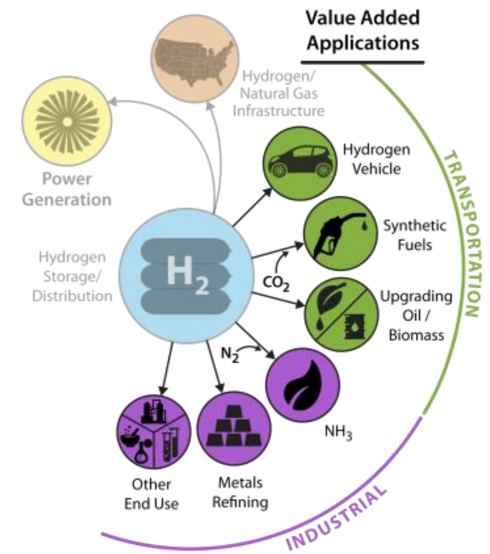
H_2 at Scale:

Enhance the U.S. energy portfolio through sustainable use of domestic resources, improvements in infrastructure, and increase in grid resiliency.

H_2 Utilization



November 16, 2016

Presented by Richard Boardman
Idaho National Laboratory
richard.boardman@inl.gov

NREL SLAC National Accelerator Laboratory · The Ames Lab · Los Alamos National Laboratory · Pacific Northwest National Laboratory · INL Idaho National Laboratory · Argonne National Laboratory · SRNL · Oak Ridge National Laboratory · Sandia National Laboratories · Lawrence Livermore National Laboratory · Berkeley Lab

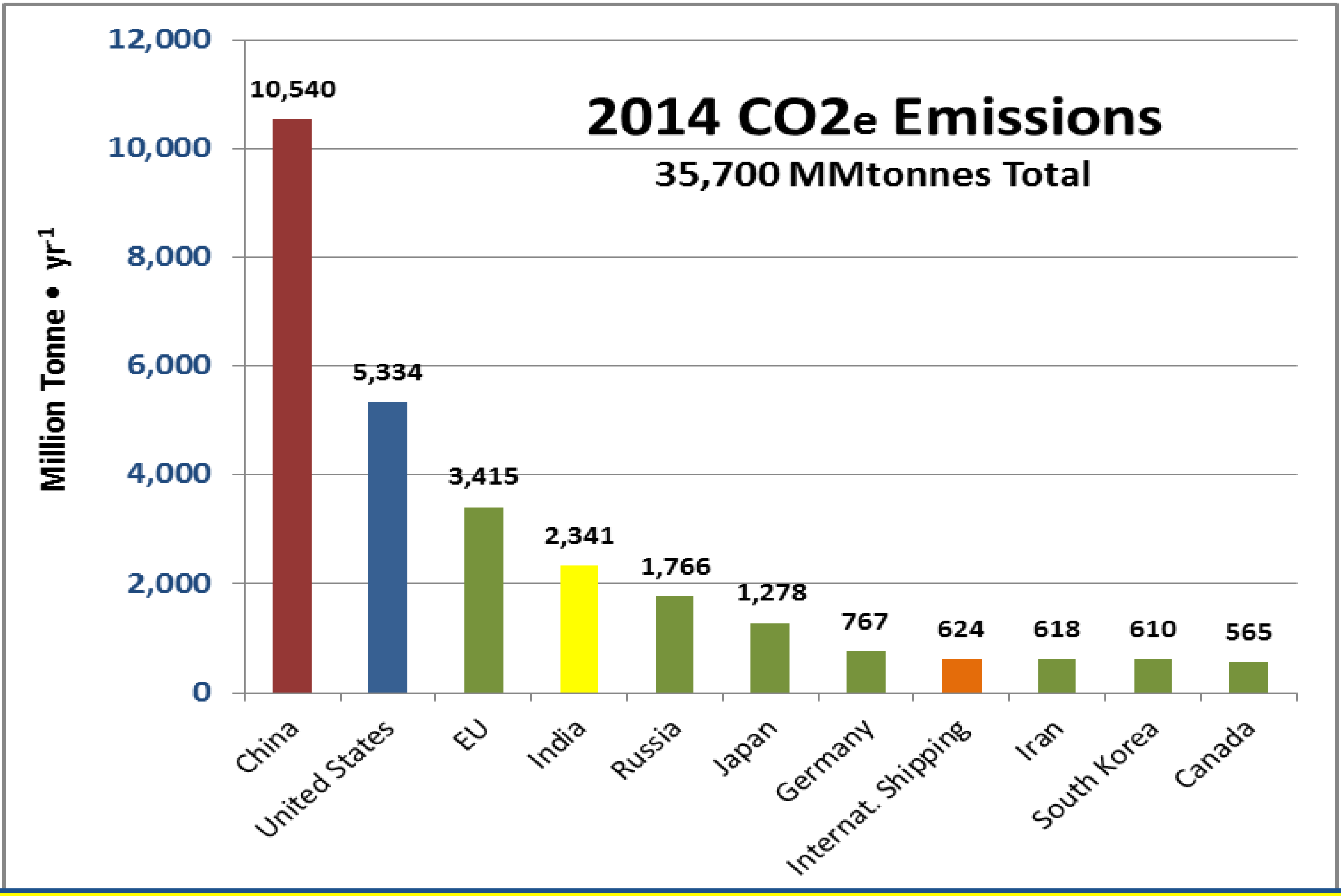
Outline

- Potential industry demand for hydrogen
- Status of high temperature electrolysis (HTE)
- Opportunity for nuclear energy
- Possible regional implementation strategies

H_2 Utilization:

Richard Boardman (INL)
Jamie Holladay (PNNL)
Don Anton (SRNL)
Amgad Elgowainy (ANL)
Christopher San Marchi (SNL)
Charles Hanley (SNL)
Colin McMillan (NREL)
Theodore Kruze (ANL)
Mark Ruth (NREL)
Mark Bearden (PNNL)
Bob Hwang (SNL)
Ting He (INL)
Kriston Brooks (PNNL)
Mary Biddy (NREL)
Geo Richards (NETL)

World GHG Emission Emissions

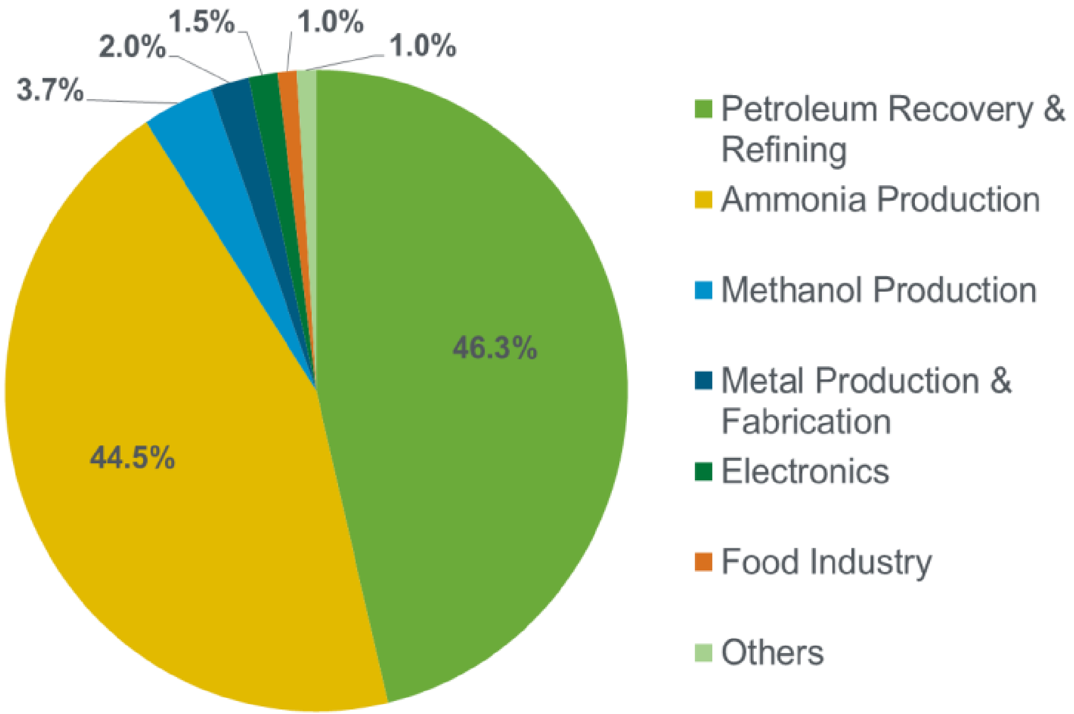


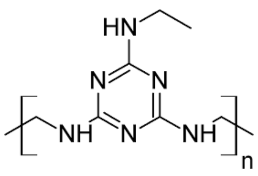
Global manufacturing accounts for 40% of total GHG

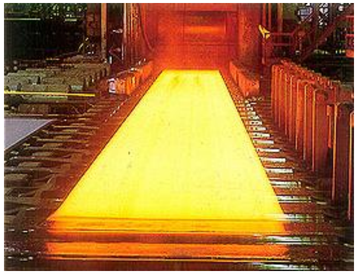
India and non-OEDC emissions are escalating

Major U.S. Industrial Hydrogen Users in 2014

~10 million tonnes-$H_2 \bullet yr^{-1}$







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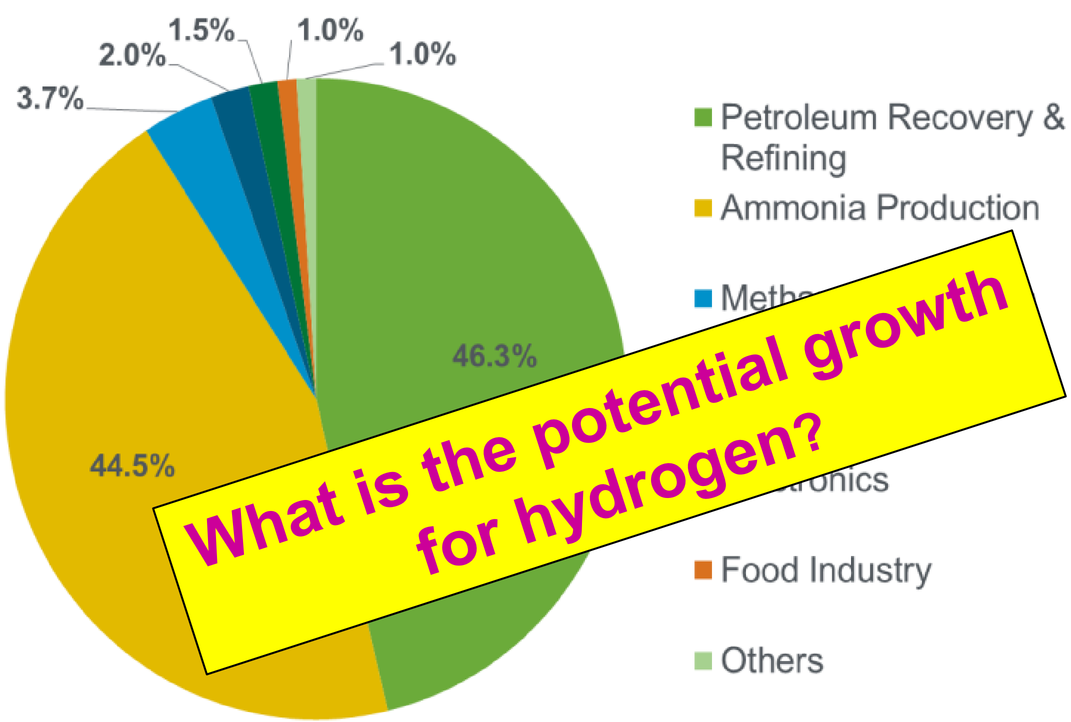
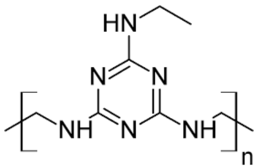
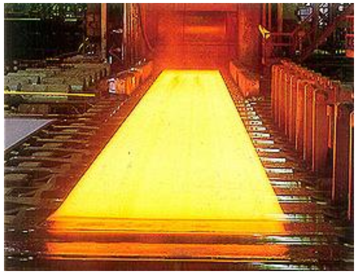
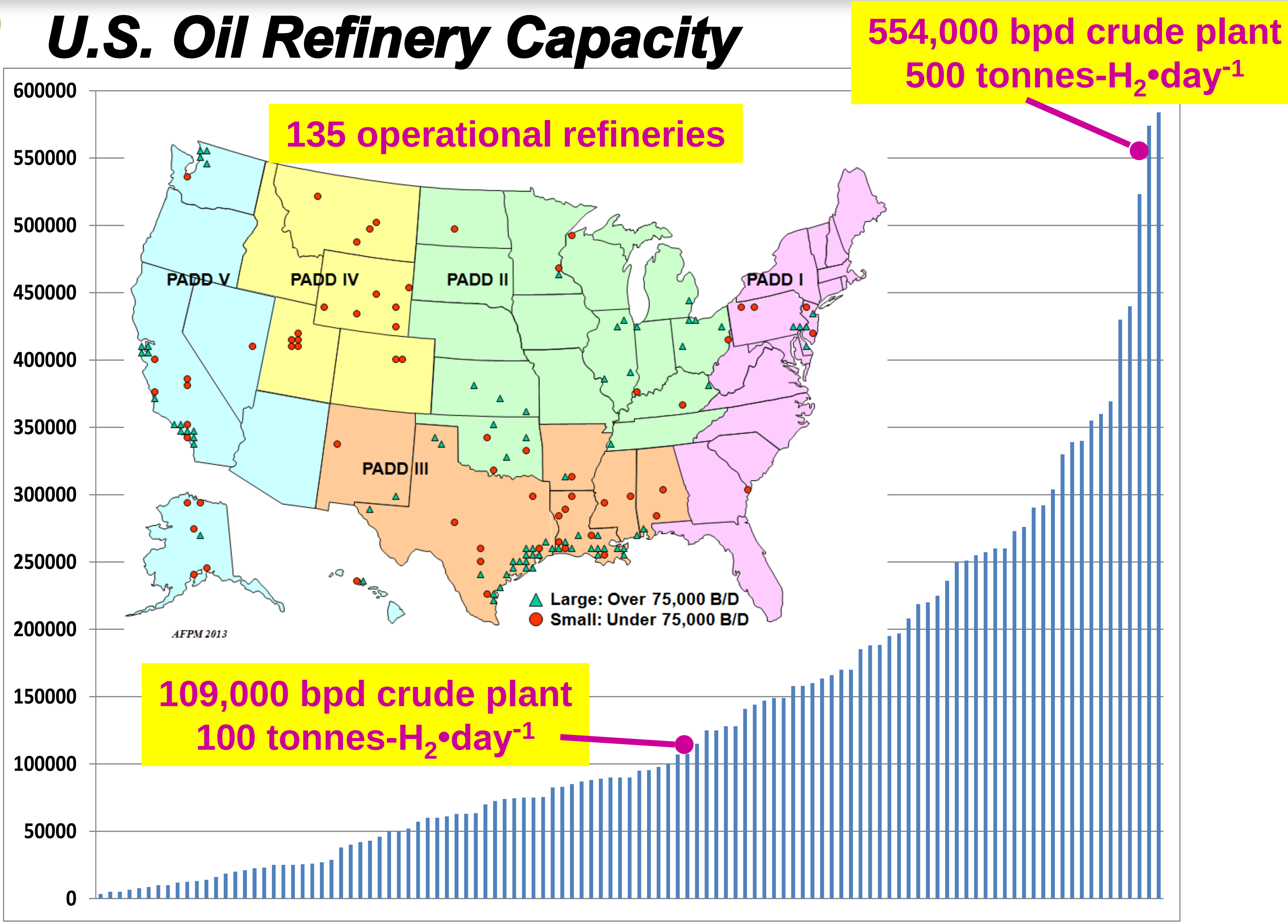


What is the potential growth for hydrogen?



