Hydrogen for Production of Clean Transportation Fuels & Industrial Processes

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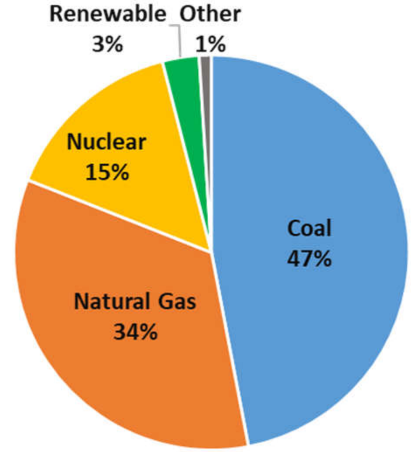
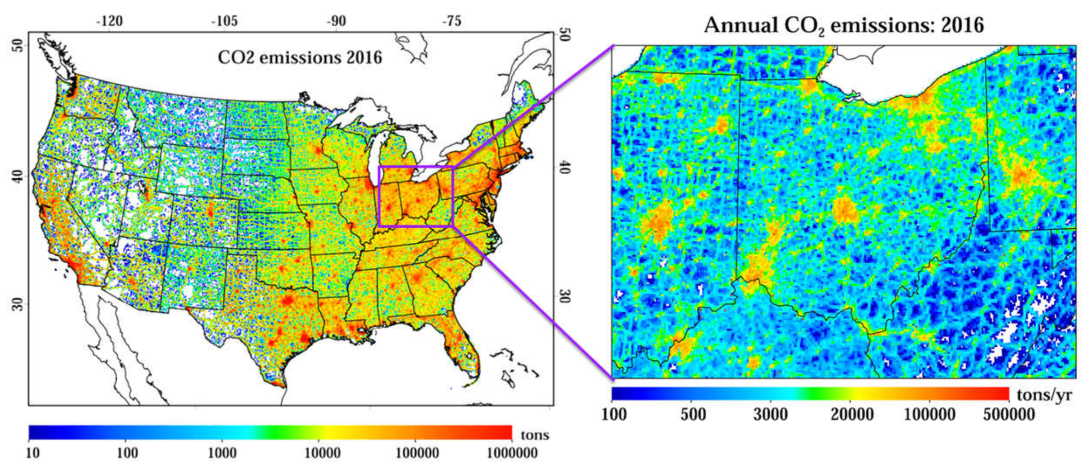
Ohio Energy Facts

- Population ~12M, with GDP ~$680B (state rank #7)
- Ohio is the third-largest coal-consuming state after TX and IN
  - ~ 90% of the coal is used for power generation
- Ohio's two nuclear power plants, along Lake Erie, supplied about 15% of the state's net generation in 2018
- Rapid increase in Ohio's NG production (Utica shale)
  - 28 times higher in 2018 than in 2012
- Ohio has the 7th largest crude oil-refining capacity
  - Four refineries can process ~ 600,000 bpd
- Ohio is the 8th largest ethanol-producing state
  - supplying about 550 million gallons per year
- Stark Area Regional Transit Authority (SARTA)
  - 7 H_2 FCEB, with 5 additional planned this year

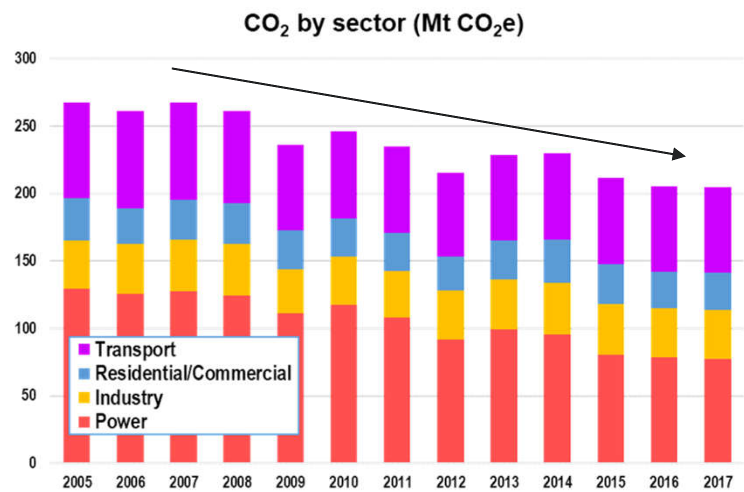


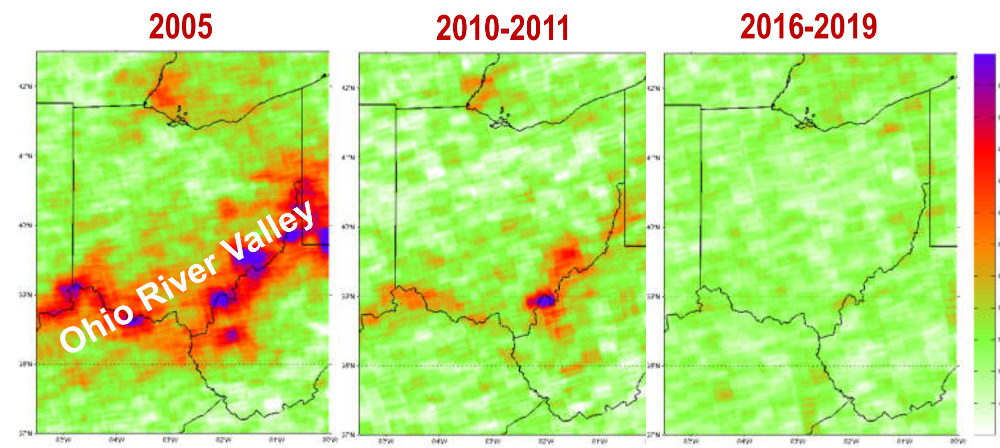
Ohio net electricity generation by source (EIA 2018)



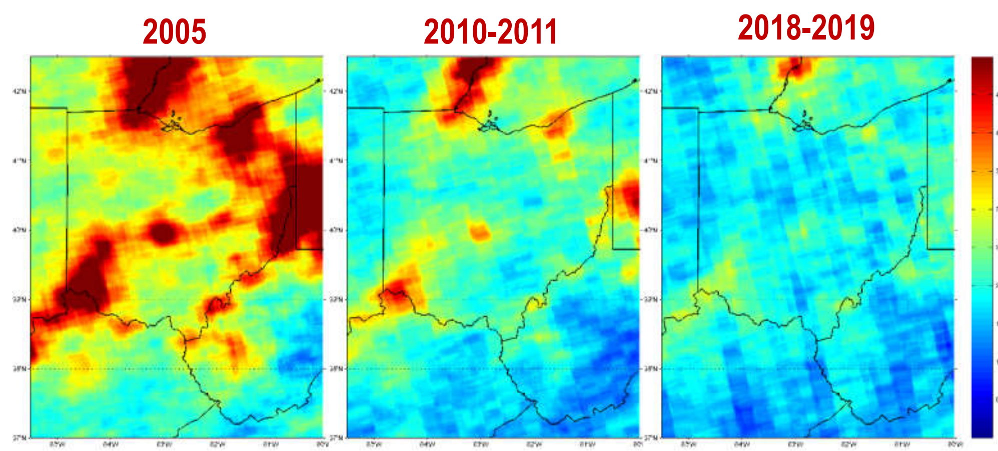
Goldberg, D., Lu, Z., Oda, T. et al., Science of The Total Environment, 695, 133805, 2019

