ Scrap constitute 15% of BF feed and almost all EA feed
    - ➢ DRI feedstock enables higher quality steel than scrap metal feedstock
    - ➢ 1,100 MT (Only 0.1%) in U.S. produced via DRI[1]
  - ✓ 35 MMT imported[2]
- Use of scrap metal can reduce quality of steel produced by EA
- DRI can provide up to 100% of the feed to EA furnace to enable higher steel quality
- 430 kg of coke is required to produce 1 MT of hot iron in blast furnace (BF)
  - ✓ DRI reduces CO_2 emissions by approximately 35% compared to BF
  - ✓ H_2 for DRI virtually eliminates CO_2 emissions from the iron-making process

1. USGS, 2017. Iron and Steel Statistics. January
2. Global Steel Monitor