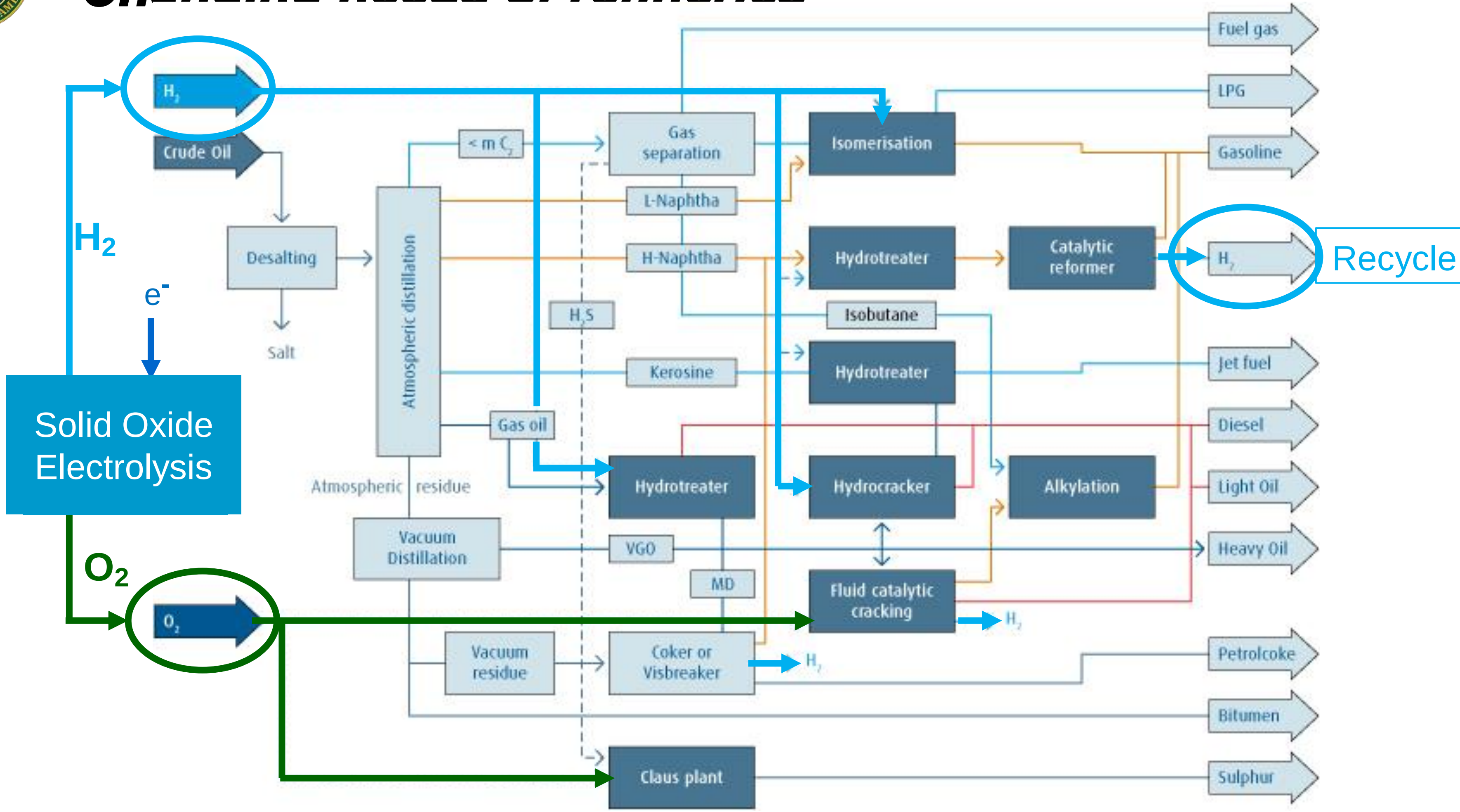


U.S. Oil Refinery Capacity



U.S. refinery operating capacity in barrels per stream day, as of January 2016

Changing needs of refineries

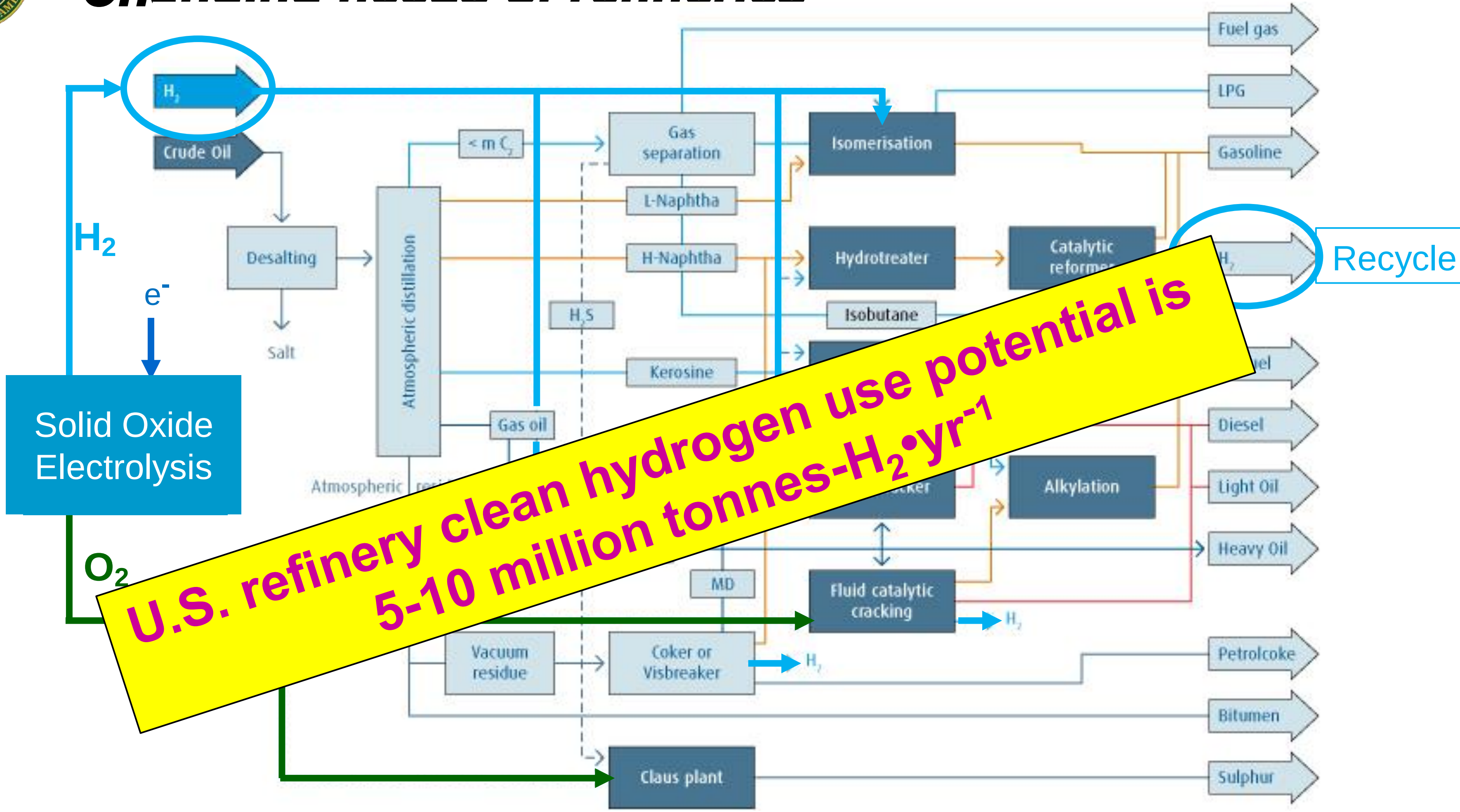


~ 5 million tonnes of hydrogen was supplied to the refinery industry in 2015.

Clean hydrogen sources would reduces GHG emissions 25%.

H_2-enriched burners could further reduce GHG emissions 20%.

Changing needs of refineries



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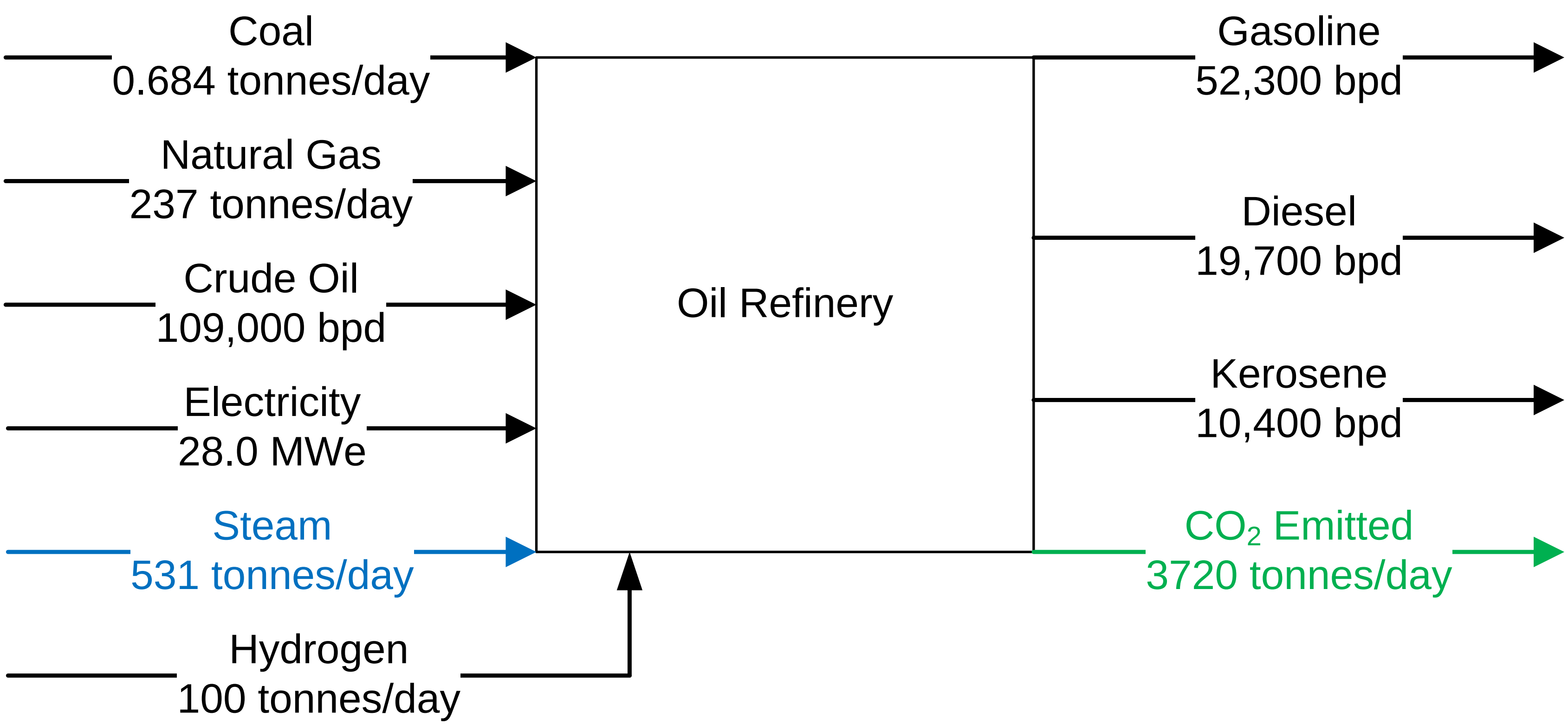
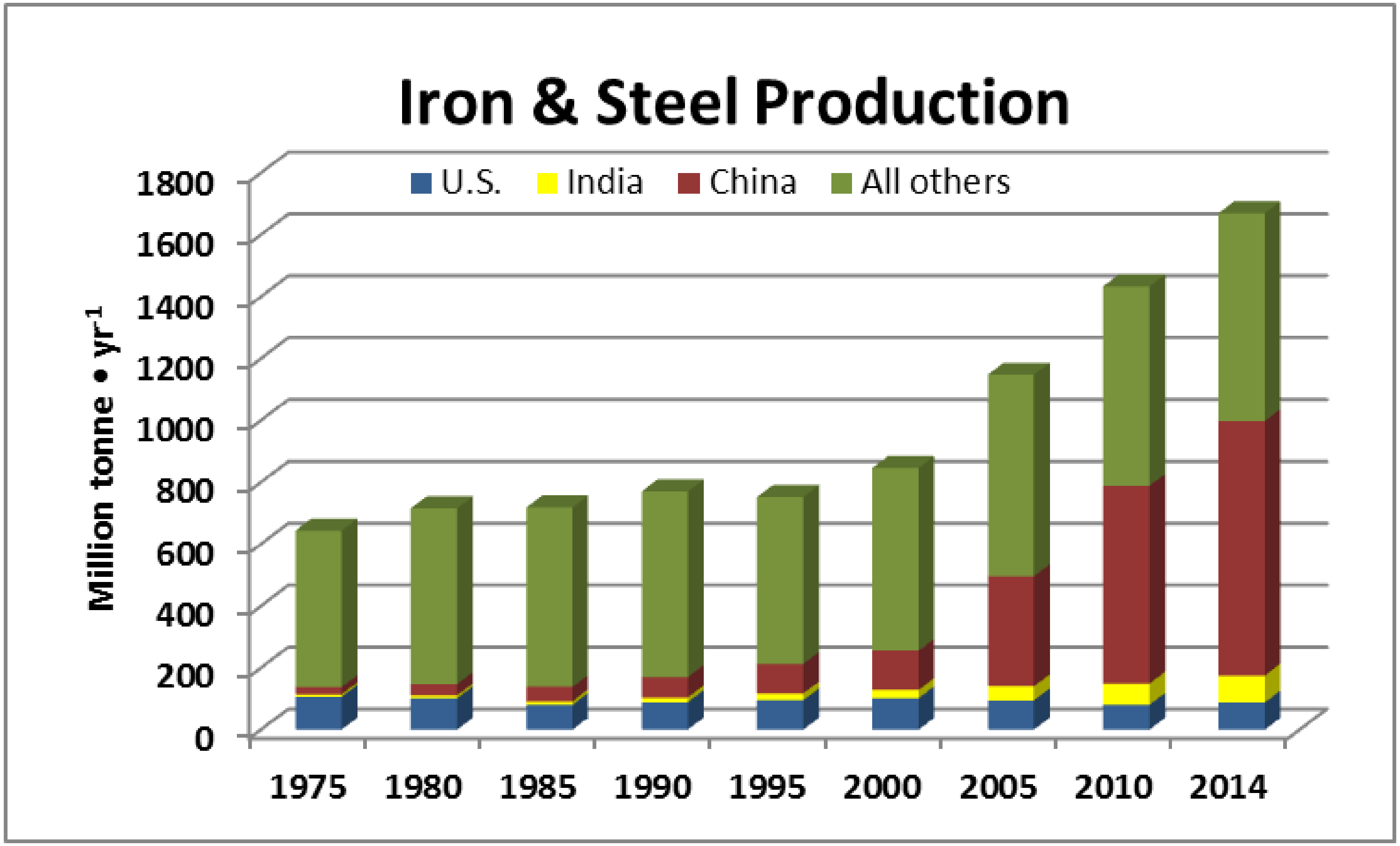
Changing combustion by industry….



As an example: Replace 20% of naturals gas with hydrogen to burn in refinery steam boilers and fired-heaters would consume

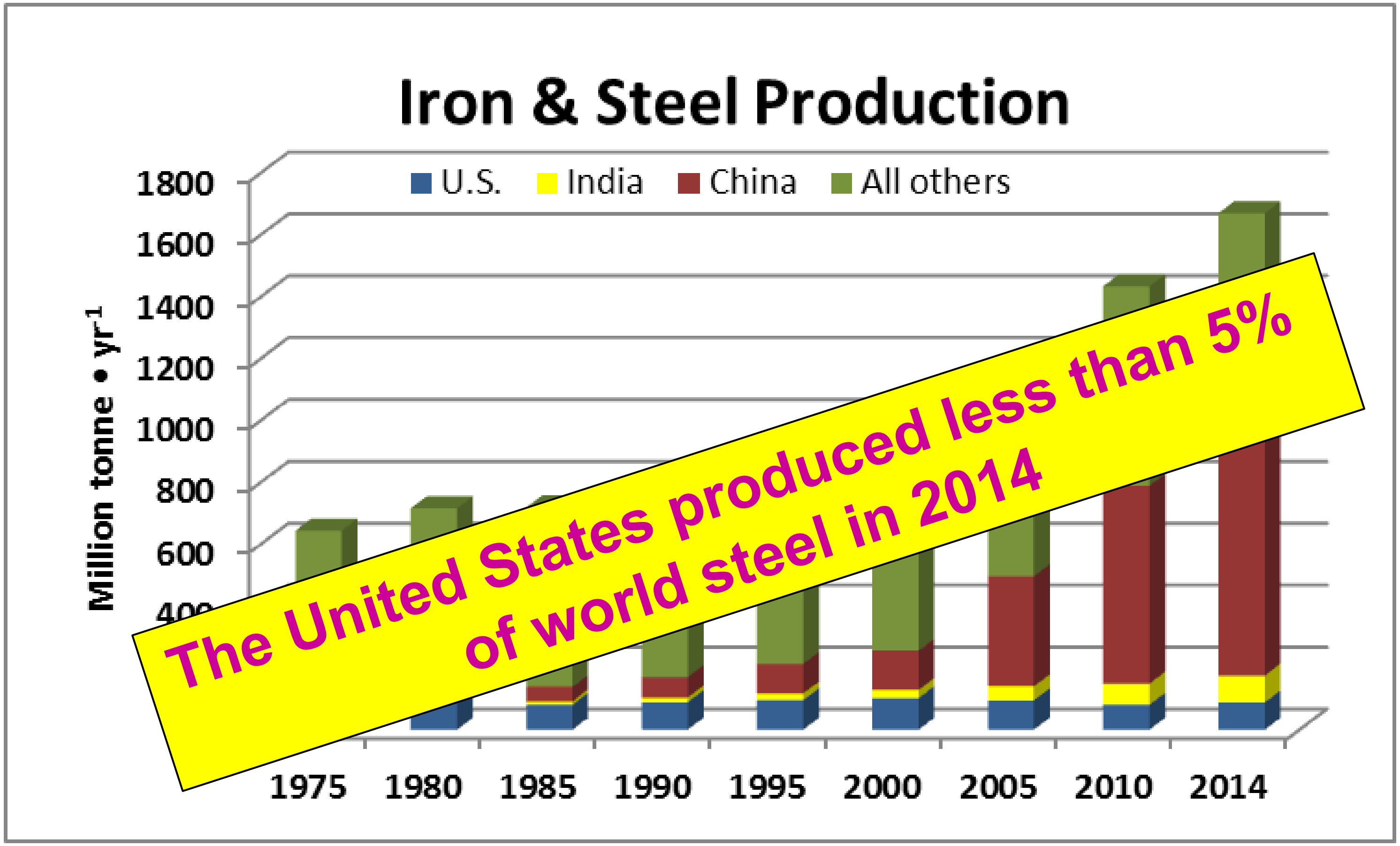
World Steel Association Steel Report



Primary metals manufacturing accounts for ~15% of world GHG emissions (8% is from ferrous metals)

95% of these emissions can be voided with clean energy

World Steel Association Steel Report



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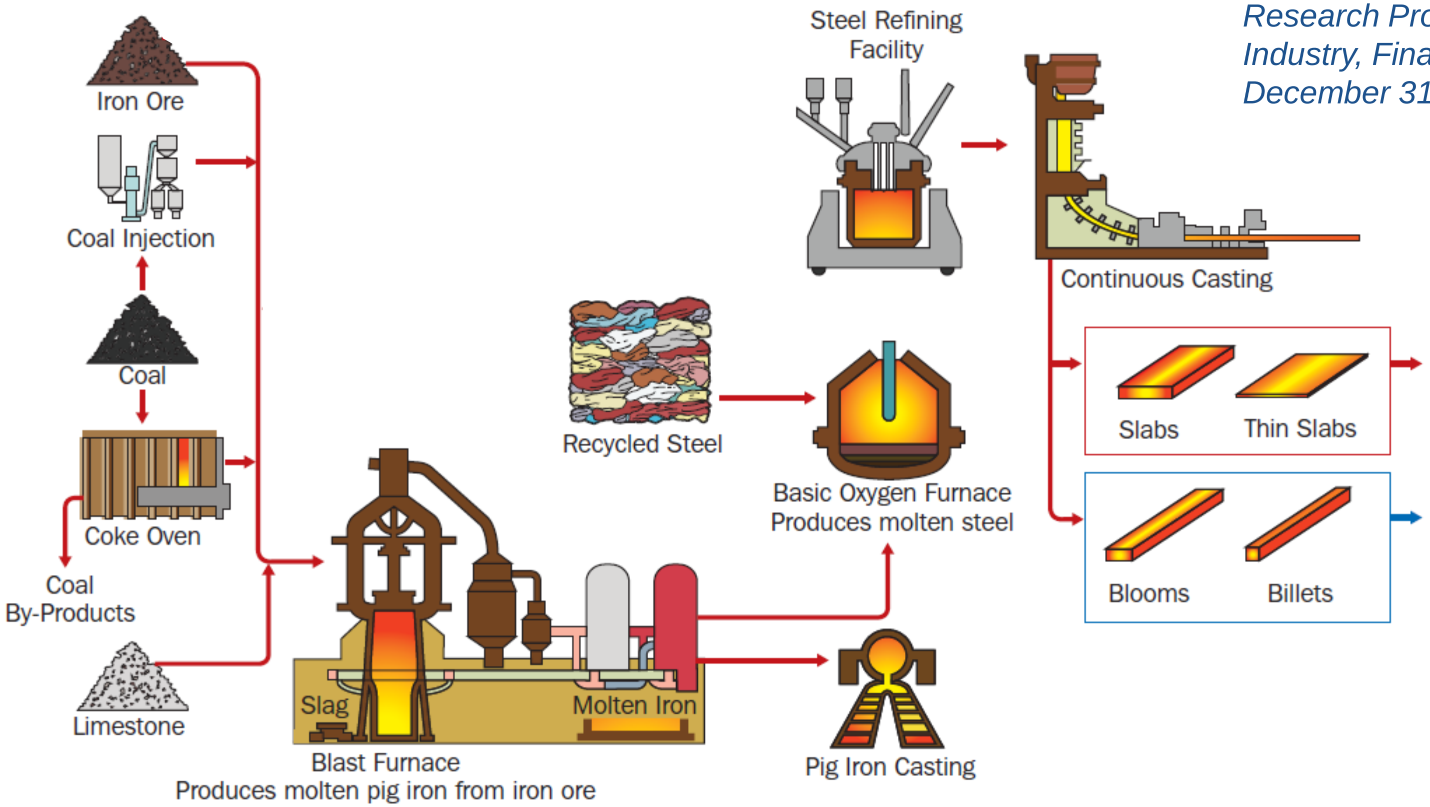
Iron & Steel Making

Figure Source:
ANSI, Technology Roadmap Research Program for the Steel Industry, Final Report, December 31, 2010



Iron and steel making employs two interrelated processes:

1) Molten pig iron is produced from iron ore with coke in a **Blast Furnace (BF)**. The Pig Iron is mixed with scrap metal and refined in a **Basic Oxygen Furnace (BOF)**.
2) Solid metallic iron is produced in a **Direct Reduction Iron (DRI).** This iron is processed with scrap metal in an **Electric Arc Furnace (EAF)** to produce molten steel.