Ohio Environmental Facts: significant reduction in CO_2, SOx, and NOx over time

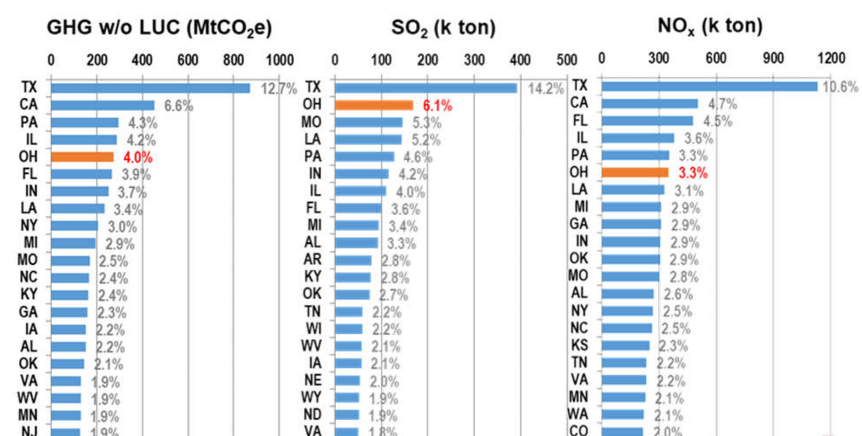




SOx emissions reduction, due to the control of SO_2 in coal-fired power plants



NOx emissions reduction control of NOx in power plants and vehicles



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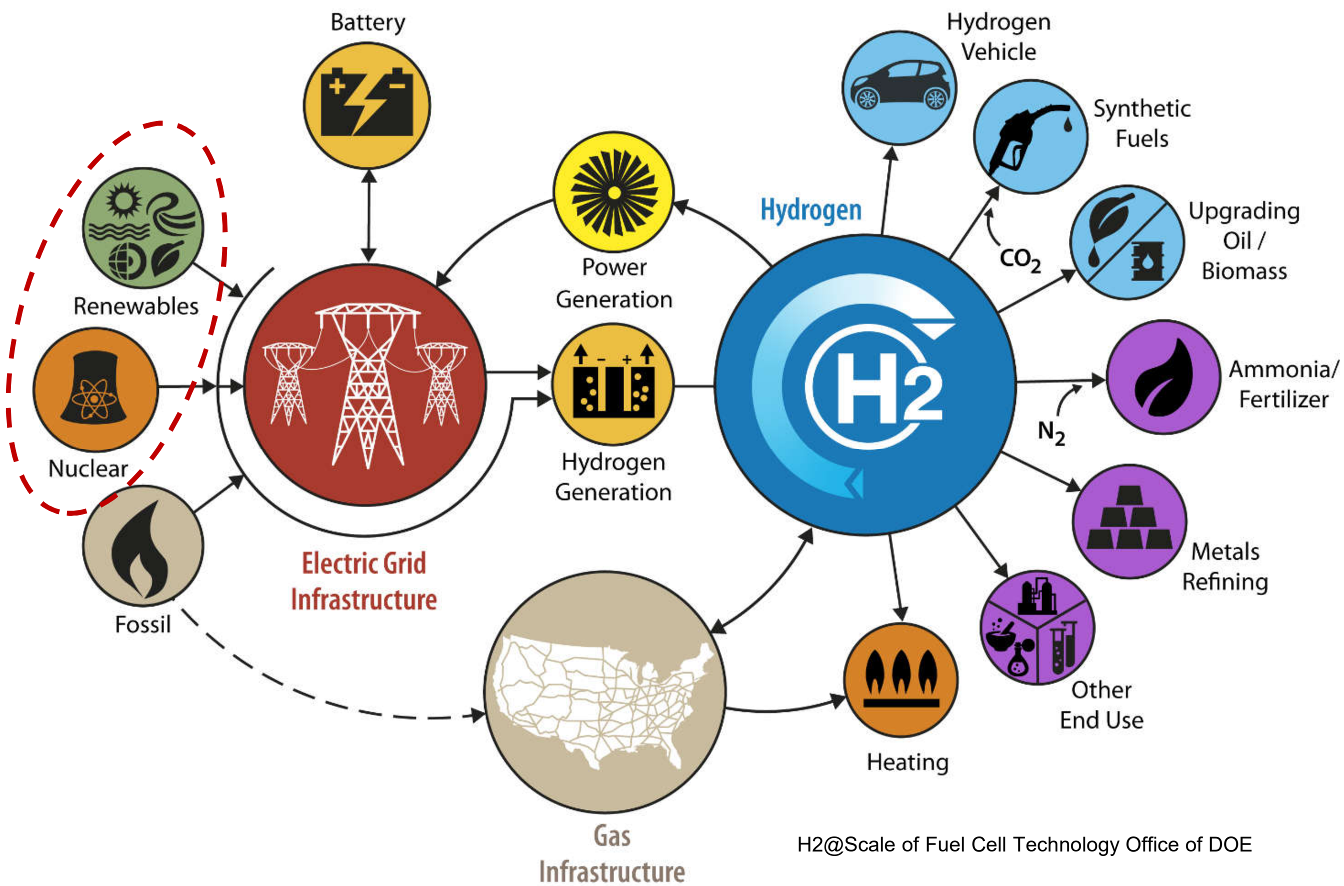
Data are processed by Zifeng Lu @ ANL, based on April to September data

H2@Scale enables grid flexibility with more renewables, while creating green opportunities across sectors*

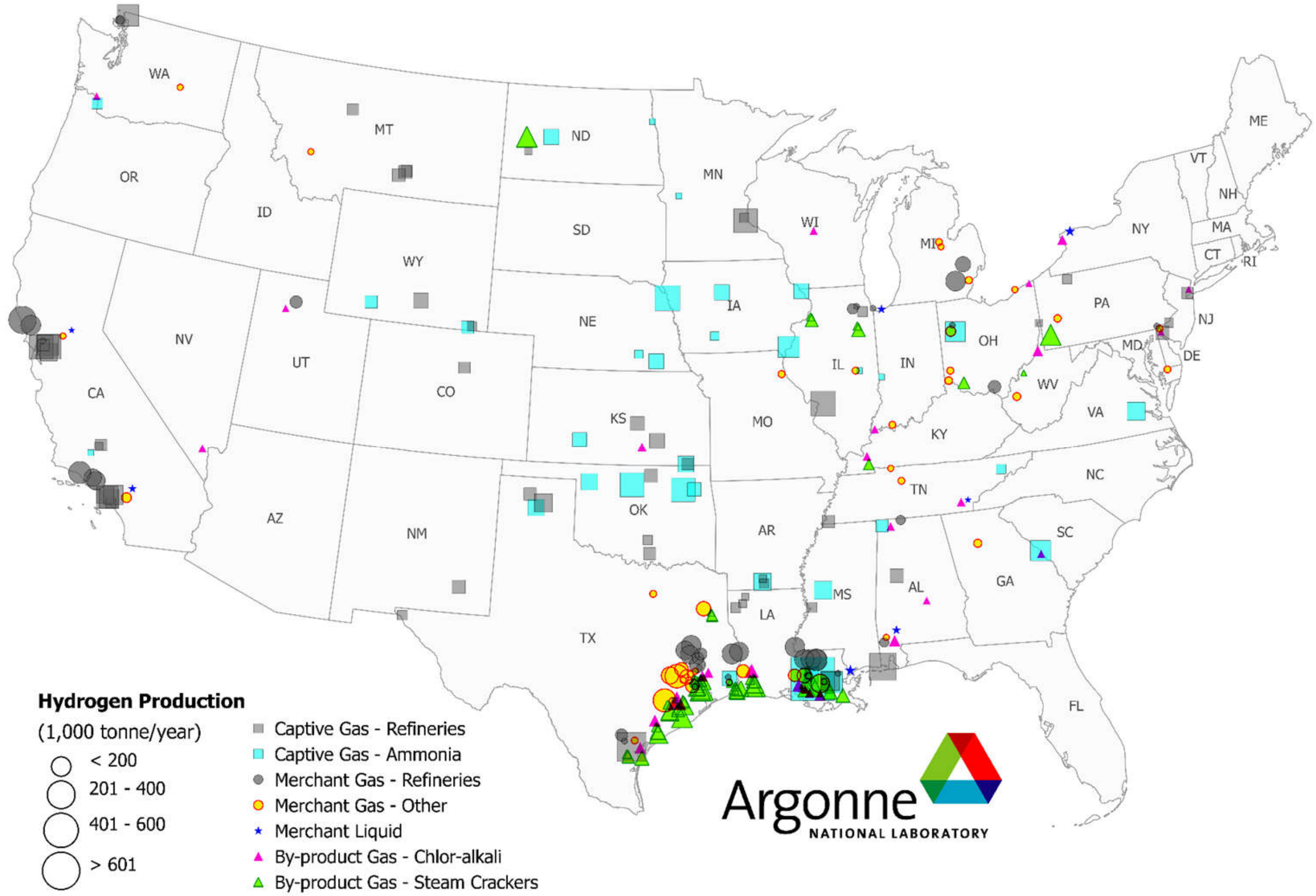


H2@Scale of Fuel Cell Technology Office of DOE

*Illustrative examples, not comprehensive

Today, more than 10M metric tons of hydrogen are produced in the U.S. annually

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



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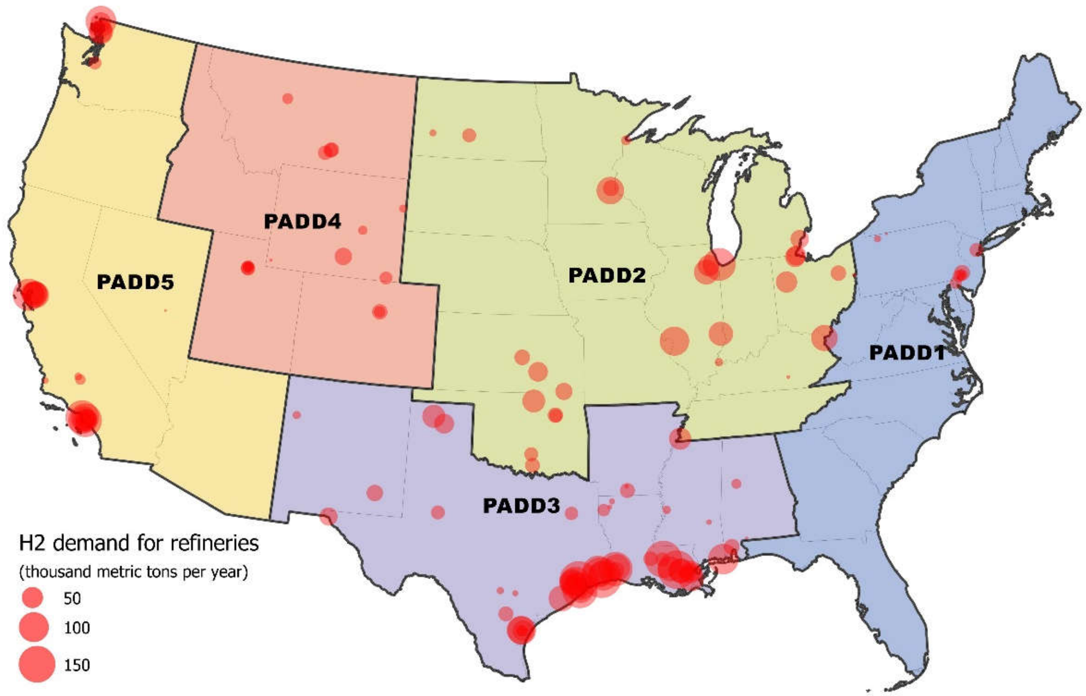
Facility-level H_2 demand for US refineries (2017)

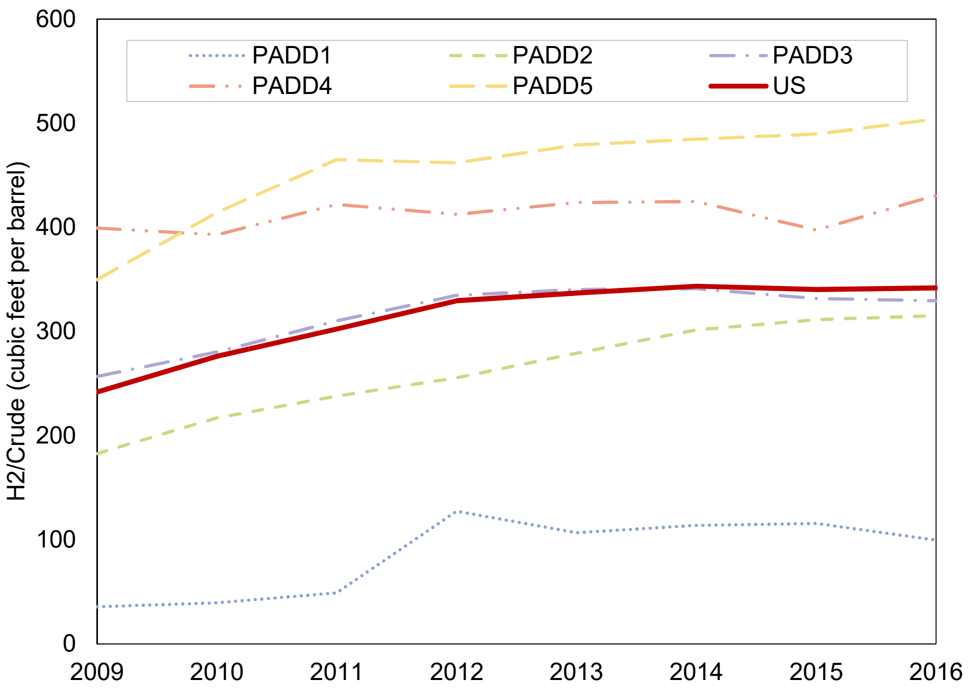
	PADD1	PADD2	PADD3	PADD4	PADD5	US
H_2 demand (MMT)	0.12	1.2	3.0	0.3	1.4	5.9
H_2/Crude (ft^3/bbl)	100	315	329	430	504	342

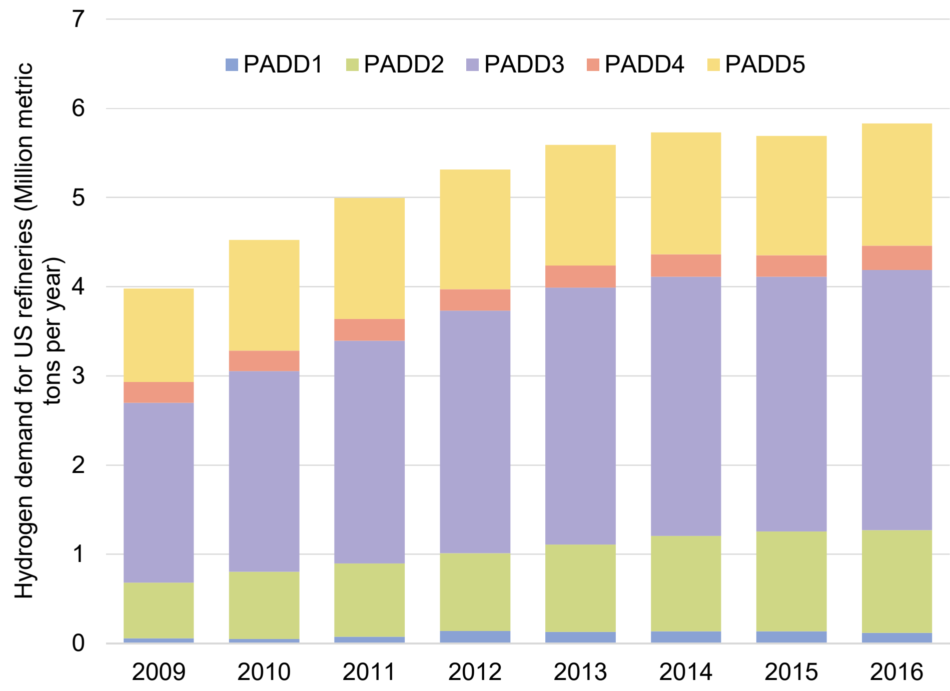


- Estimated based on facilities' crude distillation capacity and PADD H2/crude ratios

Recently, H_2 demand for US refineries has increased significantly

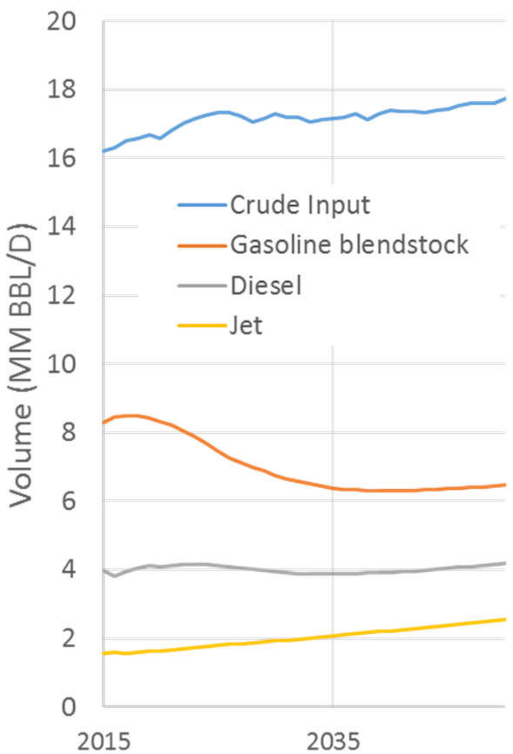
- H_2 demand has been increased due to increased diesel demand and more stringent regulations.
- H_2/Crude ratio shows regional variation; H_2/Crude increases over time.



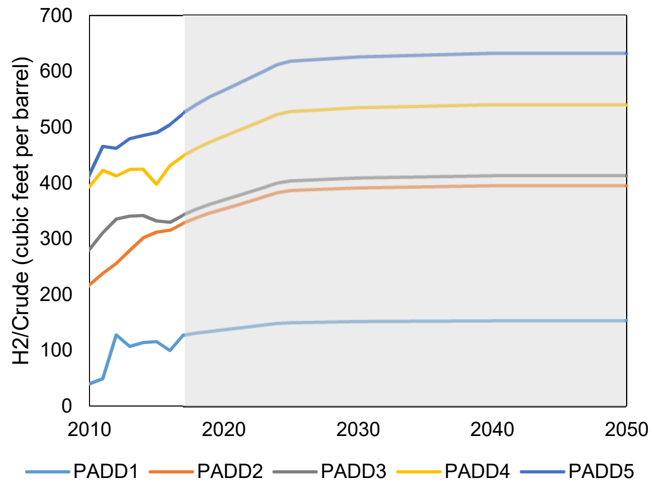


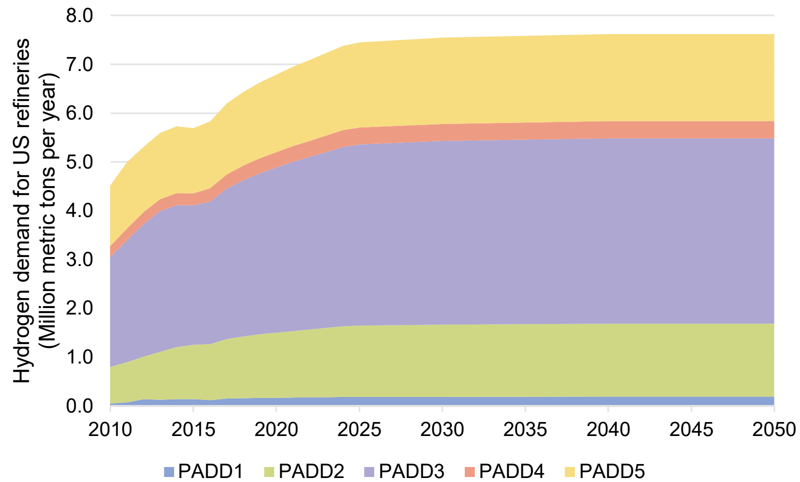
Estimation of future H_2 demand for US refineries

- H_2/Crude will increase through 2030
- Crude capacity would increase 9% from 2015 to 2021 and remain stable for the subsequent years (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