Iron & Steel Making

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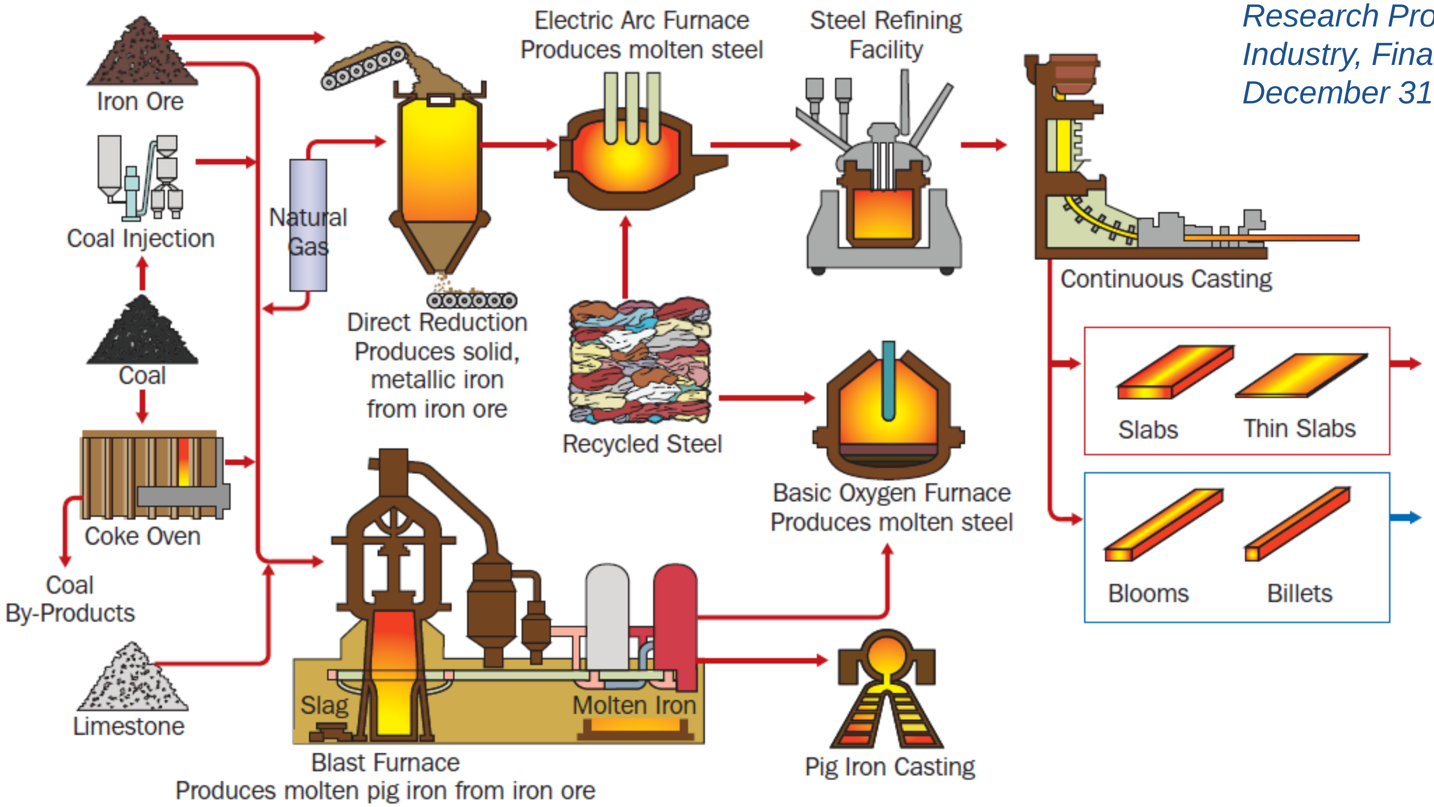

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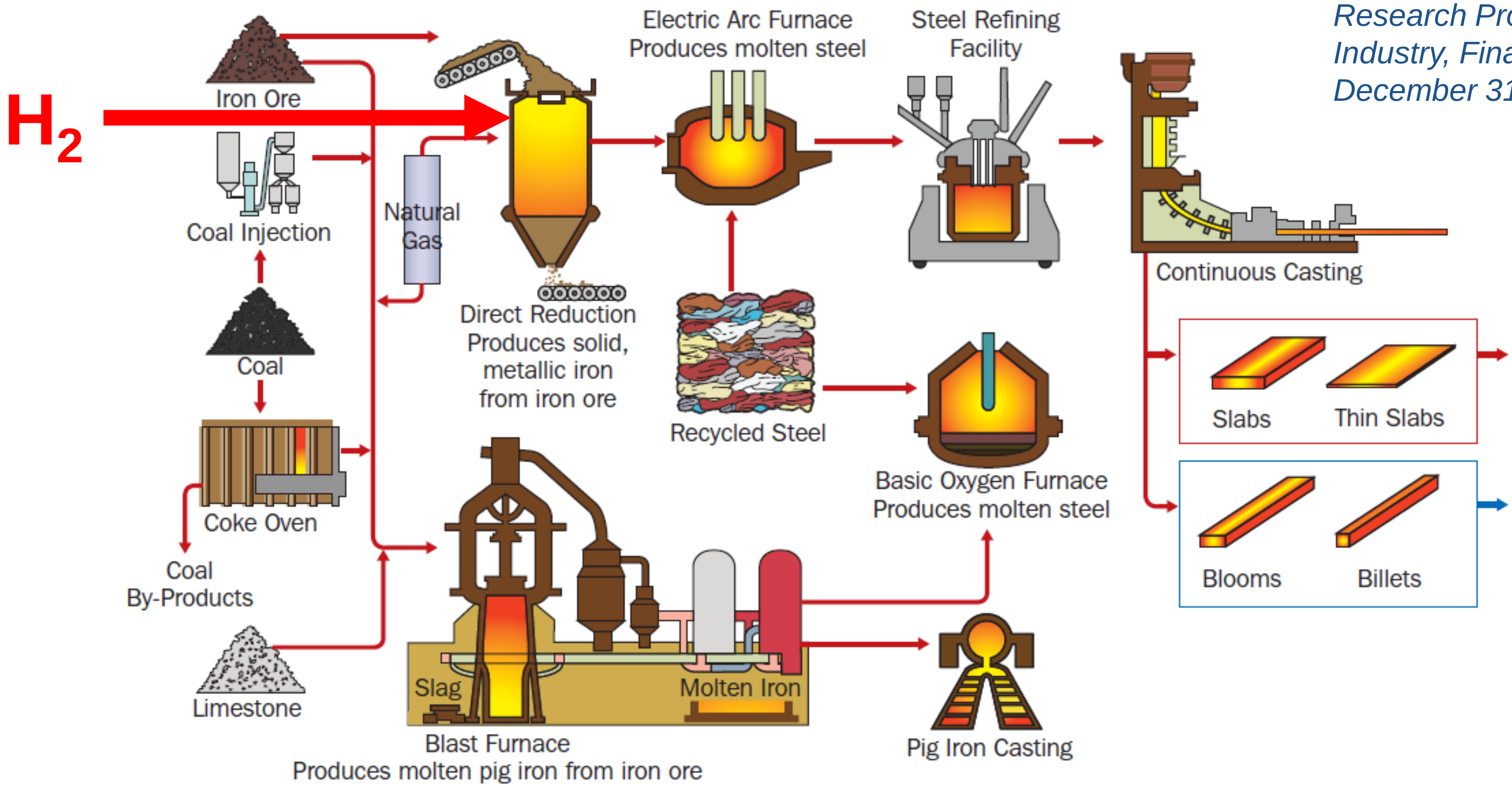

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Direct Recovery Iron

DRI Process Development Examples

- MIDREX™
- U.S. CO_2 Breakthrough Program
- Europe: ULCOS
- Japan: COURSE 50
- Korea: POSCO
- University of Utah **(FIT)**

BELOW: The ZR Process accepts any reducing gas source – direct natural gas, syngas from a coal gasifier, coke oven gas or H_2/CO mixtures.

LEFT: MIDREX™ DRI shaft furnaces are being installed around the world to use various reducing gases and solids

- DRI process technology is no longer considered nascent
- Benefits include: Process intensification; Reduced capital; Increased energy efficiency: Reduced GHG emissions; Iron ore concentrates processing`

Direct Recovery Iron

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BELOW: The ZR Process accepts any reducing gas source – direct natural gas, syngas from a coal gasifier, coke oven gas or H_2/CO mixtures.

Current U.S. DRI steel industry hydrogen potential is: > 6 million tonnes-H_2 • yr^{-1}

LEFT: MIDREX™ DRI shaft furnaces are being installed around the world to use various reducing gases and solids

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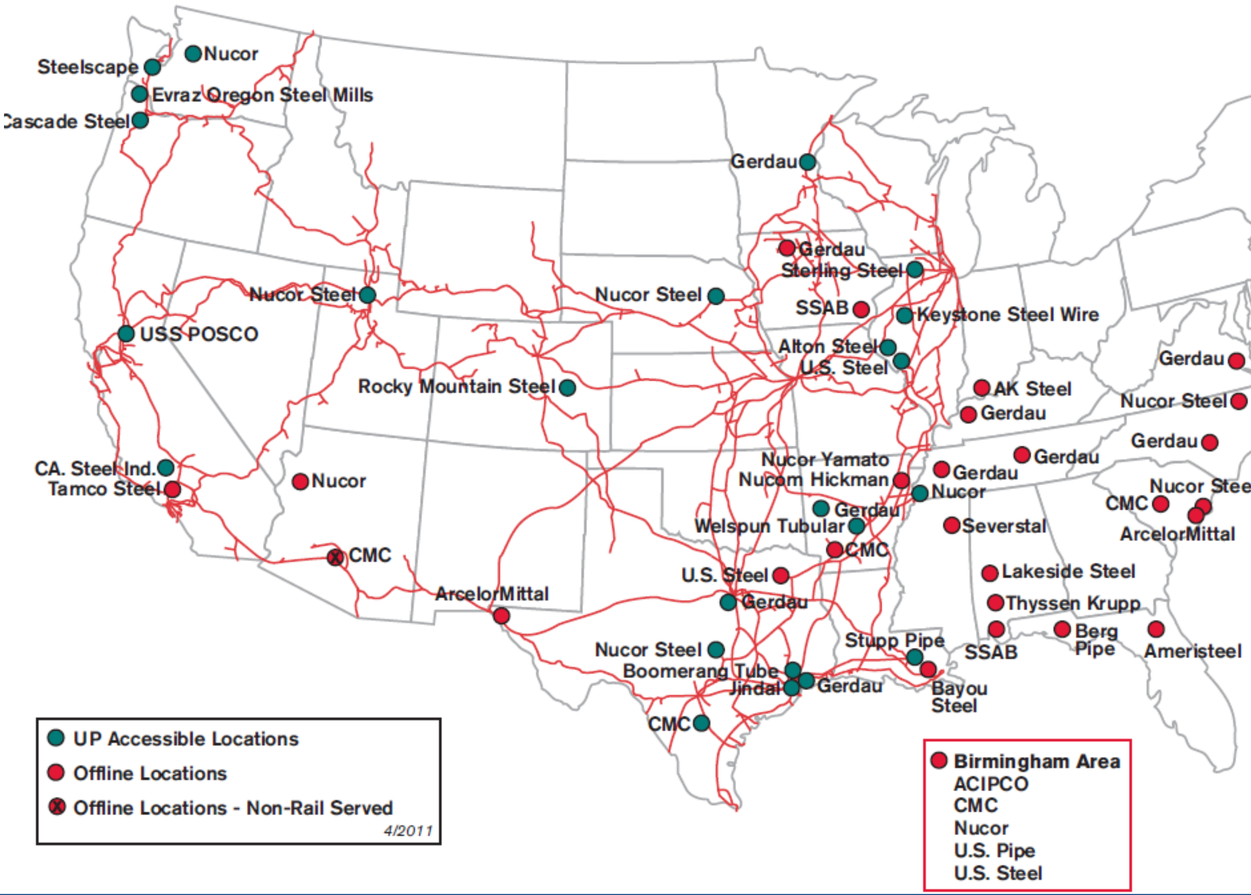
US Steel Mill Locations

The average steel mill produces 5,000 – 10,000 tonnes steel billets or slabs



Canadian Mills
ArcelorMittal Canada, Contrecour, PQ
ArcelorMittal/DoFasco, Hamilton, ON
Camrose Pipe, Camrose, AB
EssarSteel Algoma, Sault Ste Marie, ON
Evraz, Regina, SK
Gerdau Ameristeel, MRM, Selkirk, MB
Gerdau Ameristeel, MRM, Whitby, ON
Ivaco, L'Original, ON
Lakeside Steel, Welland, ON
U.S. Steel, Hamilton, ON
U.S. Steel, Nanticoke, ON

MI-NY-OH-PA-WV Mills
AK Steel, Middletown, OH
ArcelorMittal, Cleveland, OH
ArecelorMittal, Weirton, WV
Durabond, McKeesport, PA
Durabond, Steelton, PA
Ellwood Group, New Castle, PA
Republic Engineered Products, Canton, OH
Severstal, Dearborn, MI
Timken, Canton, OH
U.S. Steel, Ecorse, MI
U.S. Steel, Fairless, PA
U.S. Steel, Irvin, PA
U.S. Steel, Lorain, OH
VM Starr, Youngstown, OH
Wheeling Pitt Steel, Wheeling, WV

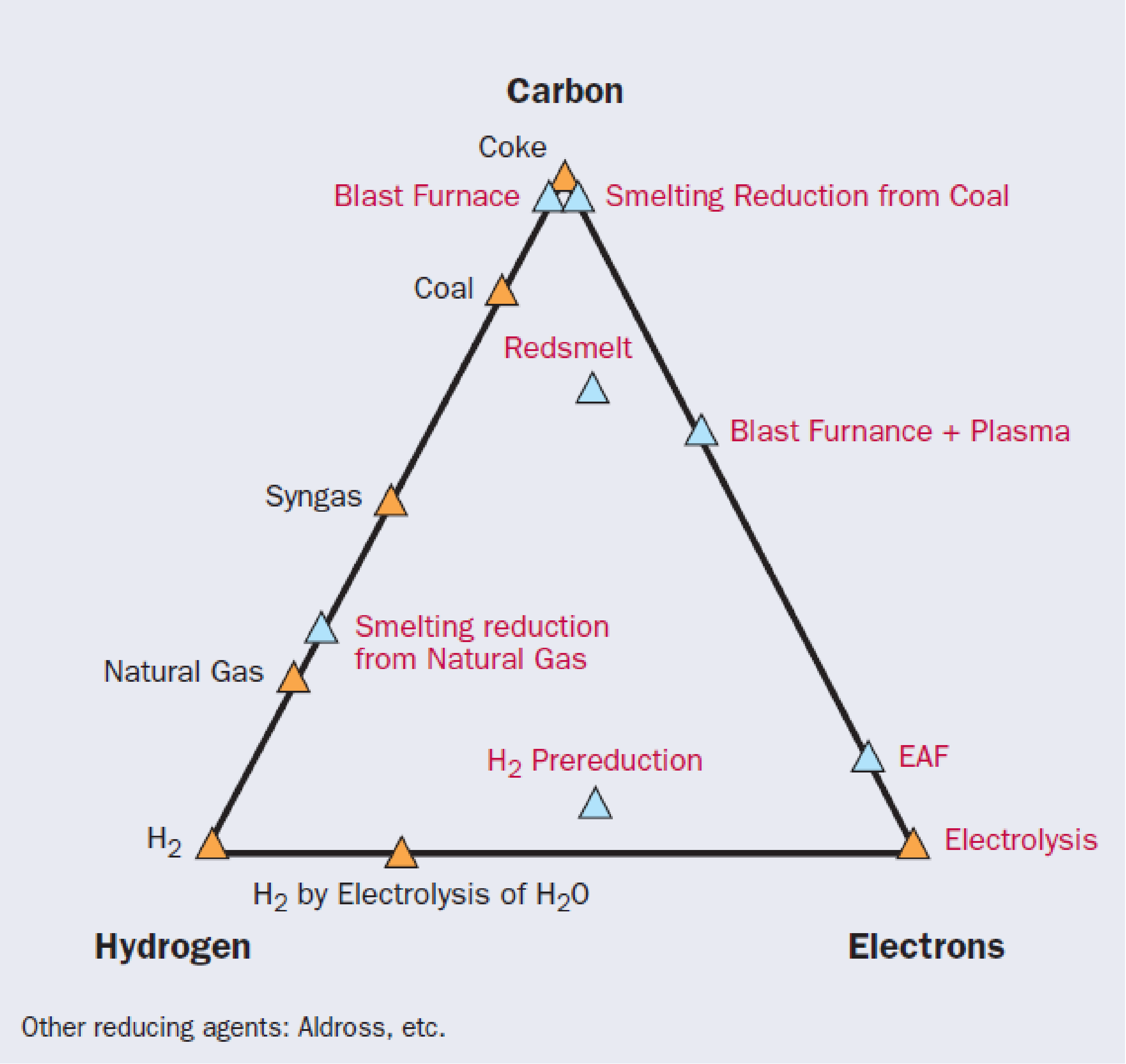
Chicago & Indiana Area
ArcelorMittal, Burns Harbor, IN
ArcelorMittal, Gary, IN
ArcelorMittal, New Carlisle, IN
Nucor, Crawfordsville, IN
SDI, Butler, IN
SDI, Columbia City, IN
SDI, Jeffersonville, IN
U.S. Steel, Gary, IN

Chicago & Indiana Area
ArcelorMittal, Indiana Harbor, IN
ArcelorMittal, Riverdale, IL
Atlas Tube, Chicago, IL
U.S. Steel, Granite City, IL

U.S. iron and steel demand is 120 million tonnes•yr^{-1}
U.S iron and steel production in 2015 was 78 million tonnes•yr^{-1}

Steps in the right direction…

- ❑ Steelmaking is an energy intensive process.
- ❑ An ideal steel making process would:
- ✓ Eliminate the need for coal and coke
- ✓ Use domestic iron ores especially concentrates, which the U.S. has in abundance
- ✓ Replace the high capital coke oven and blast furnace
- ✓ Be capable of producing 5,000-10,000 so that it can support the rate of production in existing steel mills



Top Chemicals / Chemical Feedstock

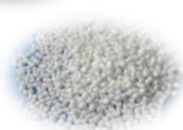
Acetic Acid	Acetone	Acrylonitrile
Ammonia	Base oils-lubes	Benzene
Butadiene	Ethyl Alcohol	Ethylene
Ethylene Glycol	Formic Acid	Isocynates
Melamine	Methanol	Oxo-Alcohols
para/ortho-xylenes	Phthalic Anhydride	Phenol
Polyethylene	Polyethlyene	Polypropylene
Polystyrene	Polyvinyl Chloride	Propylene
Styrene	Terephthalate	Toluene

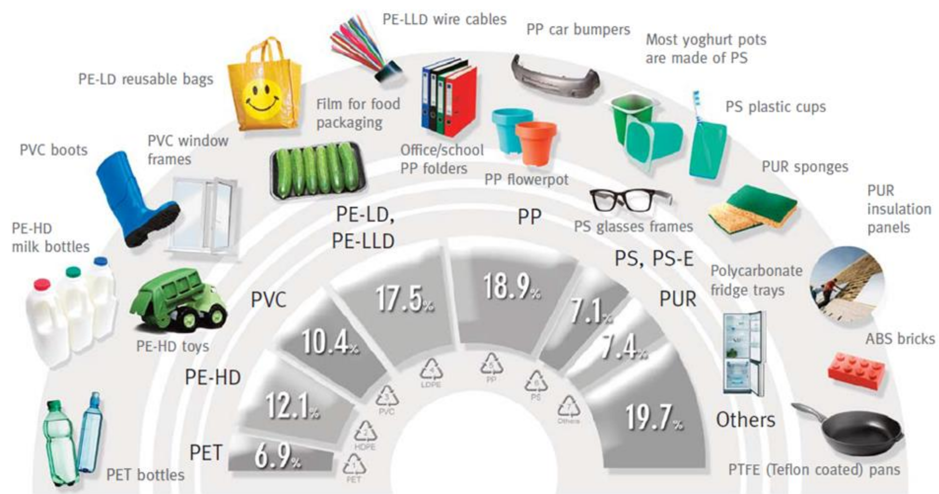
Fertilizers

Fuels

Synthetic Lubes

Plastics & Resins

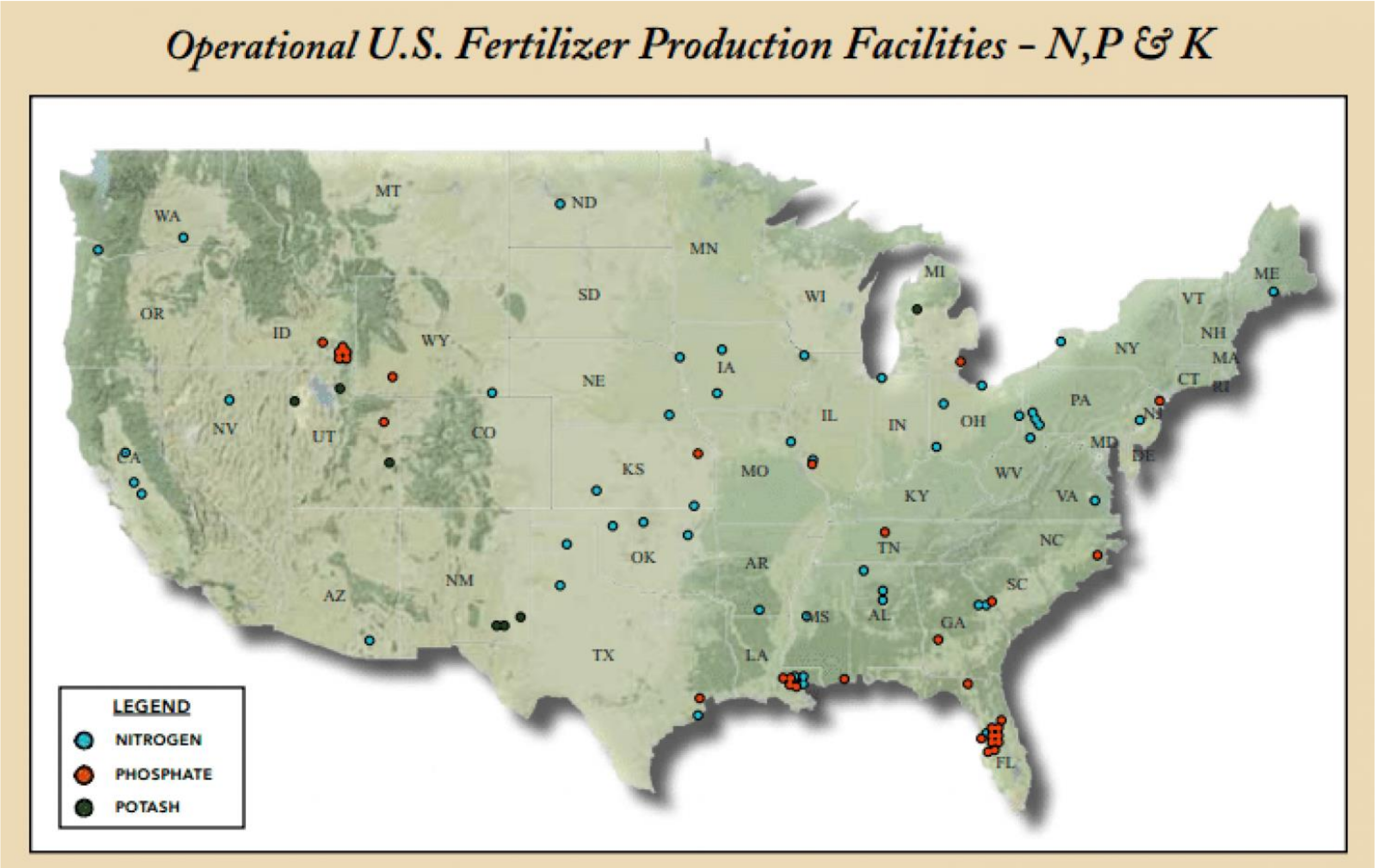




European plastics demand* by polymer type 2013
Source: PlasticsEurope (PEMRG) / Consultic / ECEBD
* EU-27+NO/CH

So how many fertilizer plants are there in the United States?