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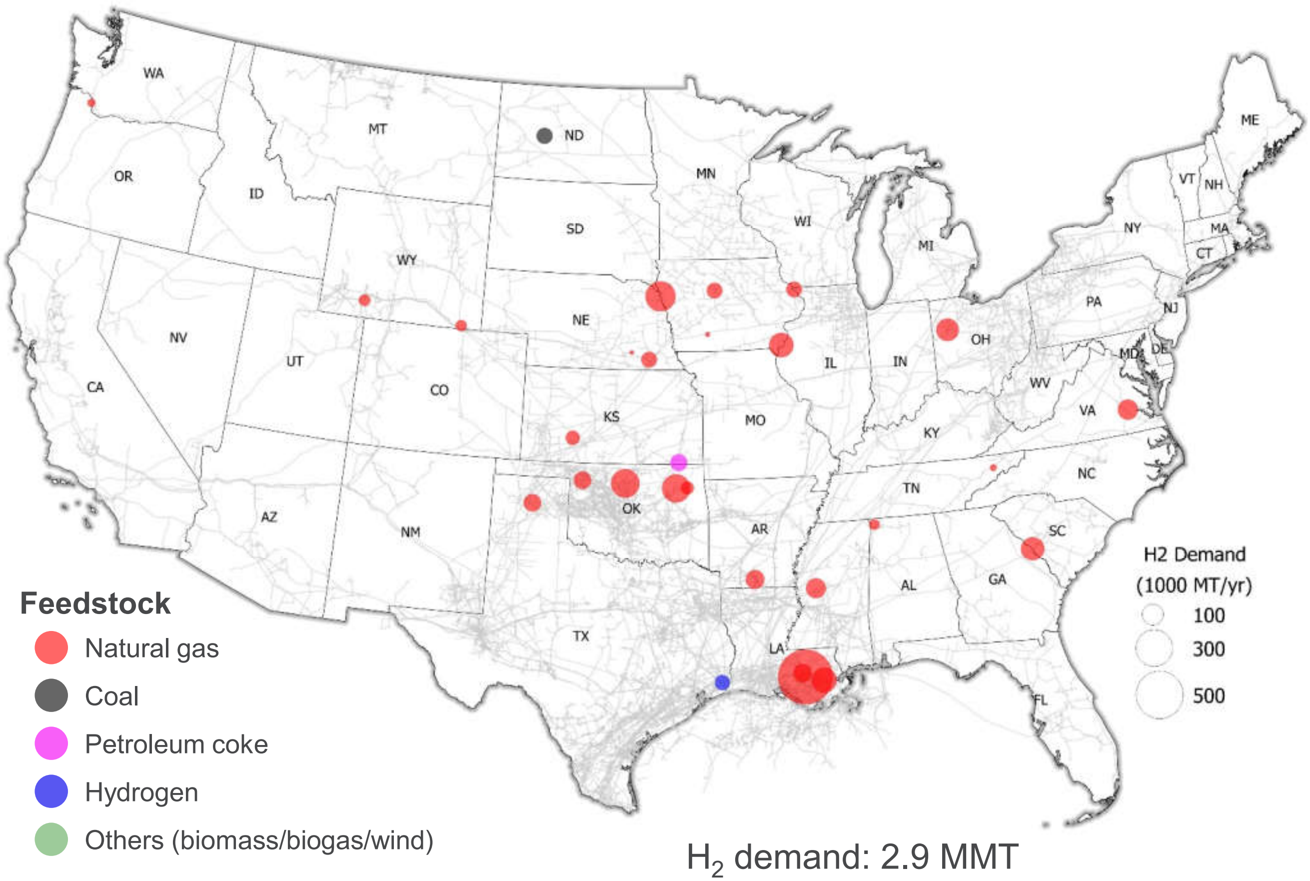
POTENTIAL HYDROGEN DEMAND FOR AMMONIA PRODUCTION

U.S. Ammonia Production 2016

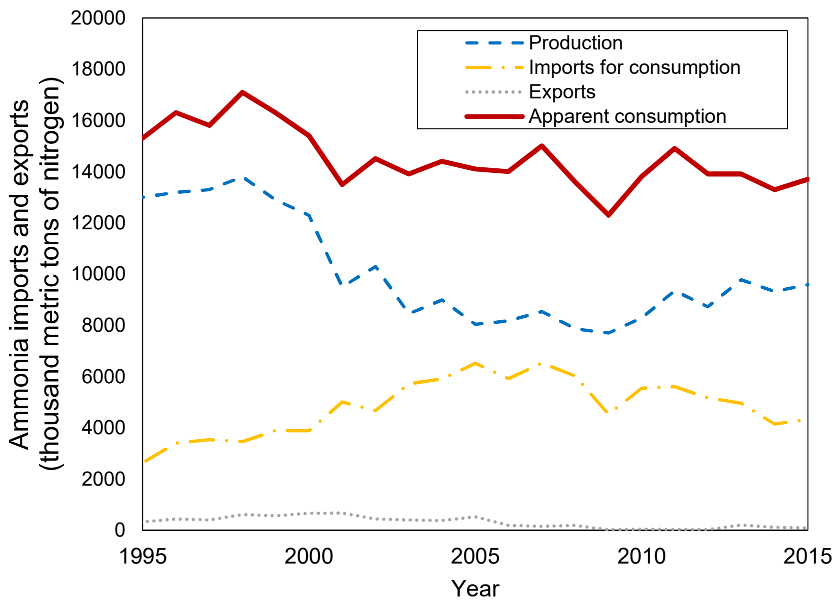


H_2 demand: 2.9 MMT
NH_3 production: 16.2 MMT

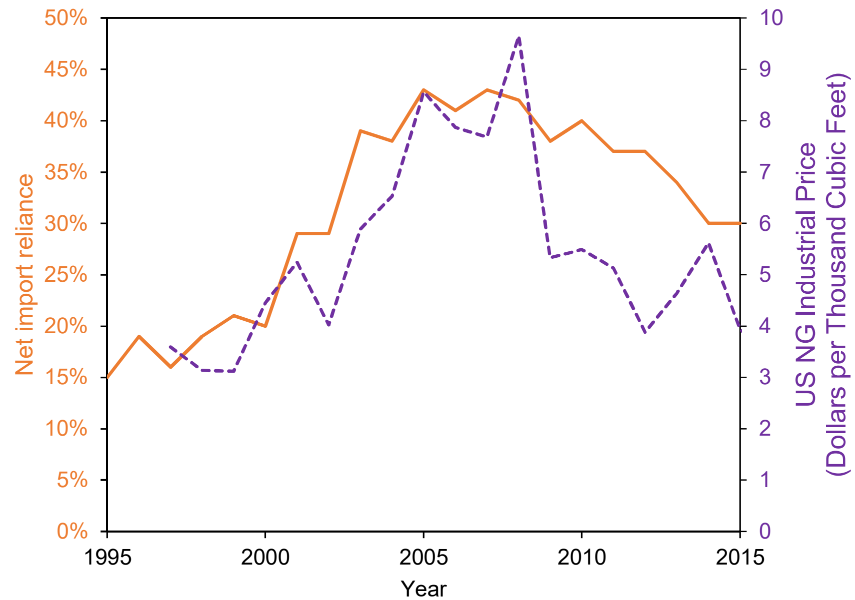
Assumption: capacity factor 90%

US domestic ammonia production and imports varied over time while consumption keeps stable

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

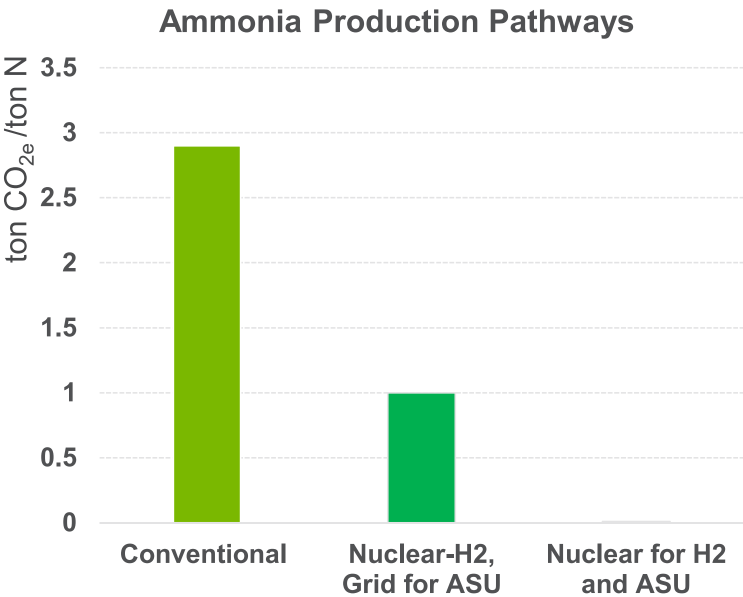


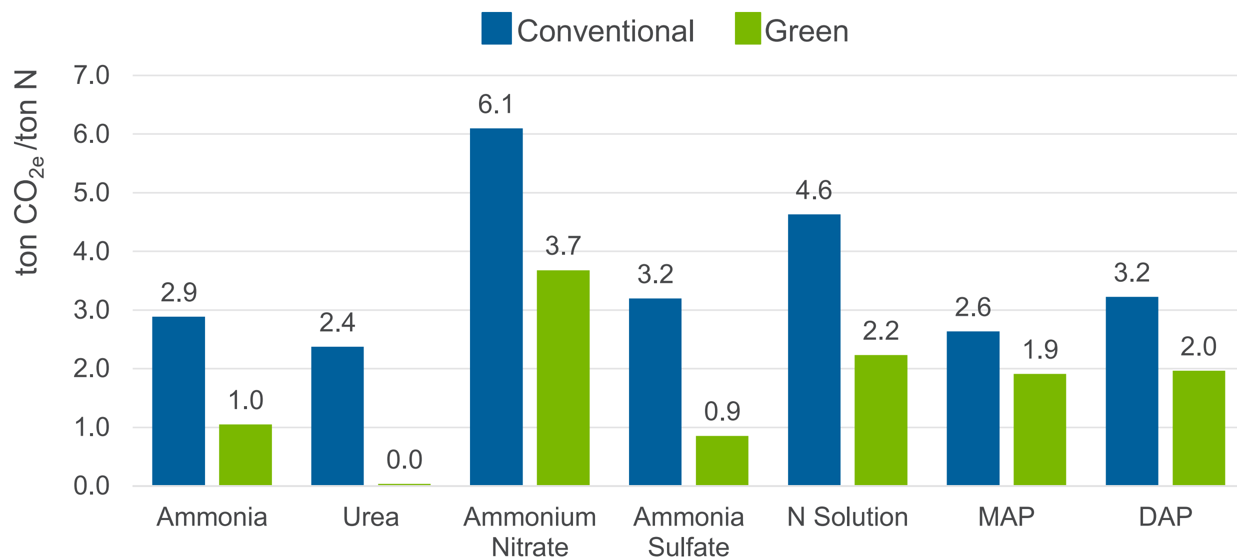
Data: USGS nitrogen (fixed)-ammonia (USGS 2016)

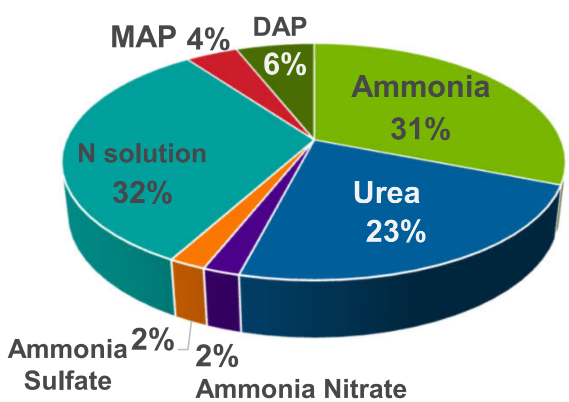


Data: USGS 2016; EIA 2017

Green ammonia reduces nitrogen fertilizer CO_2 emissions







- 2019 US grid electricity for ASU and HB
- Zero carbon electricity for H_2 (nuclear HTGR)

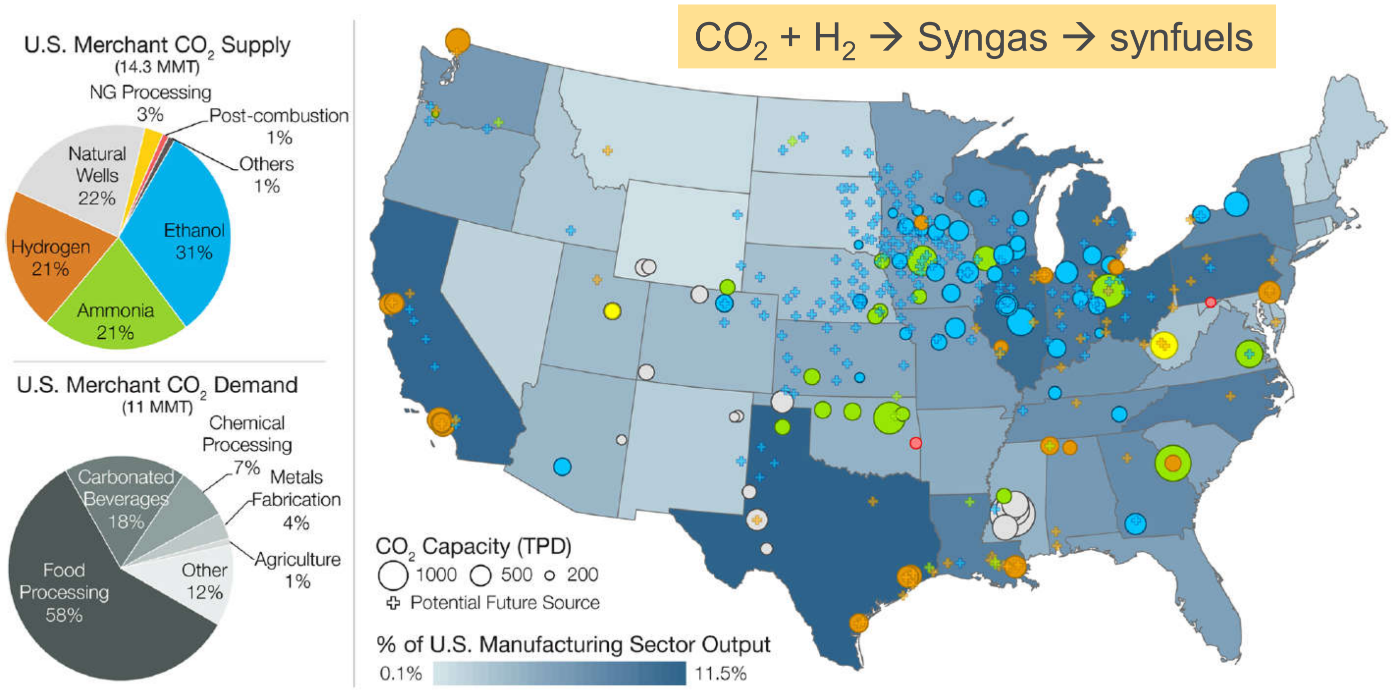
Green ammonia with current N fertilizer shares, reduces CI per ton of N fertilizer from 3.4 ton CO_{2e} to 1.3 ton CO_{2e}, a 61% reduction

E-fuels

SYNTHETIC FUEL PRODUCTION (H_2 +CO_2 →LIQUID HC)

Demand for synthetic fuel production → CO2 sources

- 100 million MT of concentrated CO_2 produced annually (out of total ~5 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)

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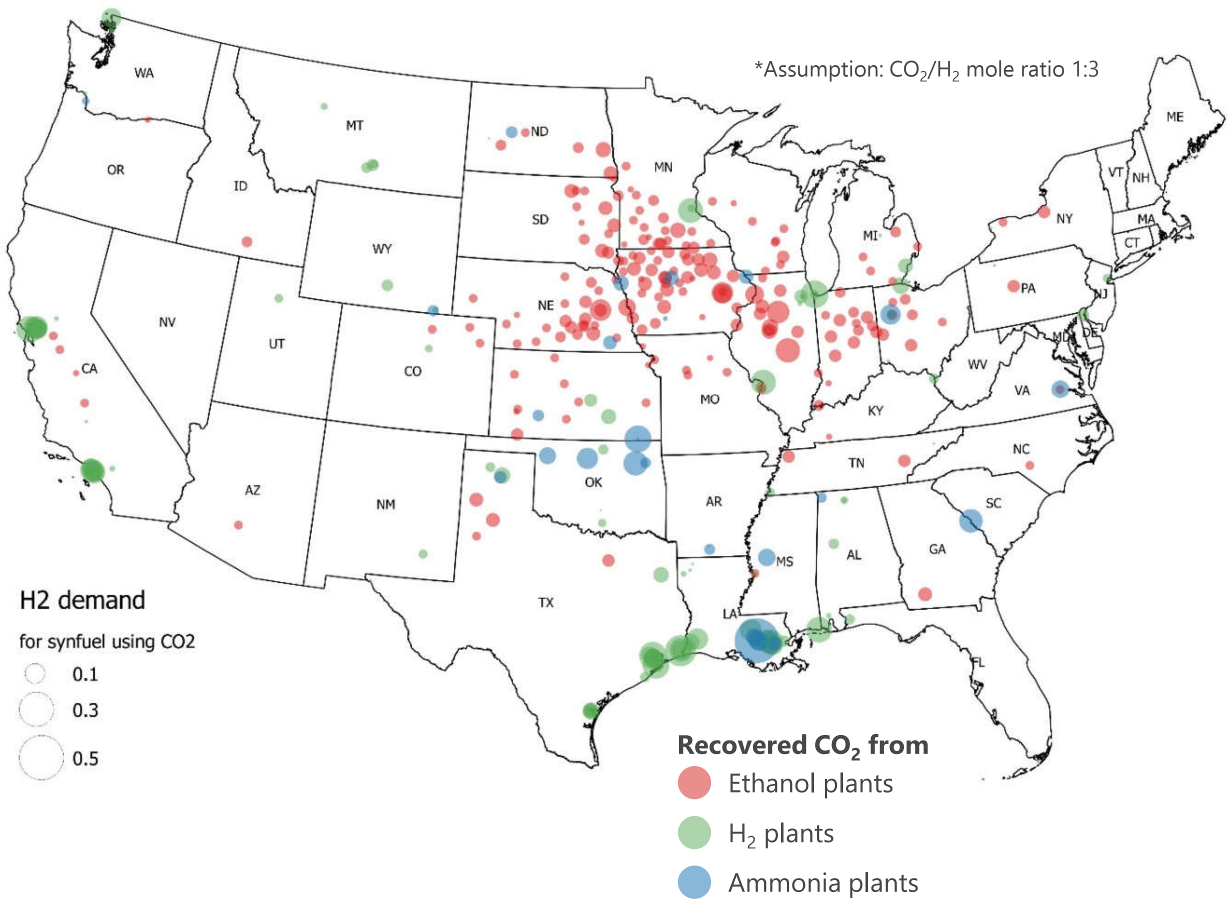
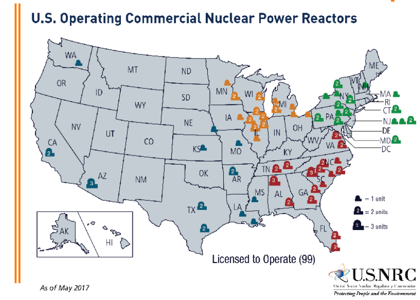
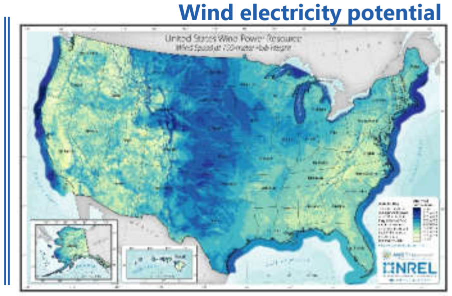
14 MMT of H_2 per year may need to be produced close to CO_2 and synfuel production locations