According to the Fertilizer Institute, there are 44 *production* plants around the country. **And 30 of those are nitrogen plants**:



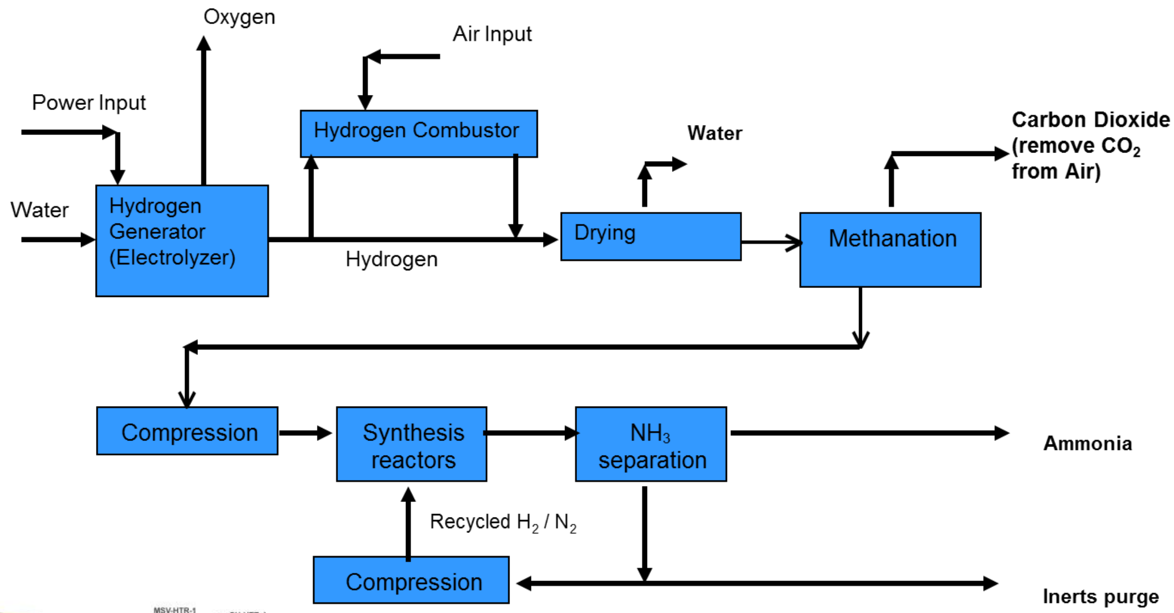
http://www.tfi.org/sites/default/files/images/usproductionmaps%28updated%29.pdf

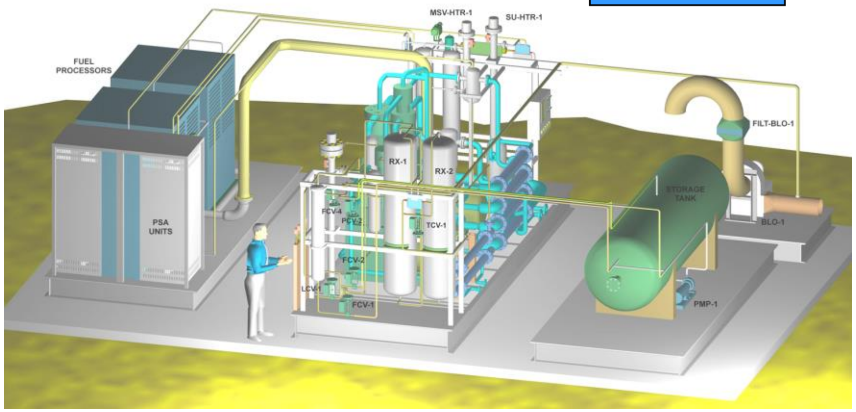
Proposed major methanol plants and ammonia-based fertilizer plants (2015-18)

New Simplot Rock Springs Plant in 2016
600 tpd•NH_3

New Dyno Noble Louisiana Plant in 2016
2,000 tpd•NH_3

Distributed Zero-Emissions Ammonia Plant Example

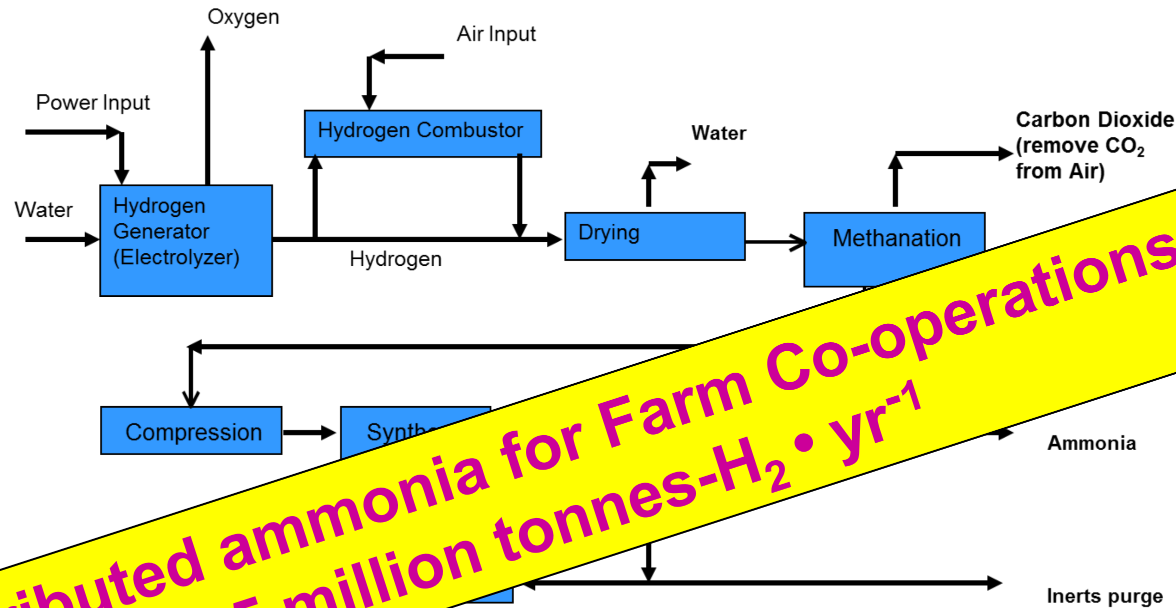




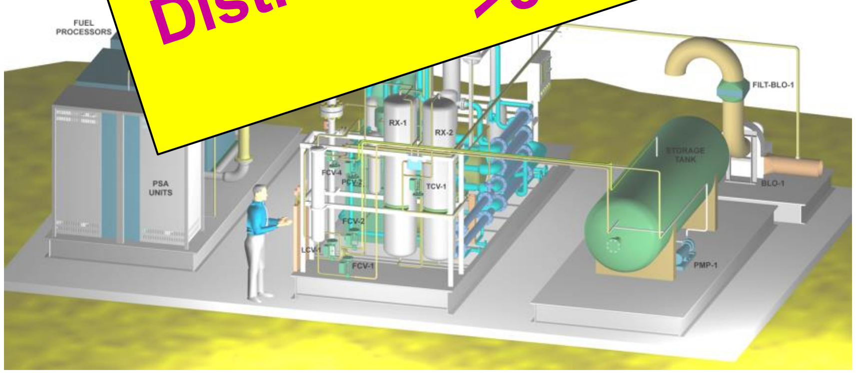
- 3 ton NH_3/day skid-mounted unit
- Hydrogen production from electrolysis
- Small scale application ~ 3 MW
- Simplified process to minimize capital costs

Distributed hydrogen generation enables distributed ammonia production.

Distributed Zero-Emissions Ammonia Plant Example



Distributed ammonia for Farm Co-operations
>5 million tonnes-H_2 • yr^{-1}



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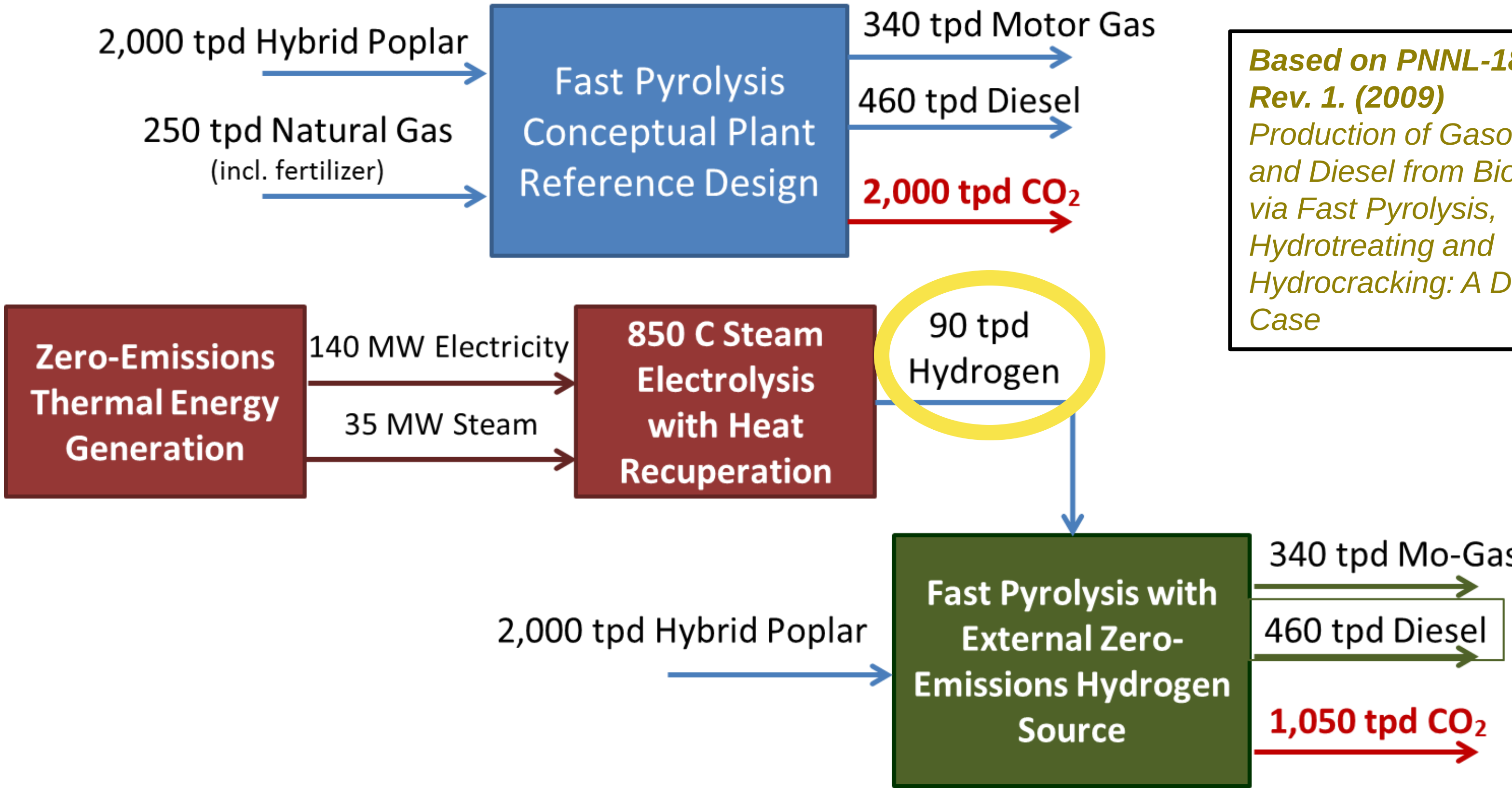
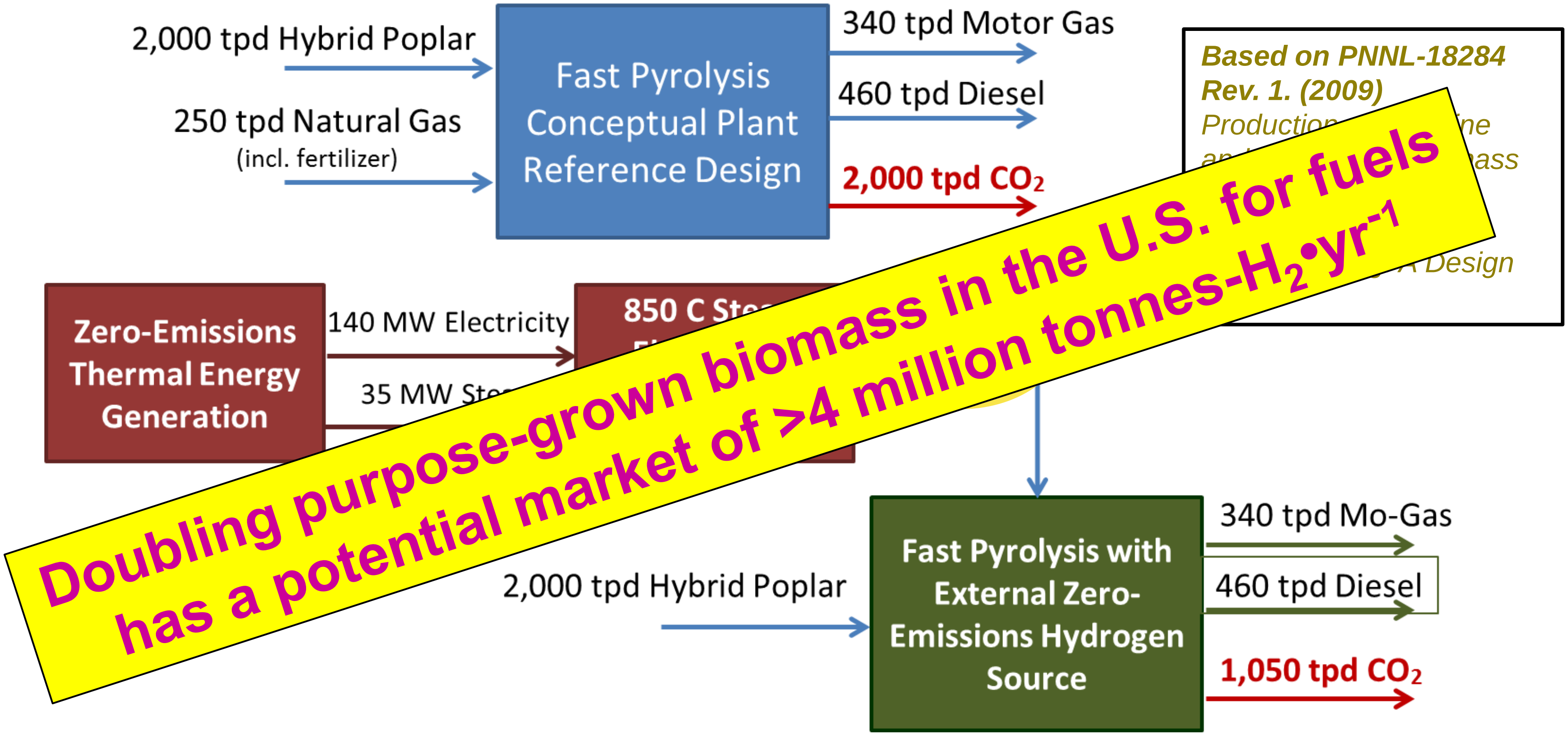
Biofuels Upgrading with Clean Hydrogen



Based on PNNL-18284 Rev. 1. (2009)
Production of Gasoline and Diesel from Biomass via Fast Pyrolysis, Hydrotreating and Hydrocracking: A Design Case

Zero emissions hydrogen reduces biofuels GHG by 50%.

Biofuels Upgrading with Clean Hydrogen



Zero emissions hydrogen reduces biofuels GHG by 50%.

Changing the way methanol is made…

Steam Methane Reforming and Methanol Synthesis:

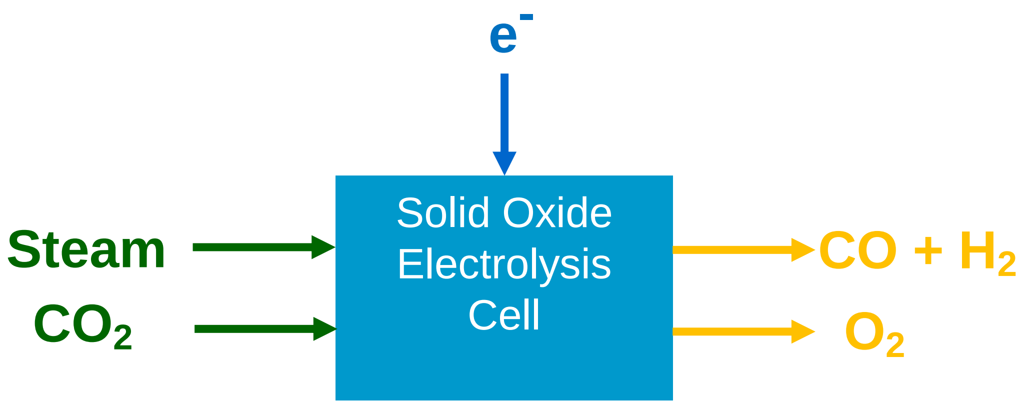
$$CH_4 + H_2O \rightarrow CH_3OH + H_2 \qquad +122.0\ kJ/mole$$

CO_2 Hydrogenation:

$$CO_2 + 2H_2 \rightarrow CH_3OH + \tfrac{1}{2}O_2 \qquad +154.9\ kJ/mole$$

Sources of CO_2

- Flue gas separation
- Oxy-fired flue gas
- CO_2 co-electrolysis with steam



Industry-based co-electrolysis provide “negative” GHG emissions when producing fungible methanol.

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CO_2 Hydrogenation:

$$CO_2 + 2H_2 \rightarrow C\ldots \qquad +154.9\ kJ/mole$$

Future CO_2 utilization has the potential for:
>5 million tonnes-$H_2 \cdot yr^{-1}$

Sources of CO_2
- Flue gas separation
- Oxy-fired flue gas
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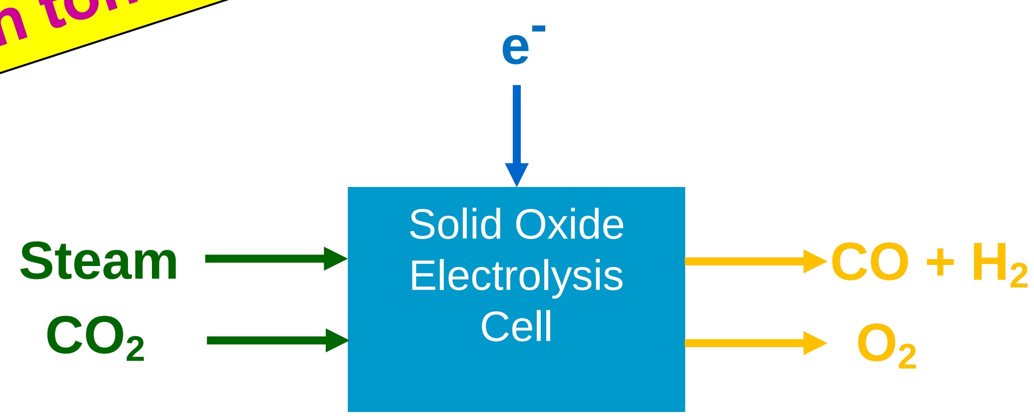

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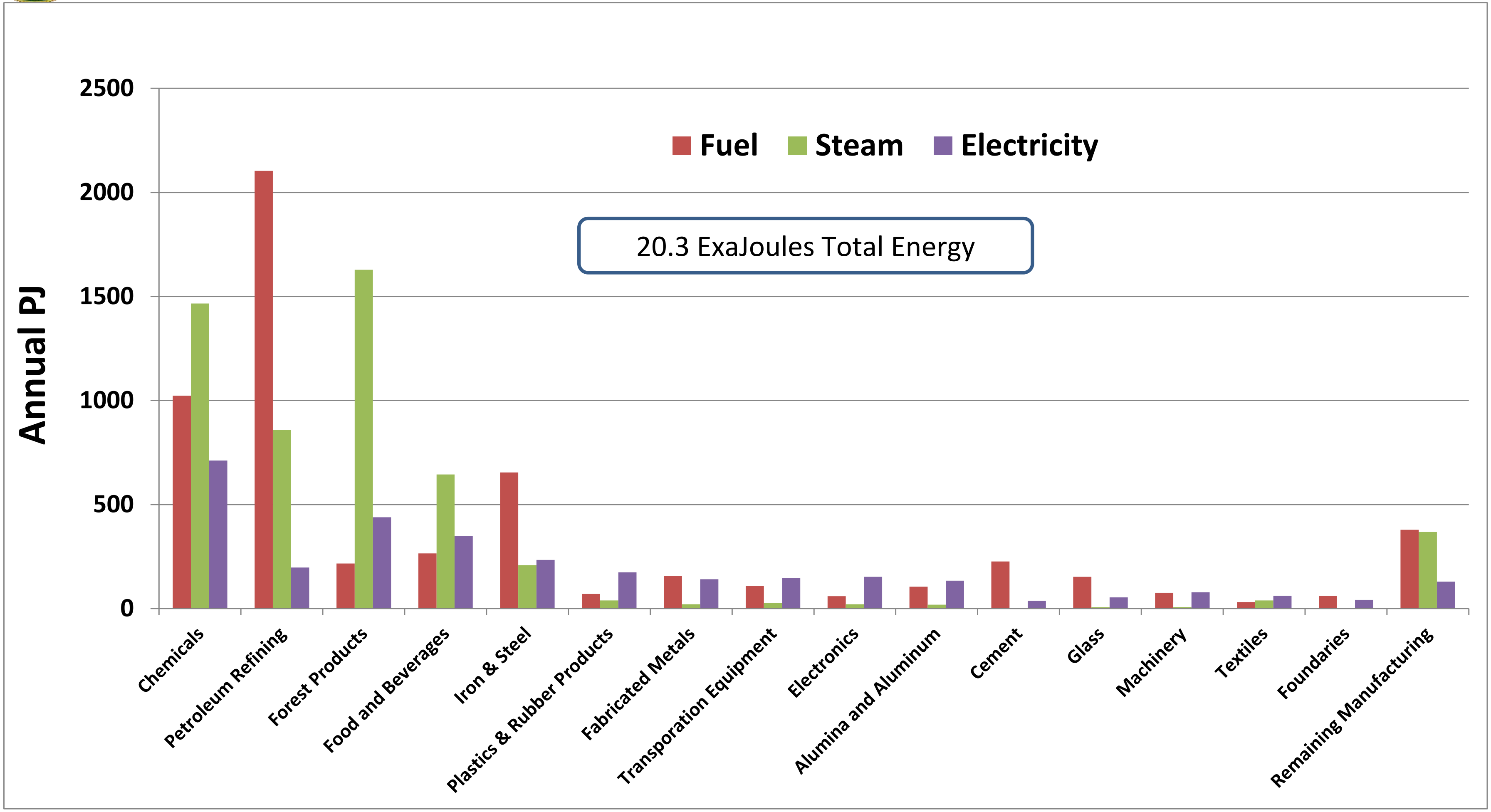
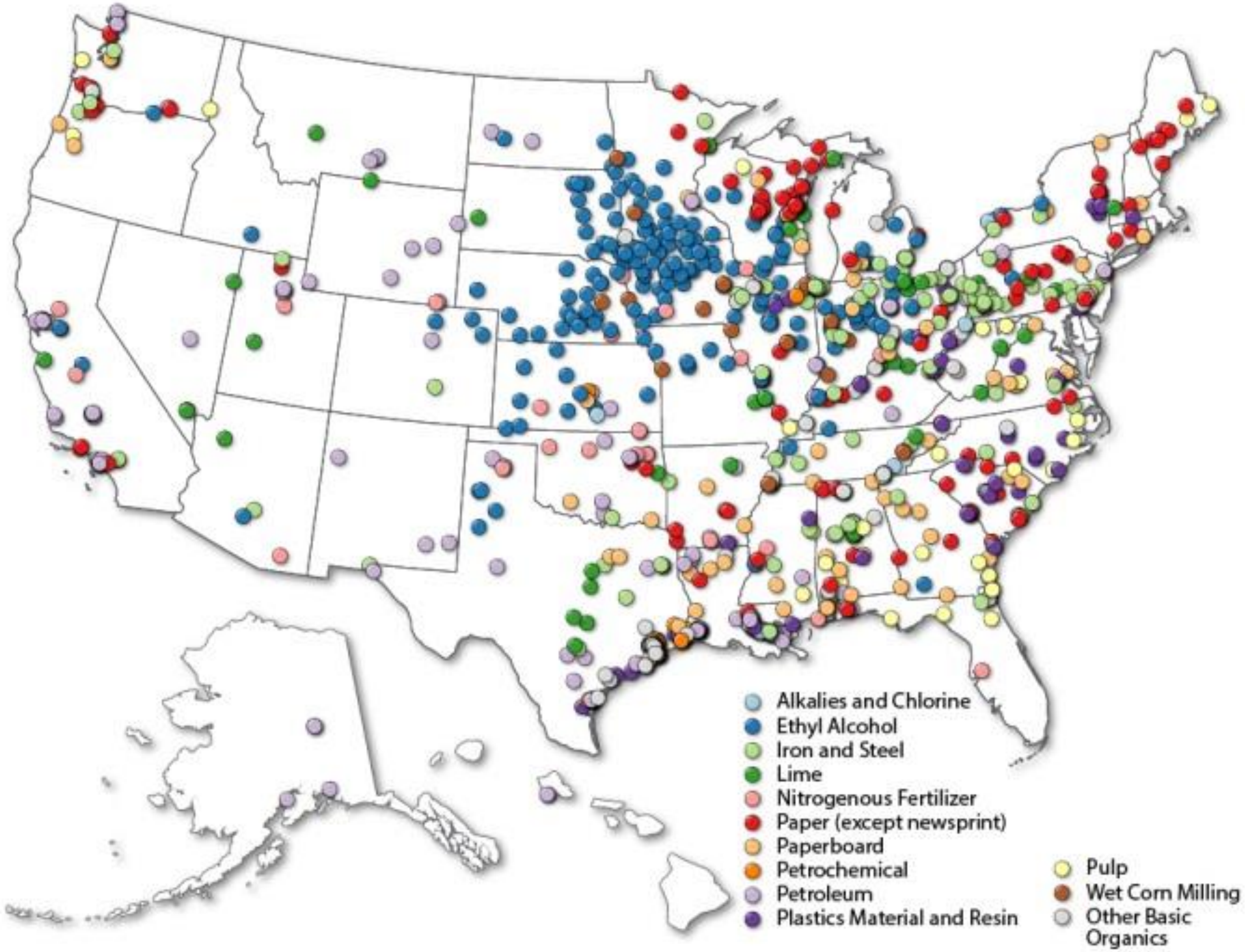
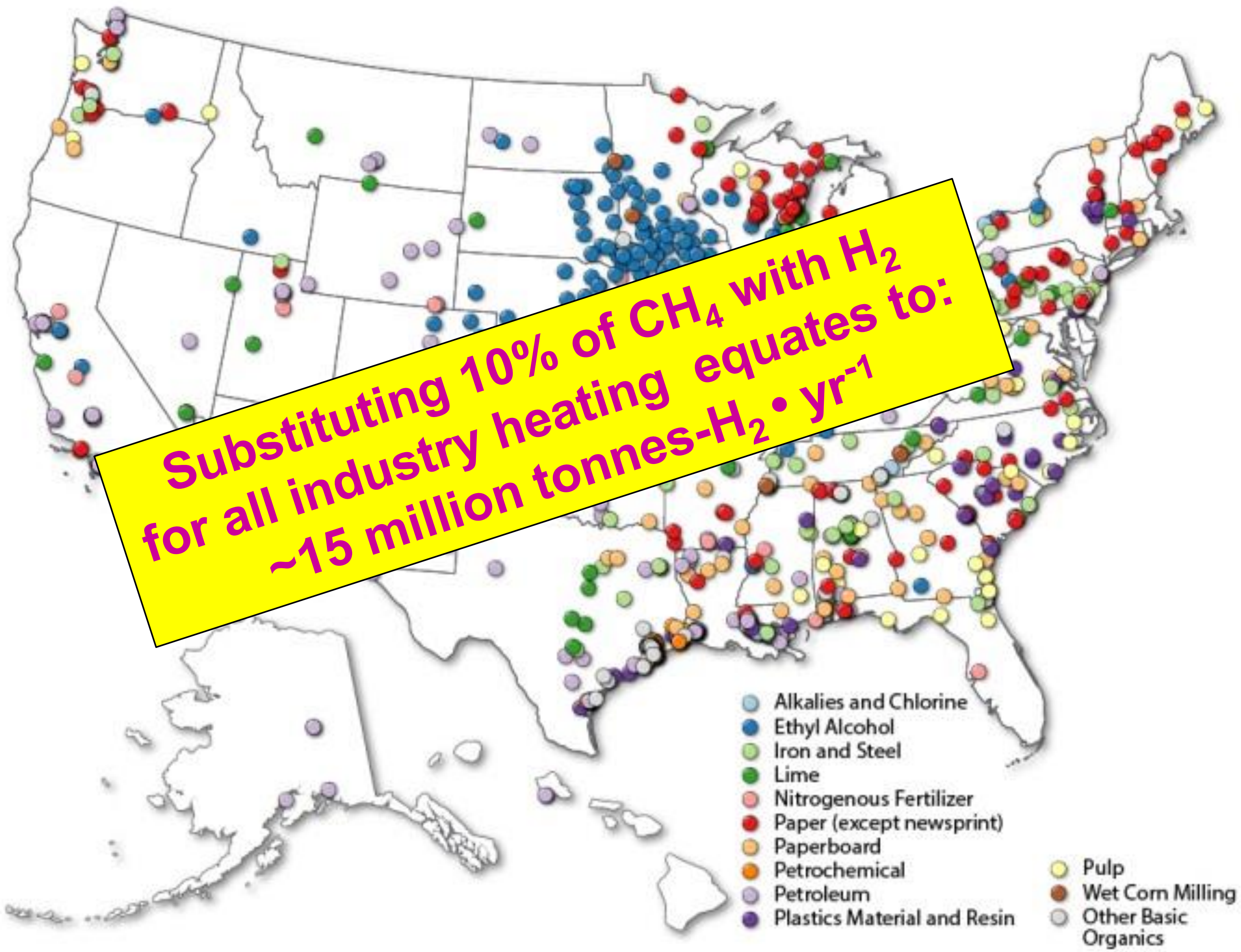
U.S. Manufacturing Energy Use in 2010



How much fuel for heating can be replaced with hydrogen?

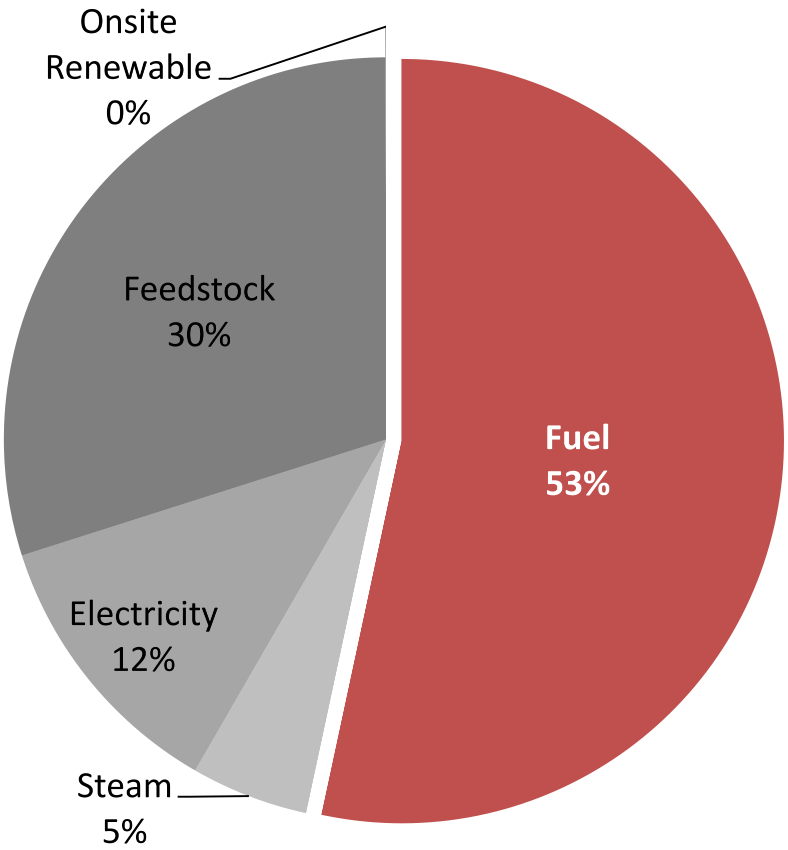


Alkalies and Chlorine
Ethyl Alcohol
Iron and Steel
Lime
Nitrogenous Fertilizer
Paper (except newsprint)
Paperboard
Petrochemical
Petroleum
Plastics Material and Resin
Pulp
Wet Corn Milling
Other Basic Organics



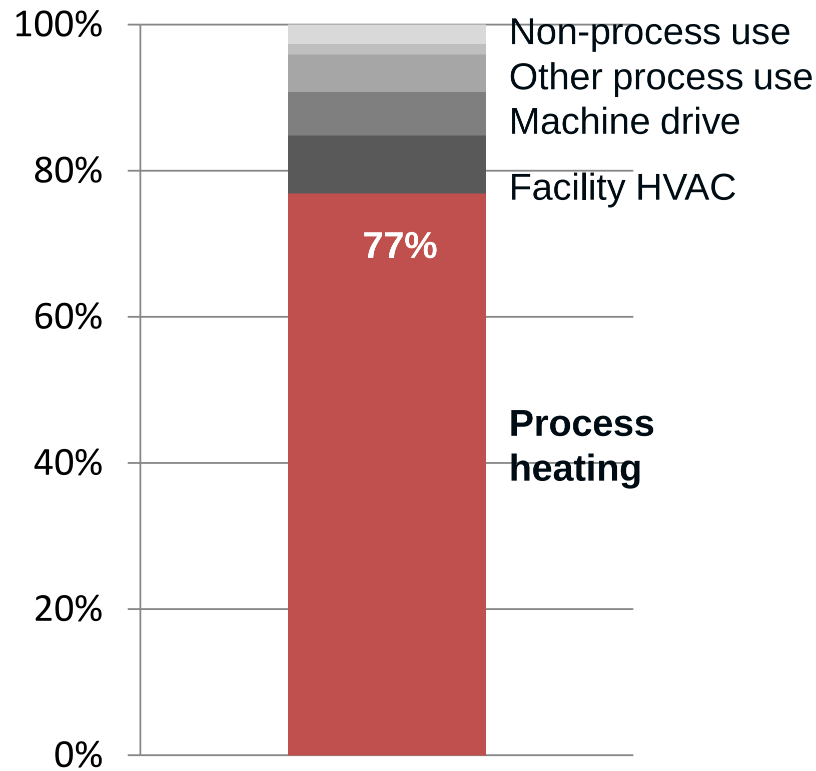
Substituting 10% of CH_4 with H_2 for all industry heating equates to: ~15 million tonnes-H_2 • yr^{-1}

Changing combustion by industry….



U.S. Manufacturing Site Energy Use (including feedstocks) in 2010

20.432 Quadrillion Btu



Fuel and Steam Consumption by End Use

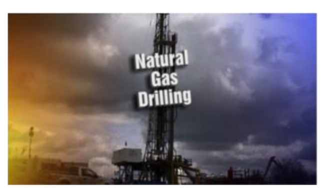
Zero Emissions Fuels: H_2, NH_3
Low Emissions Fuels: CH_4, DME, DMC

Data source: U.S. DOE. 2015. "Manufacturing Energy and Carbon Footprints (2010 MECS)"

Sum of Industrial Hydrogen Demand Profile

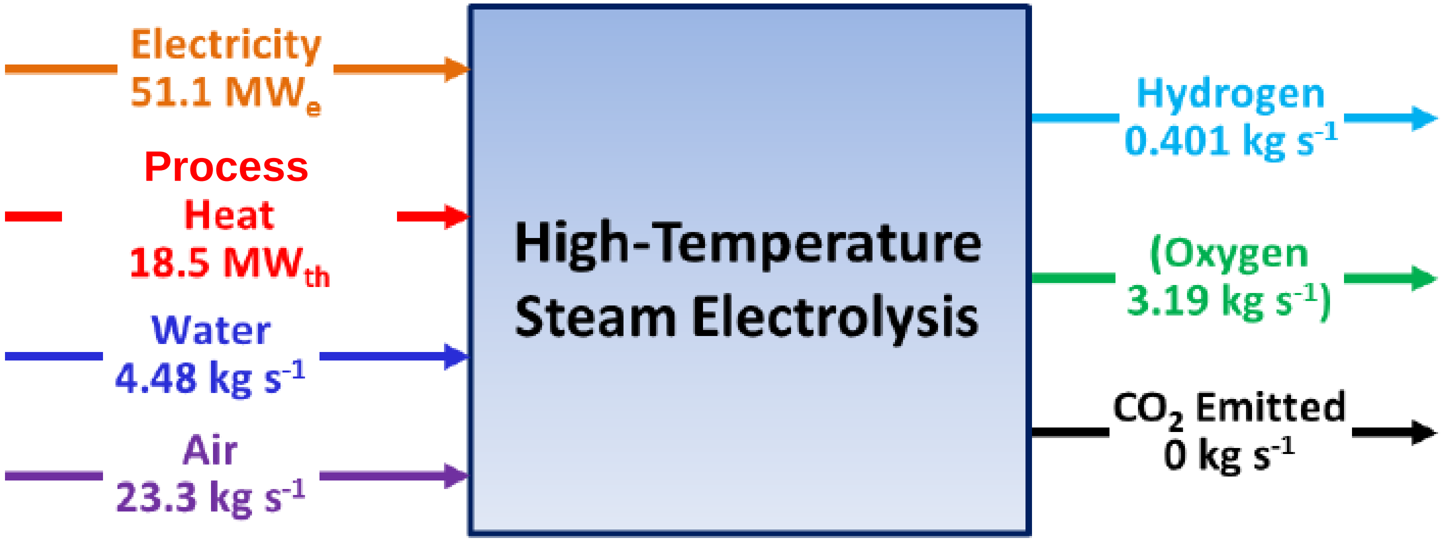
- Refineries: 5 – 10 MM tonnes
- Steel making: 3 – 6 MM tonnes
- Biomass upgrading: 4 MM tonnes
- Ammonia-based fertilizers: 5-10 MM tonnes
- Combustion: 15 MM tonnes
- TOTAL: 32 – 45 MM tonnes

H_2 CH_4 H_2O



Okay! Where and how do we produce this hydrogen?