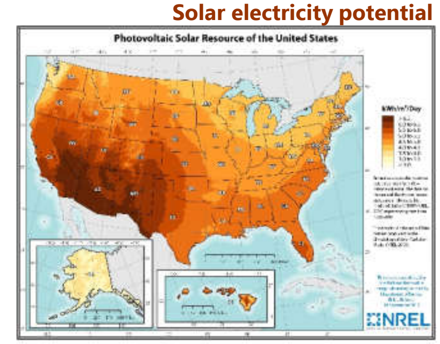
Installed nuclear plants



Wind electricity potential

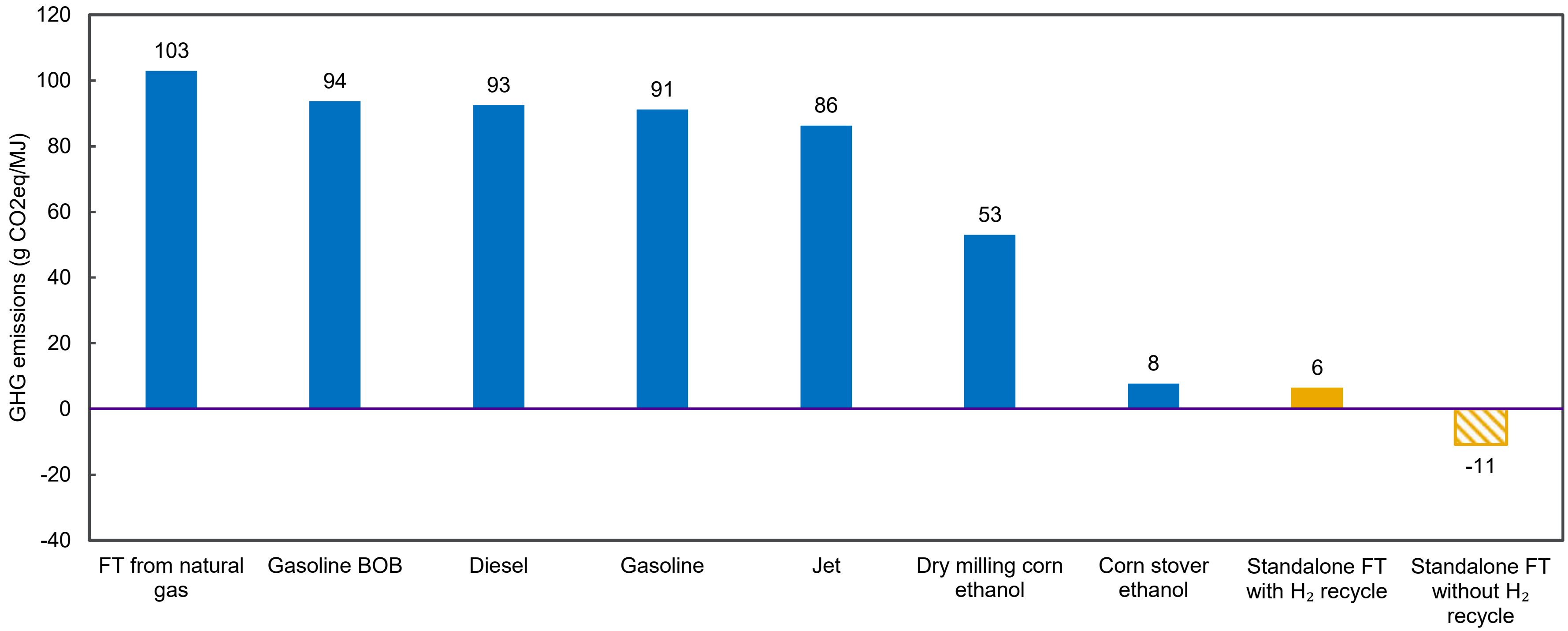


Solar electricity potential



FT fuel WTW GHG emissions

- FT fuel (the mixture of naphtha, jet fuel, and diesel) production without H_2 recycle has the lowest WTW GHG emissions of -11 g CO_{2eq} /MJ [a]
- Based on carbon neutrality of fermentation CO_2 in ethanol plants, GHG emissions reductions of the standalone FT fuel pathway are estimated to be 93% to 113% compared with petroleum pathways



[a] GHG emissions are evaluated based on GREET 2018

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METAL REFINING

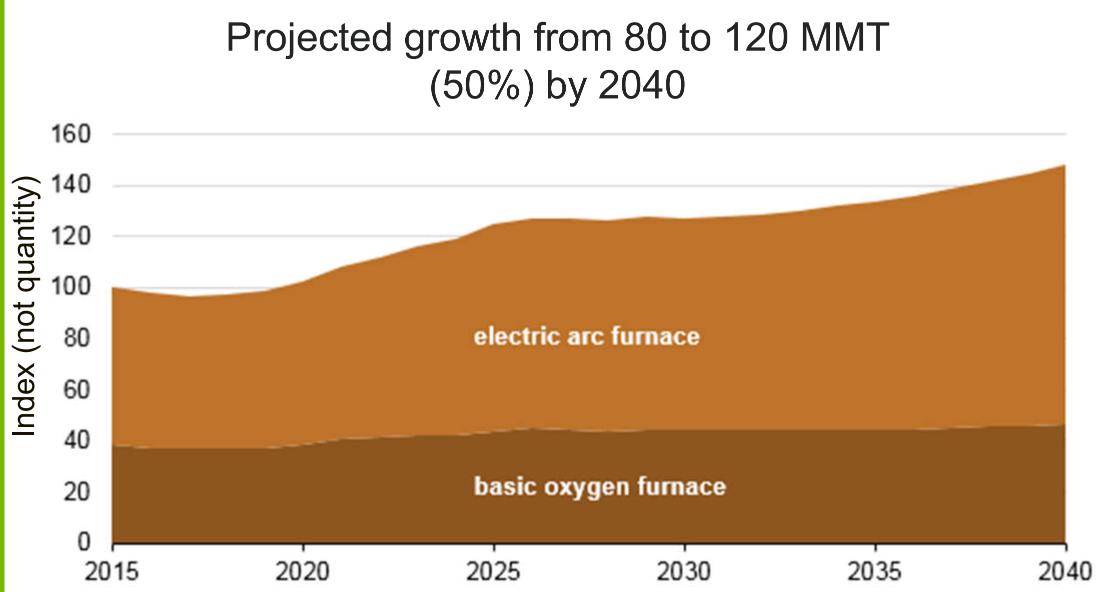
Steel making via DRI and FIT can provide virgin feed to electric arc steel production

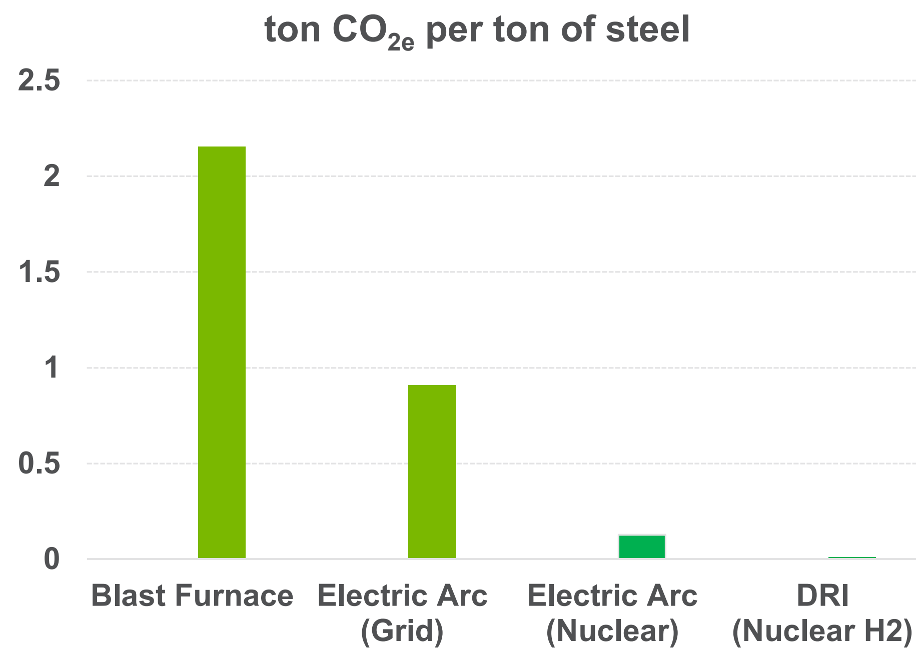
- 106 million MT of steel consumed in the U.S. in 2017[1]
  - ✓ 81 MMT produced (68% electric arc [EA], 32% blast furnace [BF]) [1]
    - ➢ Scrap constitute ~15% of BF feed and most of EA feed
    - ➢ Direct Reduction of Iron (DRI)[2] or Flash Ironmaking Technology (FIT)[3] feedstock enables higher quality steel than scrap metal feedstock
  - ✓ 35 MMT imported[4]
  - ✓ ~2 tons of CO_2 per ton of steel

- 60-100 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 up to 7 tons of coke

1. USGS, 2017. Iron and Steel Statistics. January
2. Midrex
3. University of Utah
4. Global Steel Monitor

Steel making via DRI can induce large hydrogen demand





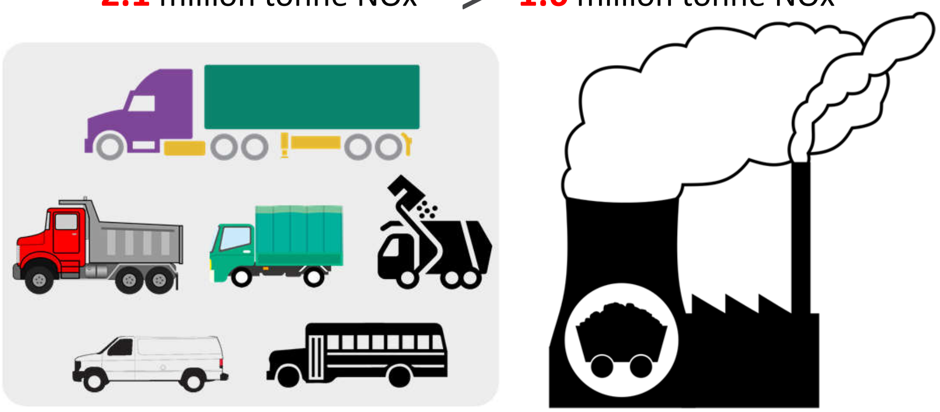
- Use of recycled scrap metal can reduce quality of steel produced by EA over time
- DRI can provide virgin feed to EA furnaces to enable higher steel quality
- 430 kg of coke is required to produce 1 MT of hot iron in BF
  - ✓ DRI using natural gas reduces CO_2 emissions by approximately 35% compared to BF
  - ✓ H_2 for DRI can virtually eliminate CO_2 emissions from the iron-making process