High Temperature Electrolysis (HTE)

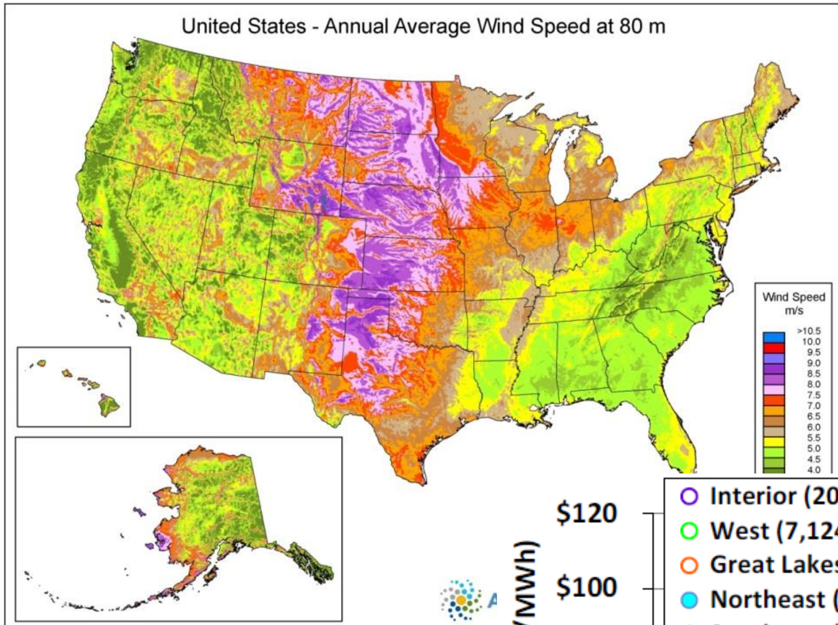


H2A Cost Analysis:

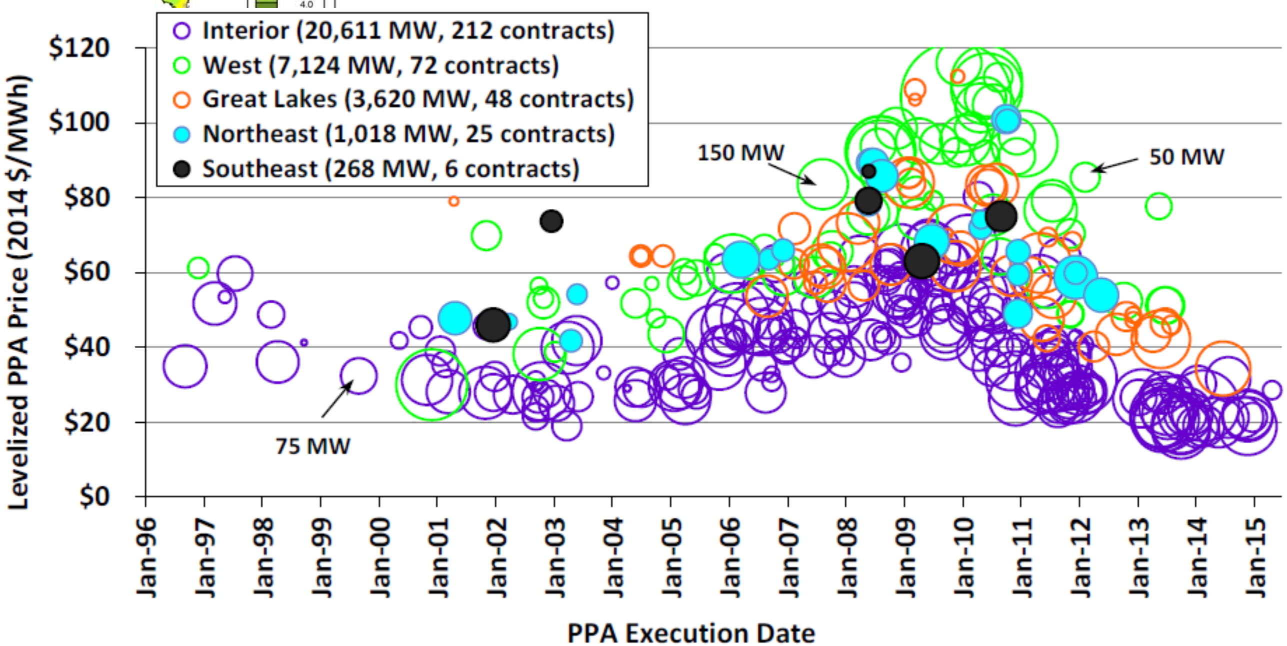
\$100/kW Fuel Cell Cost and \$30/MW$_e$•h $\rightarrow$

\$1.99/kg•H_2

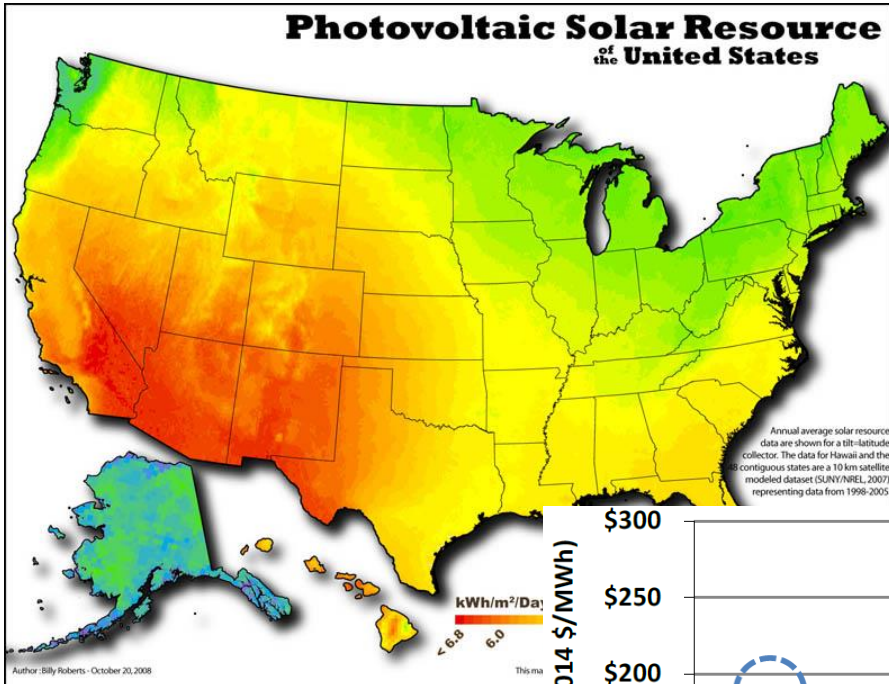
Where is the Wind Resource?



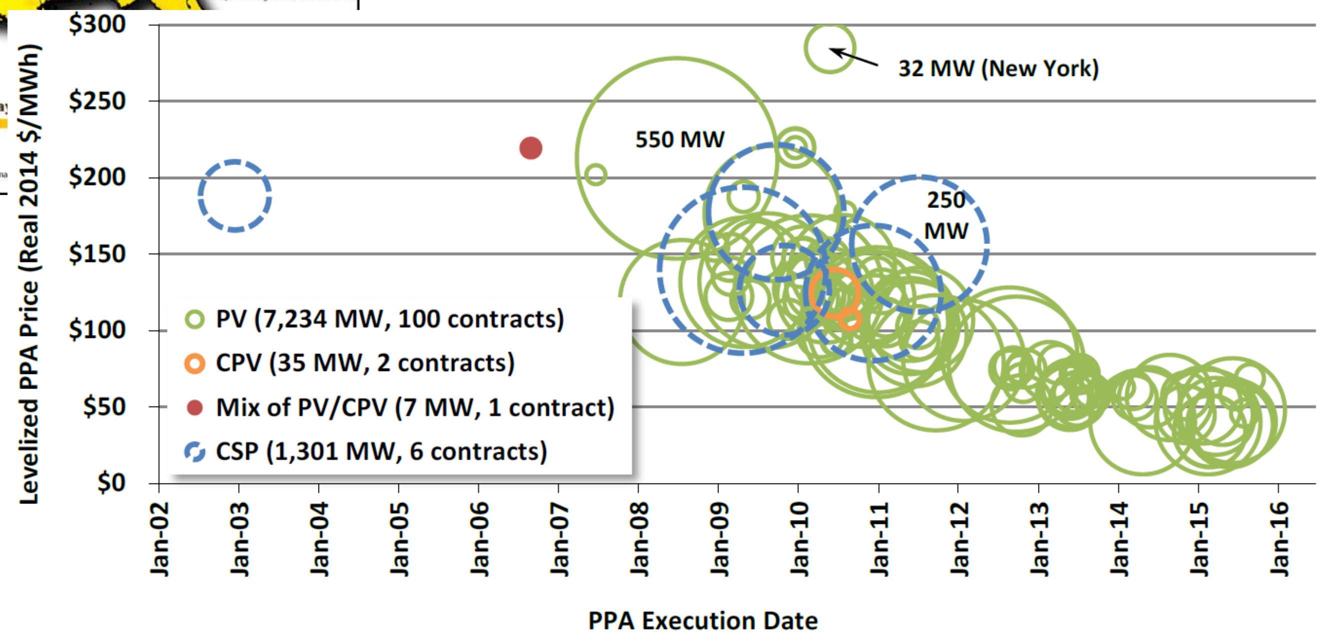
Levelized power purchase agreement for wind by contract size, location and vintage (DOE-EERE)



Where is the Solar Resource?

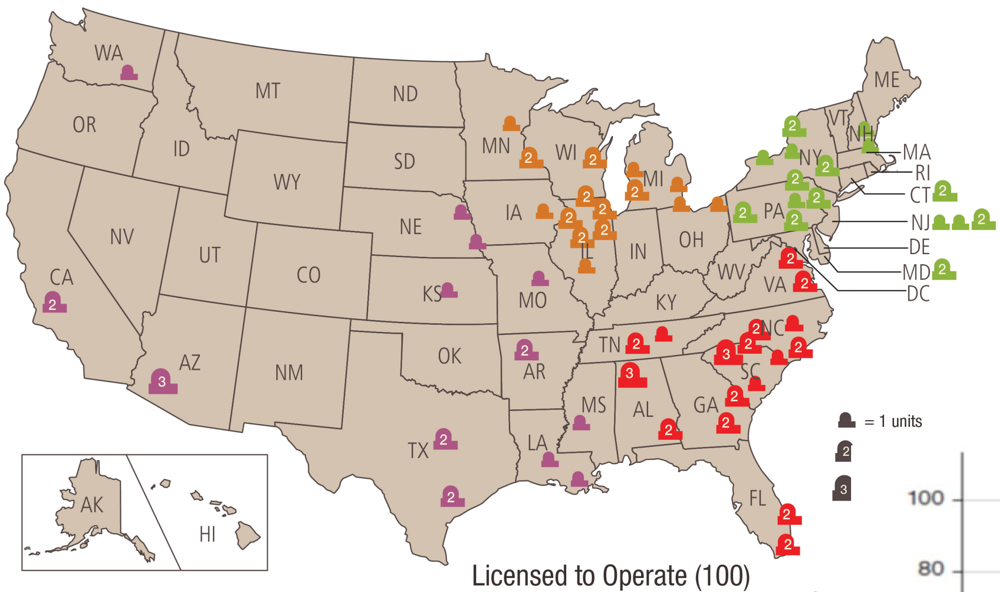


Levelized Power Purchase Agreement for Solar PV by technology, project size, and contract vintage (LBNL)



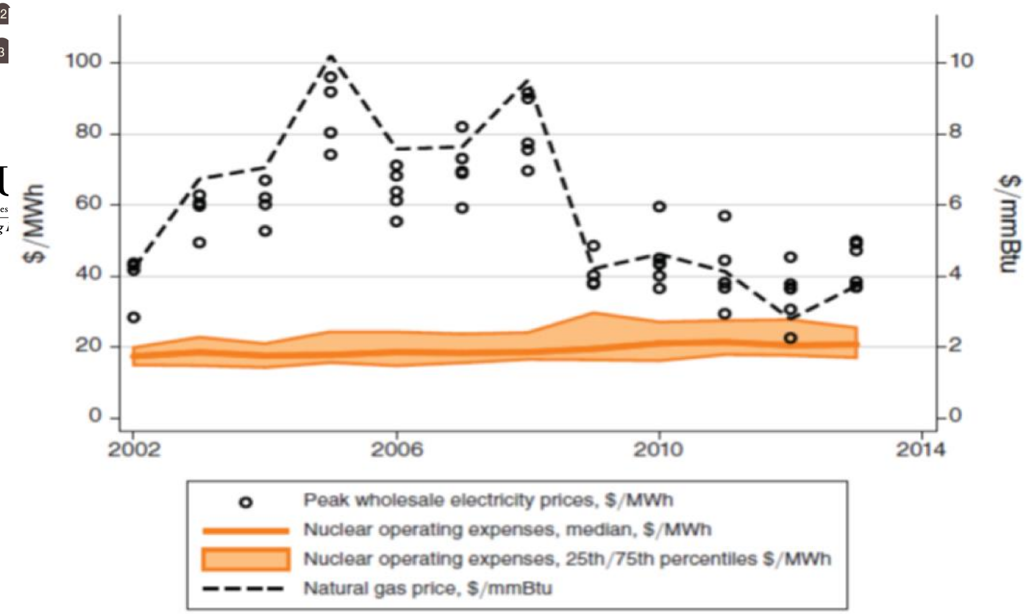
Nuclear reactors

U.S. Operating Commercial Nuclear Power Reactors



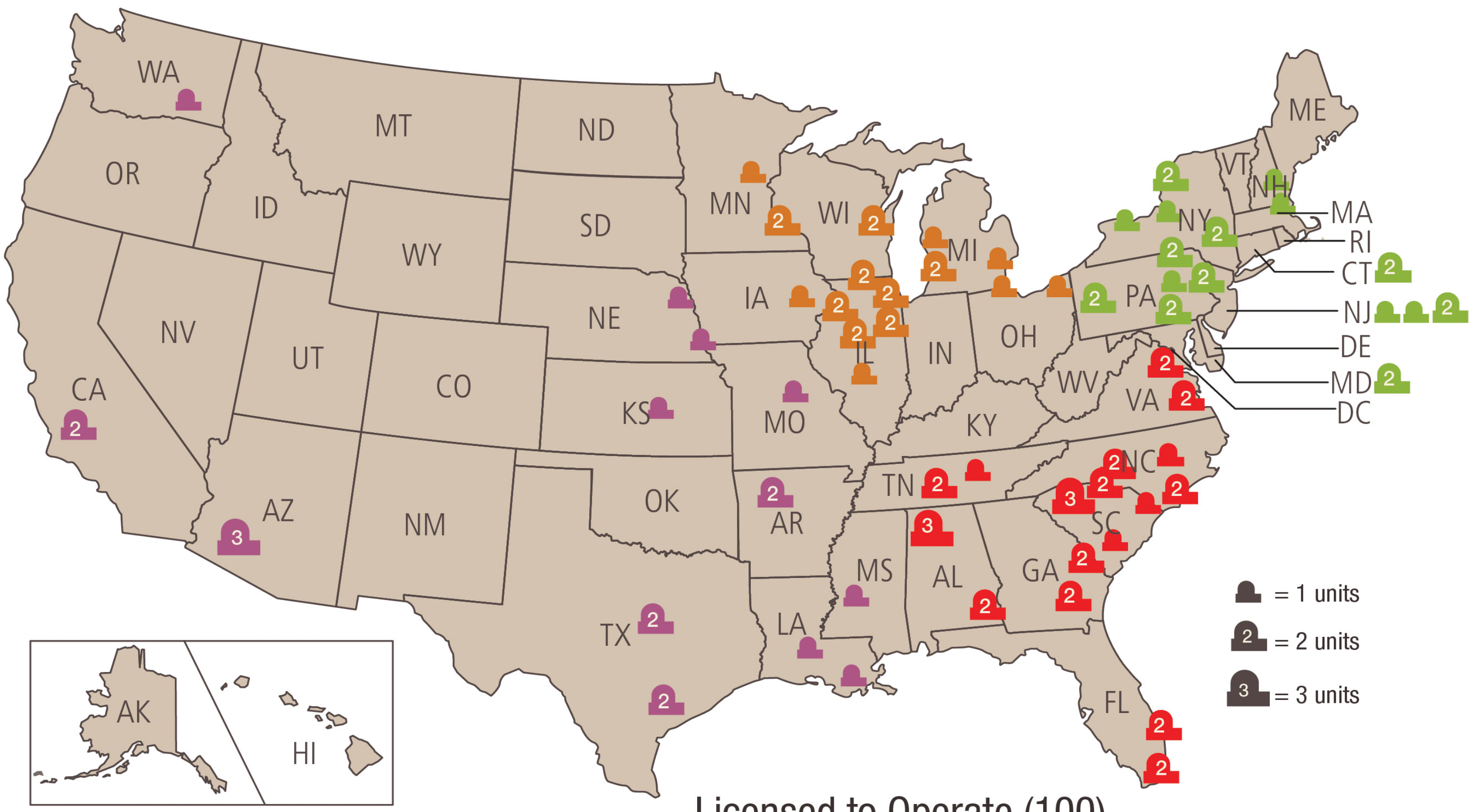
Actual cost of electricity production by nuclear plants in the United States

- 100 plants licensed to operate
- 20-40 year more operations with NRC re-certification



Nuclear Energy in the United States

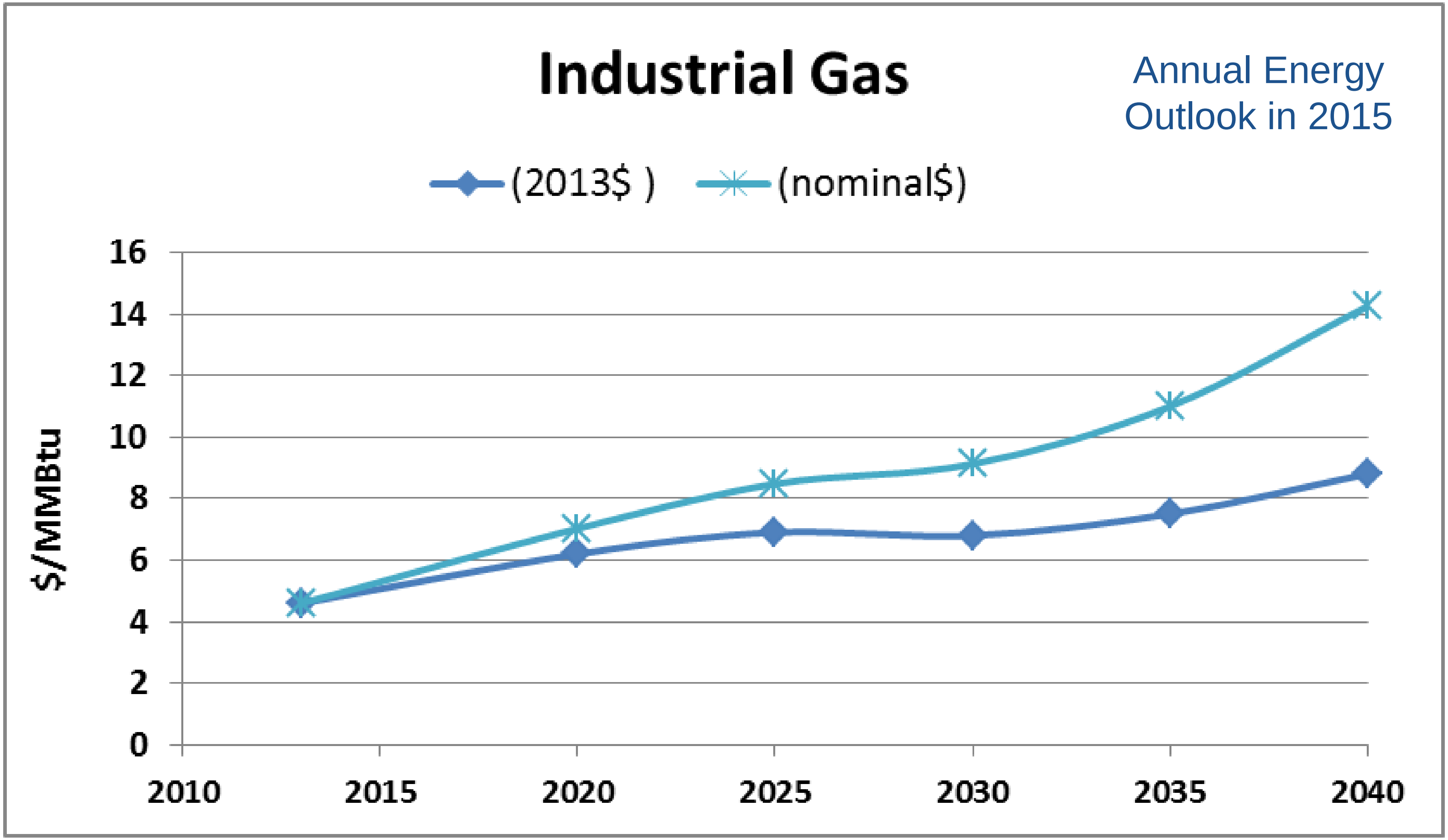
- ***100 plants licensed to operate;*** 100 reactors → 100 GW_e Capacity → 18 MM tonnes-H_2 • yr^{-1}
- ***20-40 year extended operation possible with NRC re-certification***



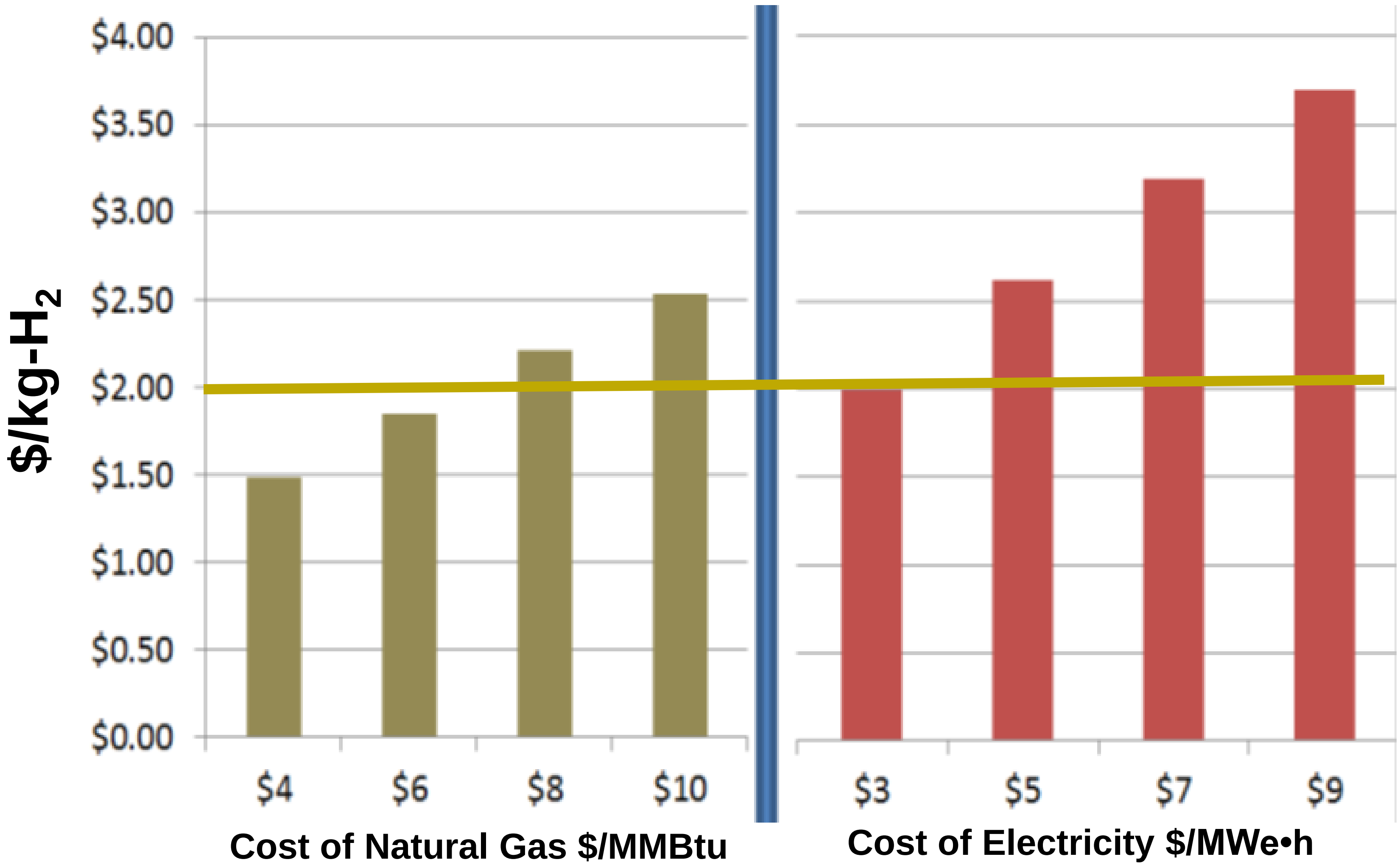
Licensed to Operate (100)

U.S.NRC
United States Nuclear Regulatory Commission
Protecting People and the Environment

SMR Comparison with HTSE

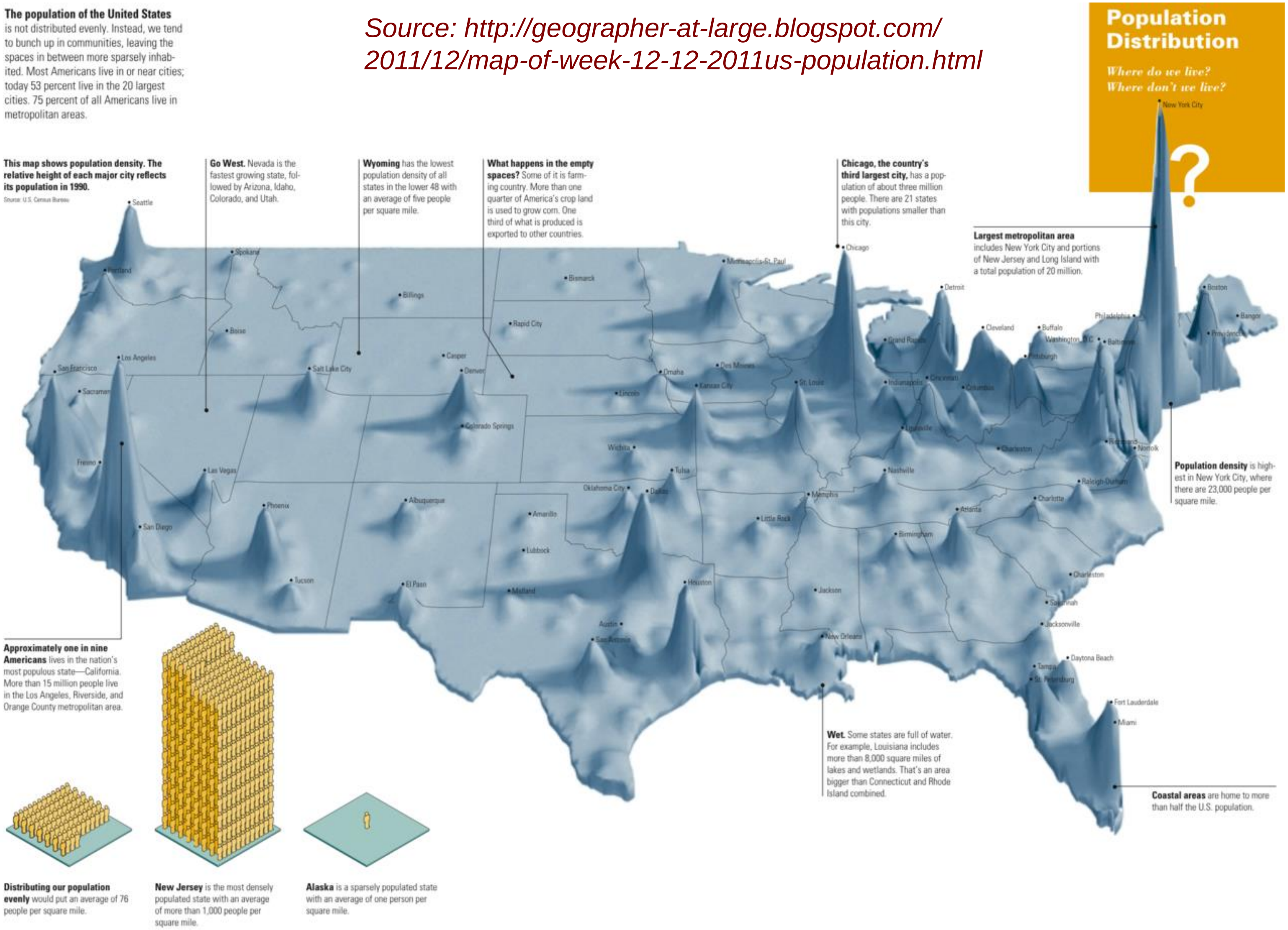


SMR Comparison with HTSE



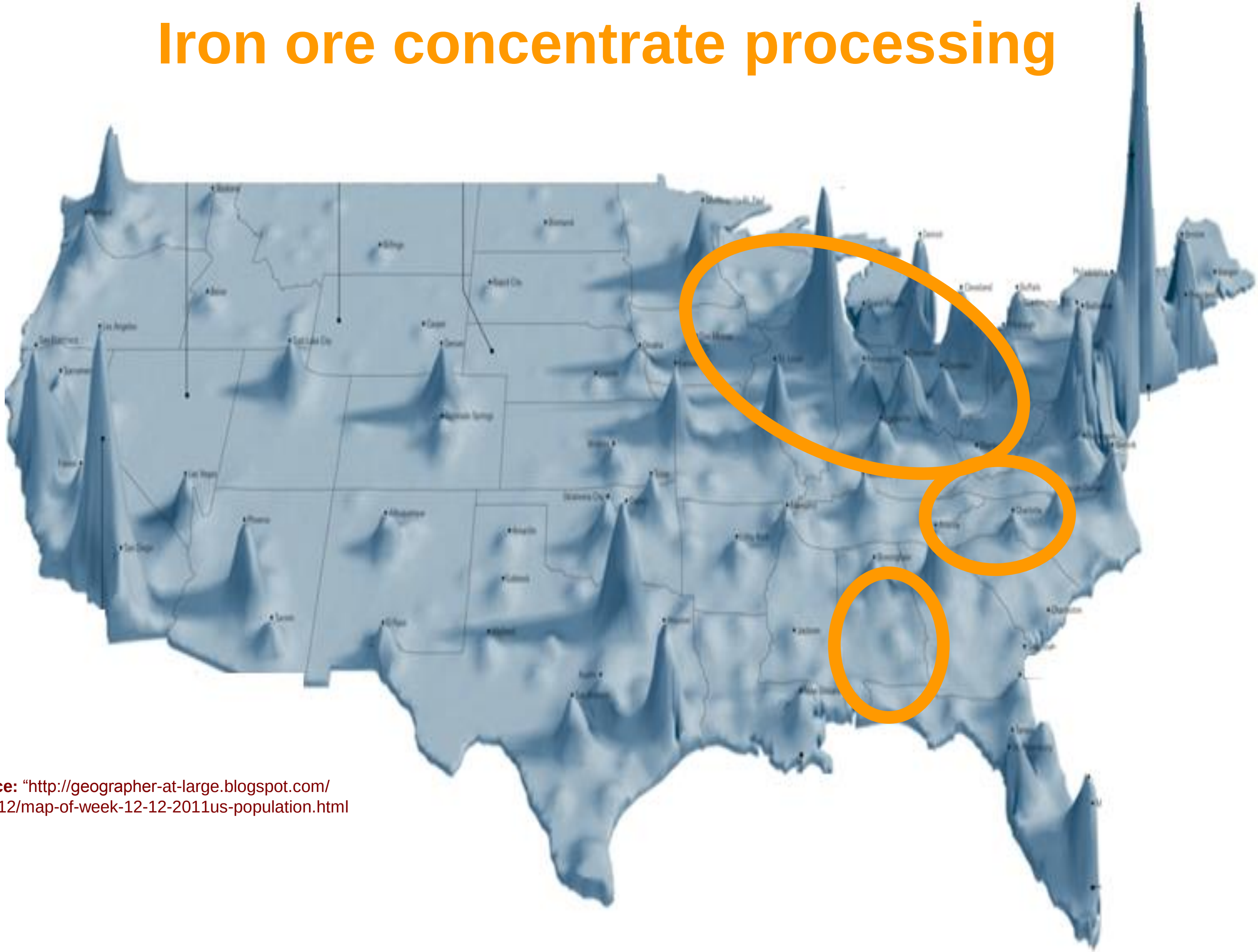
Where is the population located?

Source: http://geographer-at-large.blogspot.com/2011/12/map-of-week-12-12-2011us-population.html



Possible Hydrogen Demand by Region

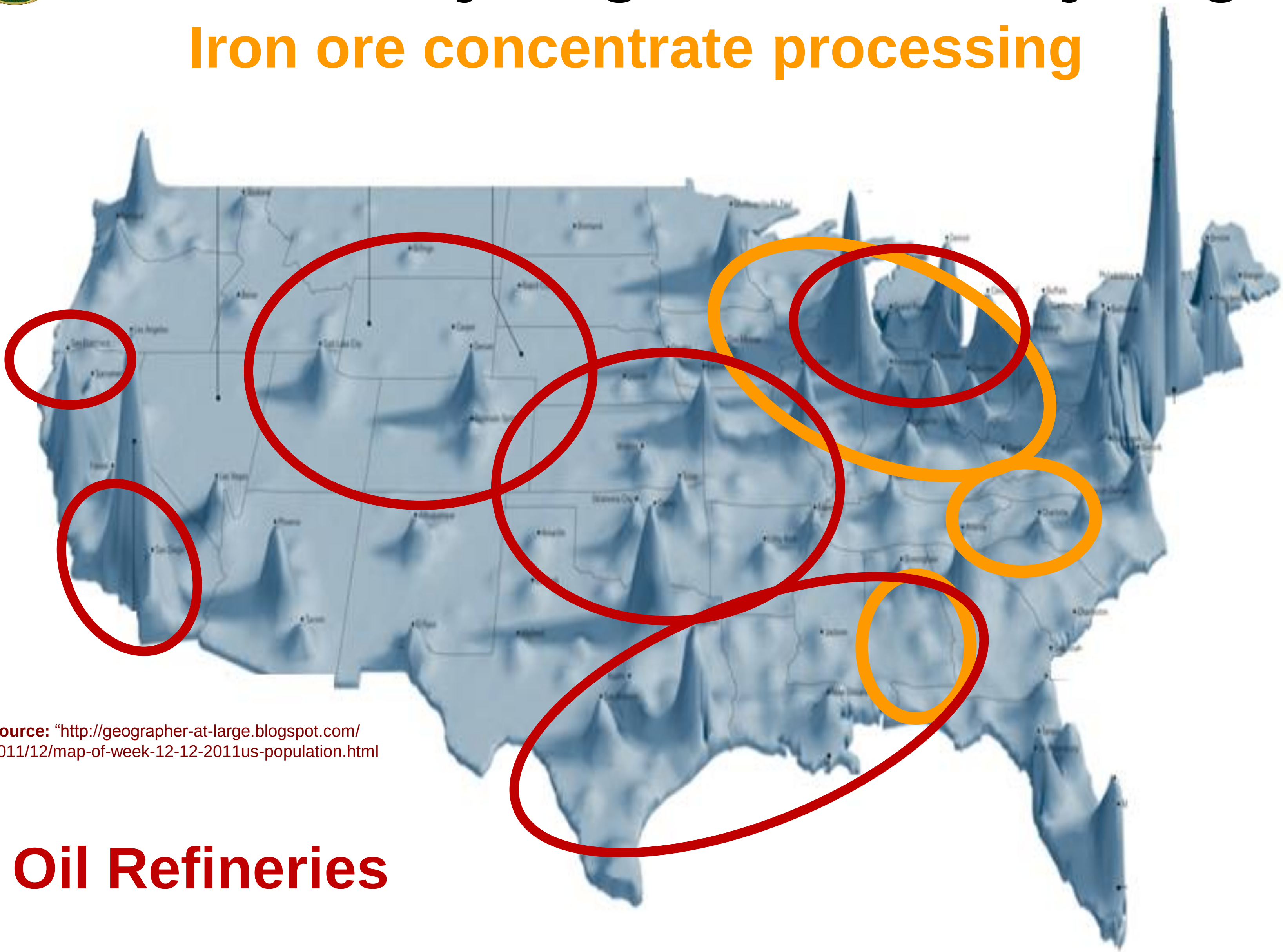
Iron ore concentrate processing



Source: "http://geographer-at-large.blogspot.com/2011/12/map-of-week-12-12-2011us-population.html

Possible Hydrogen Demand by Region

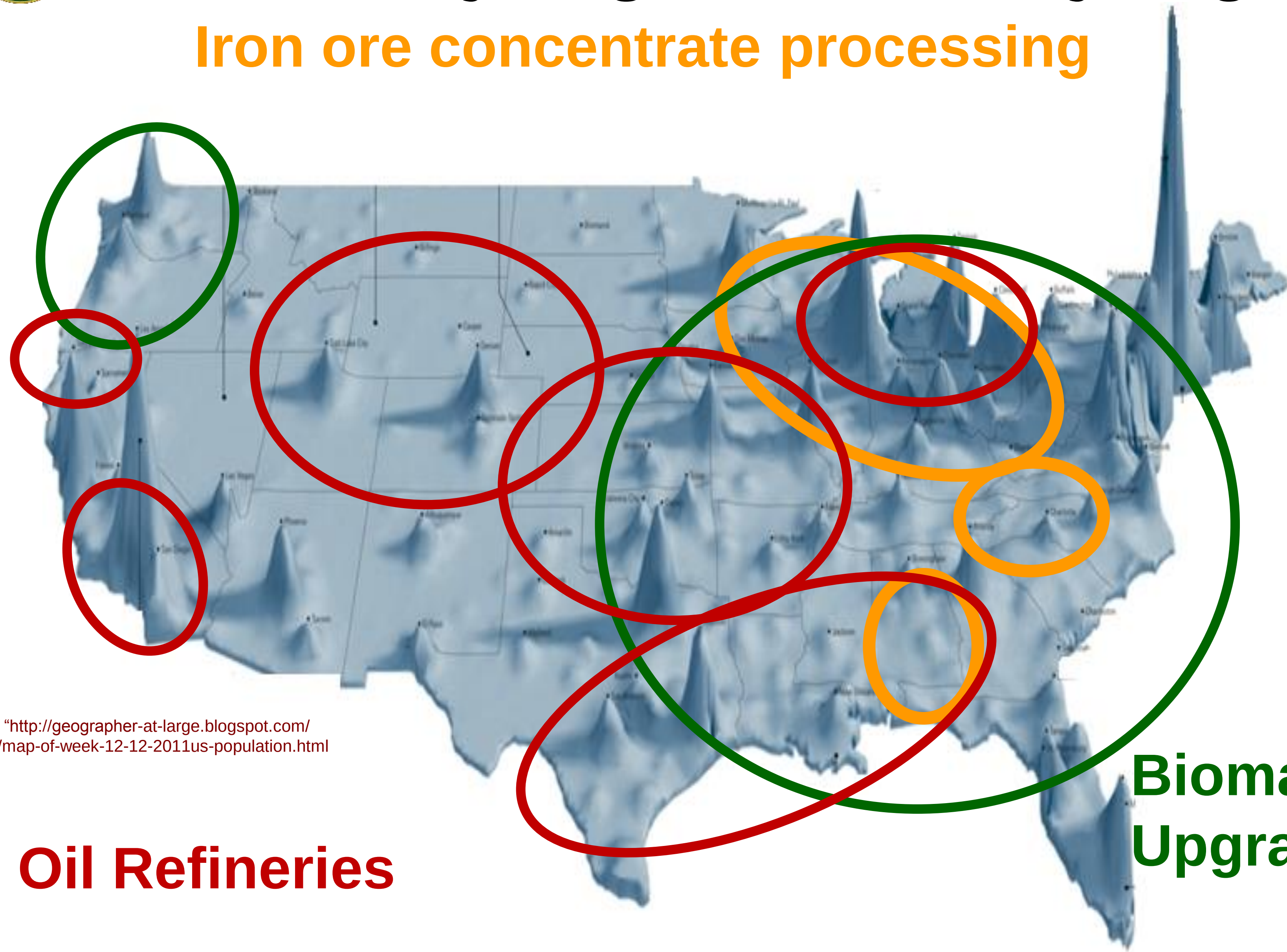
Iron ore concentrate processing



Source: “http://geographer-at-large.blogspot.com/2011/12/map-of-week-12-12-2011us-population.html