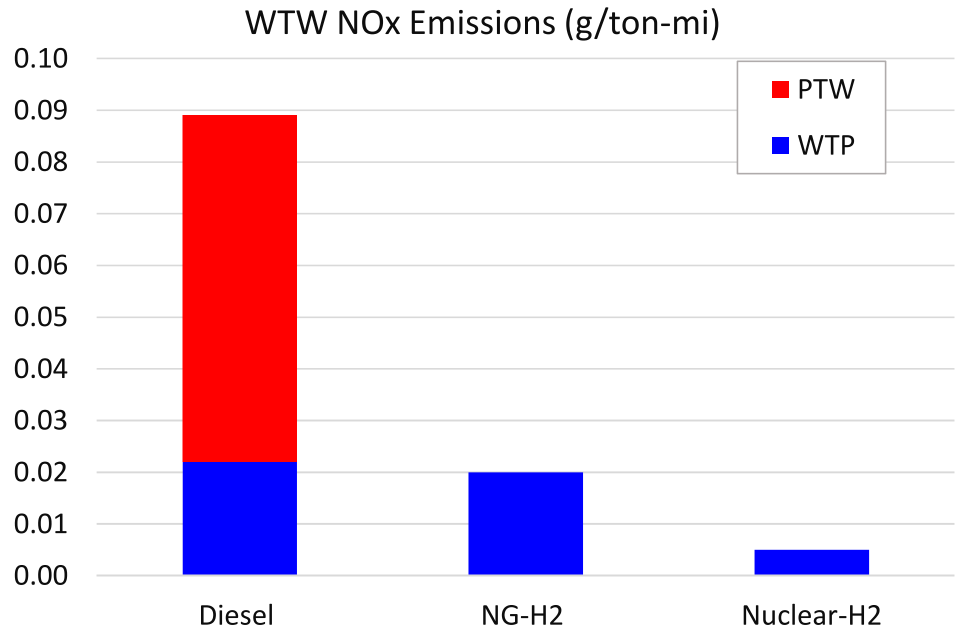
FUEL CELL VEHICLES

MHDVs (Medium- and Heavy-Duty Vehicles)

- Medium- and Heavy-duty Vehicles (MHDVs)
  - Have a wide range of vocations, e.g. pick-up & delivery, refuse, tractor-trailer, and sleeper cab
  - Contributing significantly to critical air emissions, even though accounting for a small portion of on-road transportation

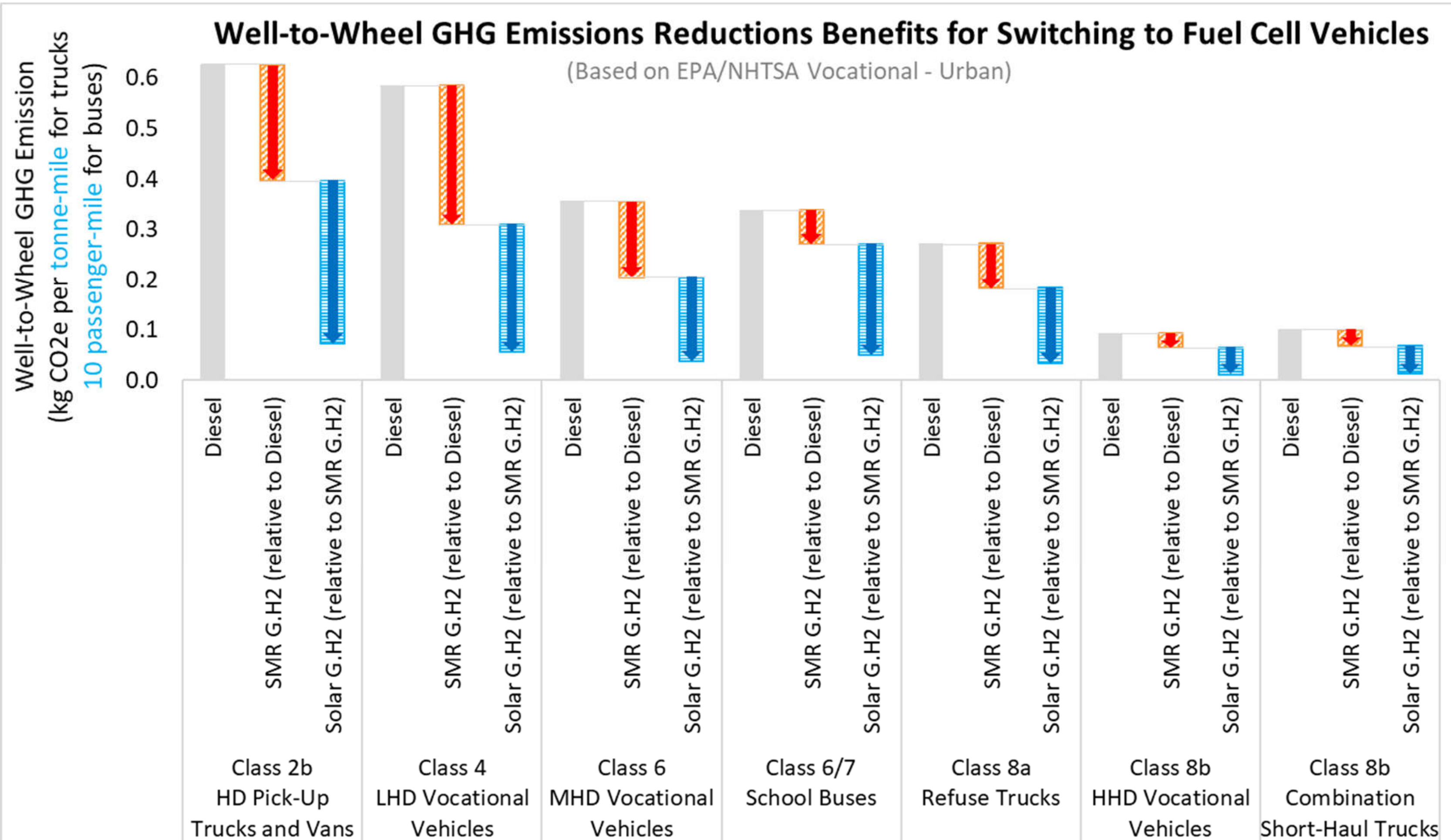
MHDVs
2.1 million tonne NOx > **All Power Plants** **1.6** million tonne NOx





Drayage trucks for port application

Compared to diesel counterparts, medium- and heavy-duty (MHD) hydrogen fuel cell vehicles create much less GHG emissions



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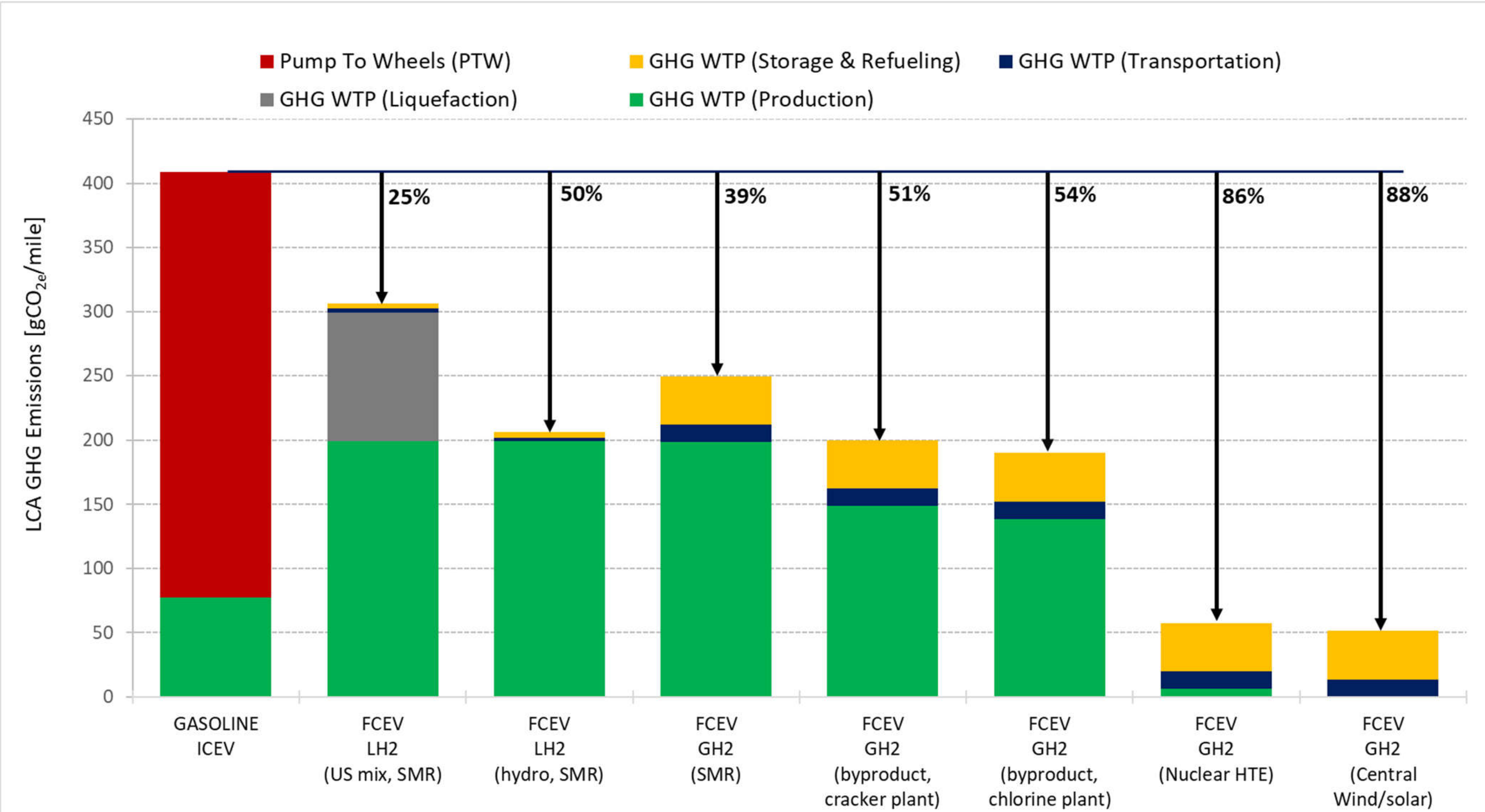
Low-carbon sources are key for sustainable H_2 production



Assuming 26 mpg for gasoline ICEV and 55 mpgge for H_2 FCEV

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OHIO NUCLEAR PLANT EXAMPLE

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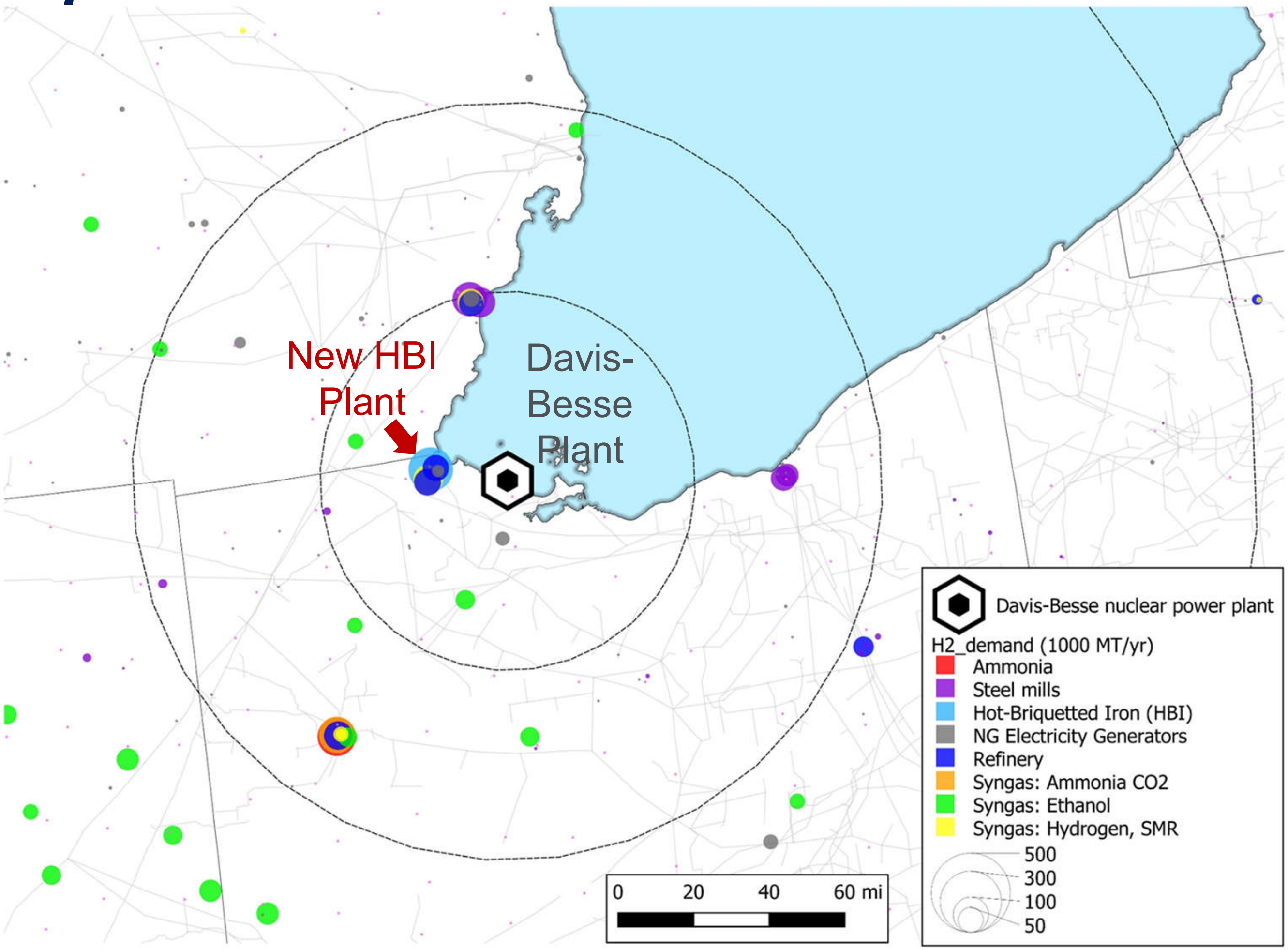
Potential annual hydrogen demand within 100 miles from the Davis-Besse plant



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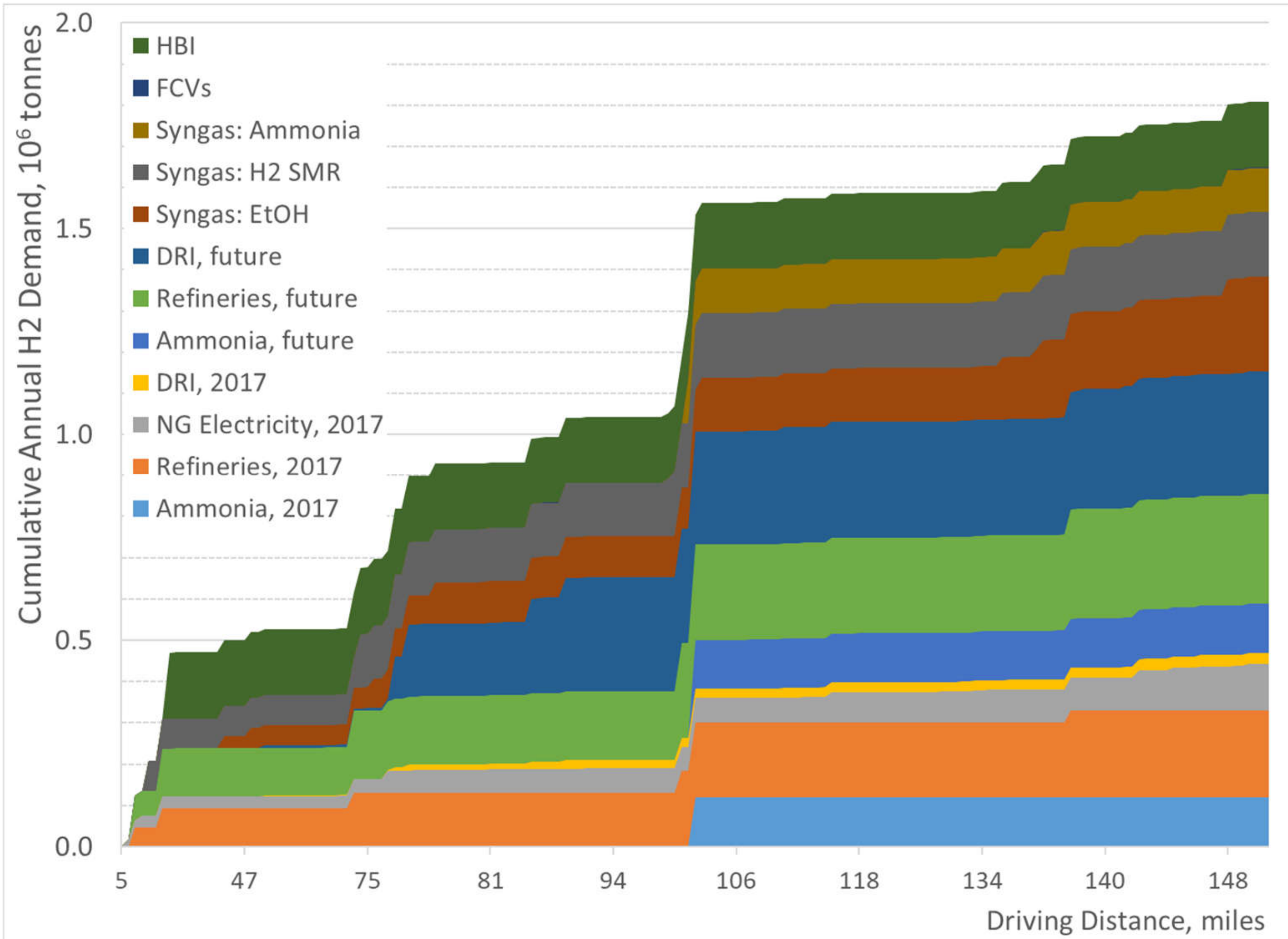
Potential annual hydrogen demand within 150 miles from the Davis-Besse plant



Points for discussion

- Competing/displacing SMR-H_2 is challenging
  - ➢ due to low cost NG
  - ➢ public support will be necessary in the transition

- Established applications (refineries and ammonia) are more likely in the near term compared to new applications (e.g., synfuel production or DRI)

- New applications that may <u>leverage existing infrastructure</u> can readily absorb H_2 production at scale
  - ➢ e.g., mixing H_2 with NG for power generation or industrial applications

- Markets will likely demand steady supply of H_2
  - ➢ H_2 storage will be necessary

- Nuclear-H_2 requires less storage compared to wind-H_2
  - ➢ <u>storage cost can be significant</u>

- <u>Proximity</u> of H_2 production to demand site is key to its economic potential in the energy system
  - ➢ demand at volume or aggregating demand will reduce infrastructure cost per unit energy delivered

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Acknowledgment

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- H2@Scale is a multi-National Lab effort. The presented analysis has been supported extensively by NREL and INL

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