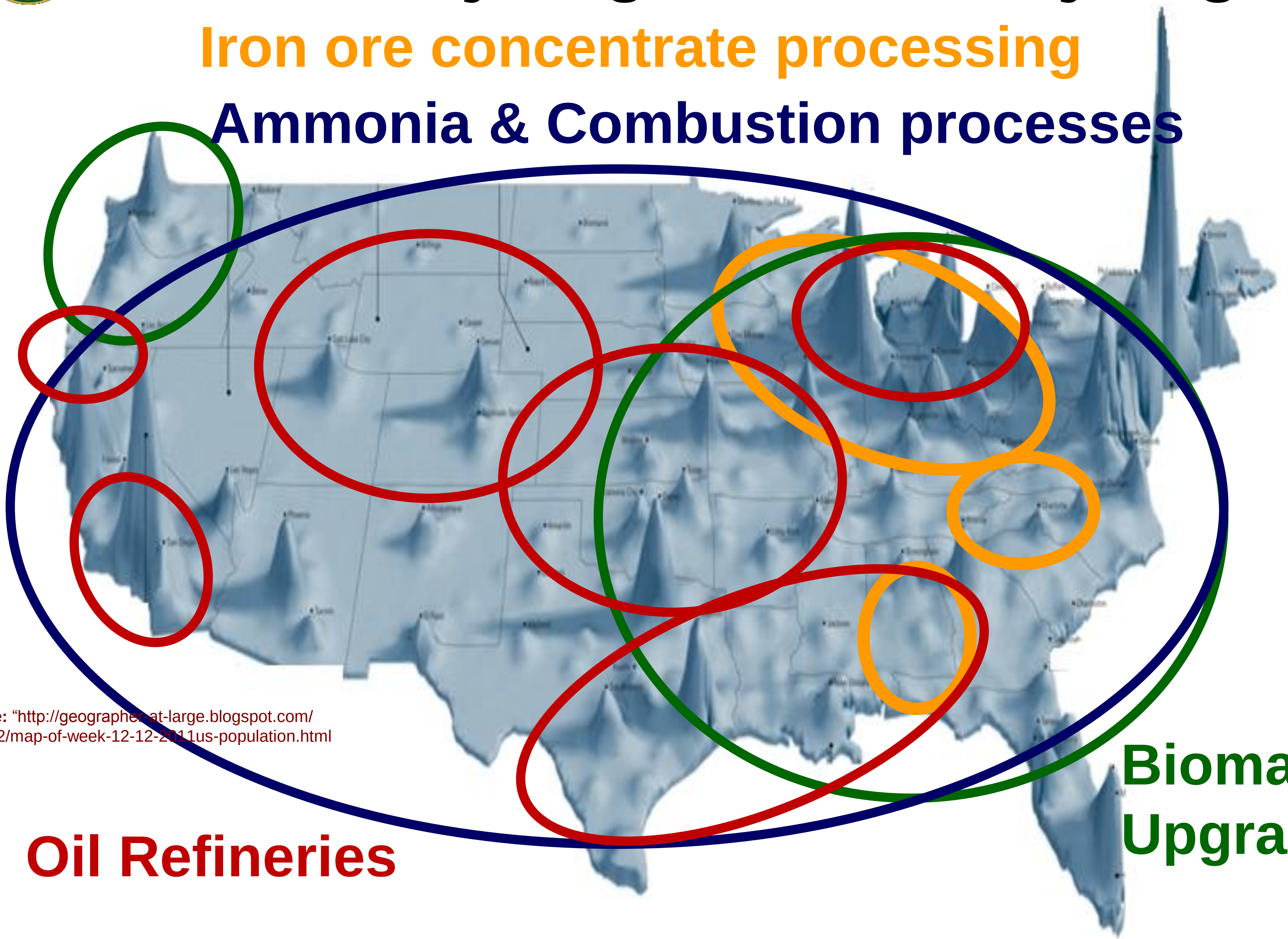
Oil Refineries

Possible Hydrogen Demand by Region



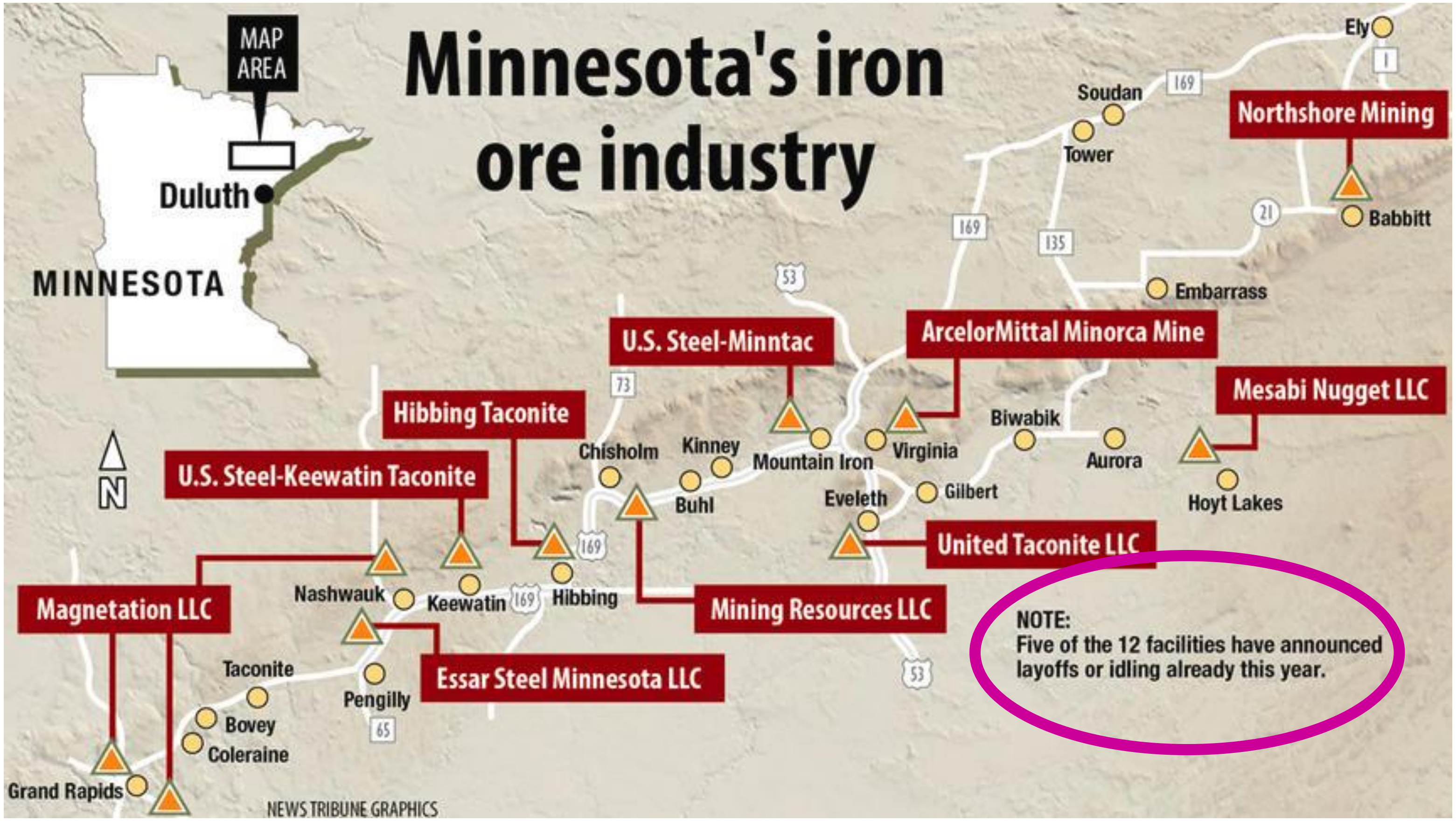
Source: "http://geographer-at-large.blogspot.com/2011/12/map-of-week-12-12-2011us-population.html

Possible Hydrogen Demand by Region



Source: “http://geographer-at-large.blogspot.com/2011/12/map-of-week-12-12-2011us-population.html

Revitalizing the iron ore industry…



- Revitalization of U.S. steel manufacturing with taconite iron ore concentrate for DRI could spur a 3-4X increase in mining jobs and supply chain industries.

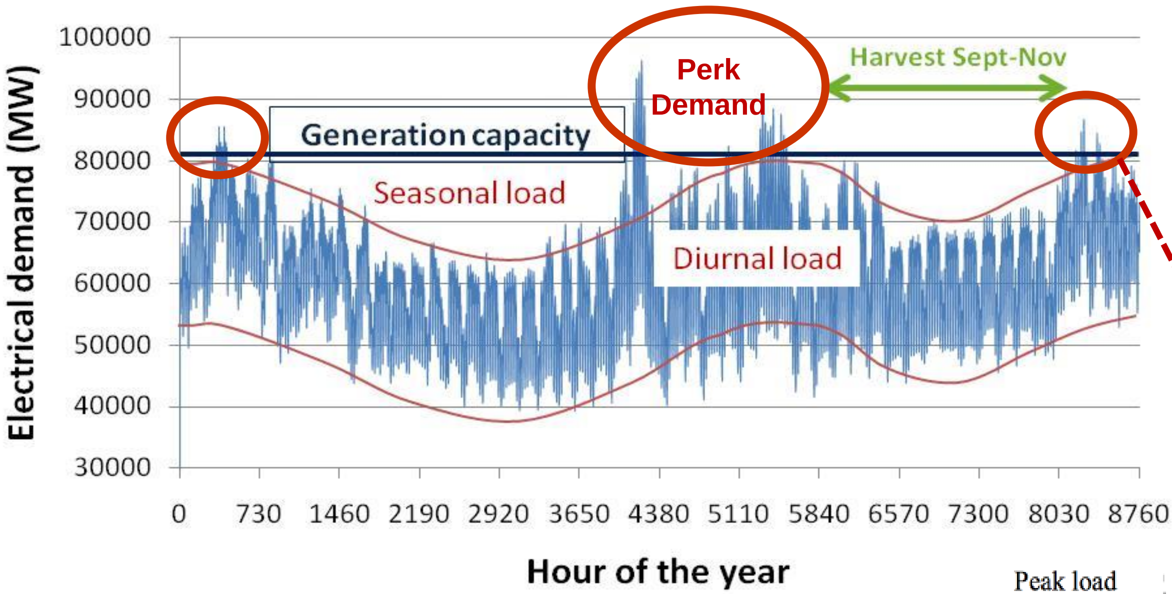
Case Study

- **Renewable wind penetration of 30% in Midwest**
- **Nuclear plants now cycle up and down 30% on average**
  - 30% of 100,350 MWe capacity
- **Hydrogen production potential is 5.5 million tonne H_2**
- **Use hydrogen near nuclear plants for:**
  - Iron ore concentrate processing in Minnesota, Michigan, and Alabama
  - Oil refineries along gulf shores
  - Chemical plants along Eastern Coast States
  - Biorefineies in Southeast
  - Fuel cell vehicles on in U.S. Northeast, East, and Upper Midwest
  - Combustion processes (Power-2-Gas)

Hydrogen at scale enhances the U.S. energy portfolio through sustainable use of domestic resources, improvements in infrastructure, and increase in grid resiliency.

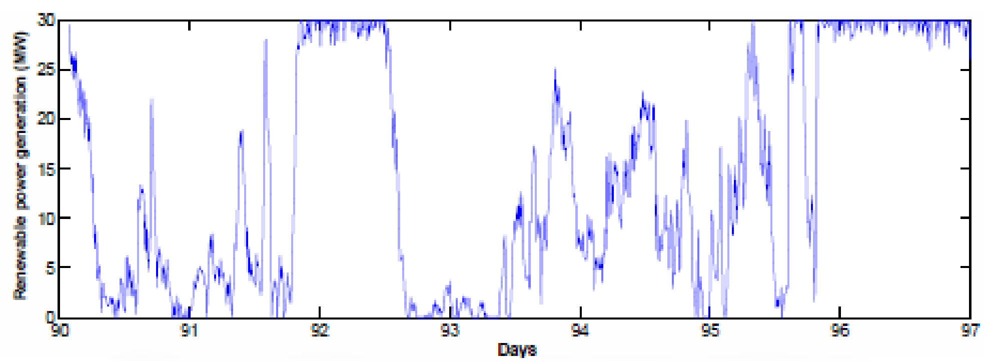
Extra Slides

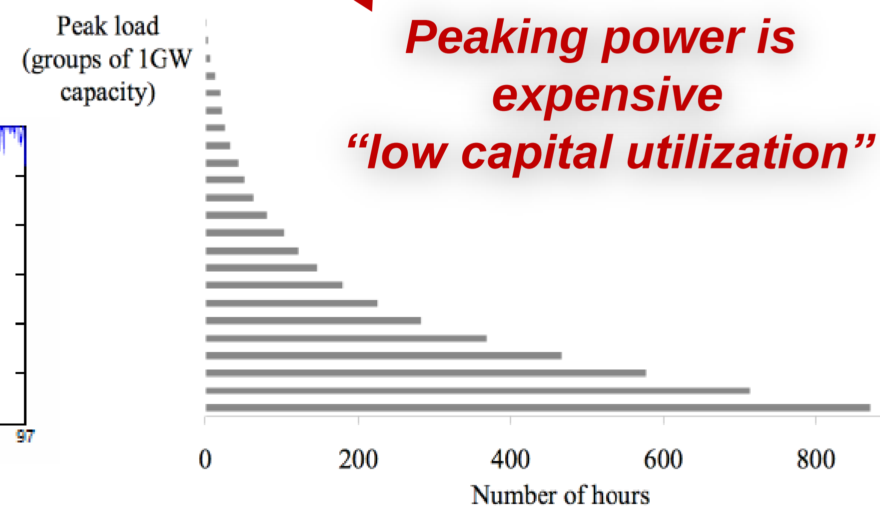
Power Dynamics Create Opportunities to Make Other Products with the Excess Energy



Excess seasonal variation Is available for other work

Excess diurnal capacity Is available year round





Peaking power is expensive “low capital utilization”

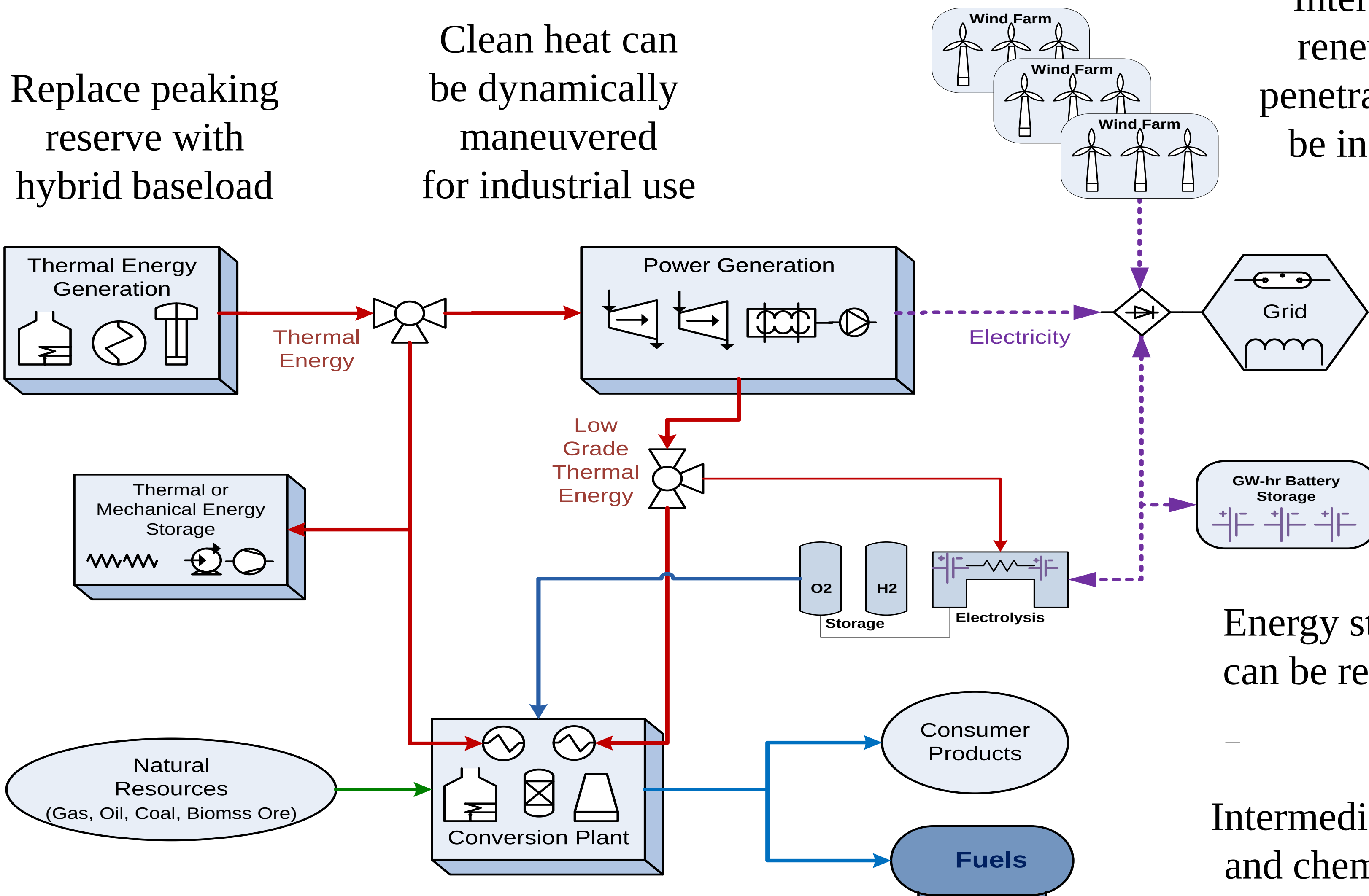
Renewable power is intermittent

Energy Systems Integration

Replace peaking reserve with hybrid baseload

Clean heat can be dynamically maneuvered for industrial use

Intermittent renewables penetration can be increased

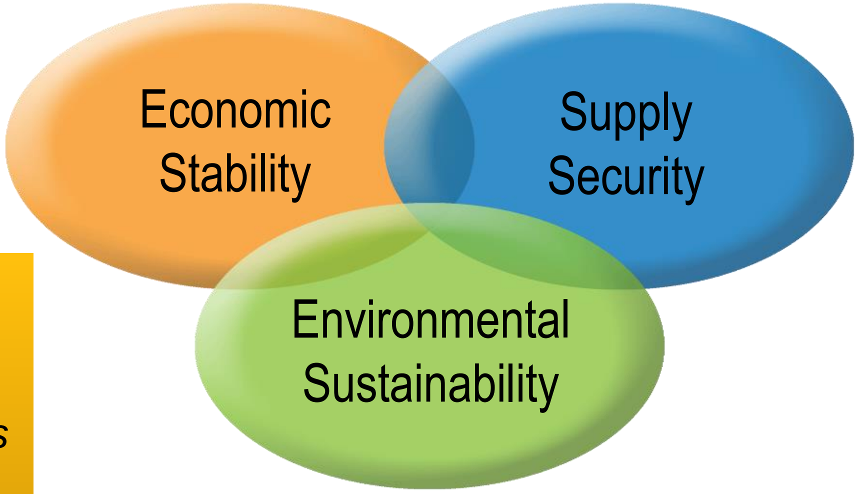


Energy storage can be reduced

Intermediate H_2 and chemicals can be produced

Source: Boardman, Idaho National Laboratory

Attaining Energy Security



- *Energy cost affordability and stability*
- *Least external costs*
- *Domestic job creation and maintenance*
- *Balance foreign trade*
- *Increase tax revenues*

- *Maximize available work from renewable wind, solar, geothermal*
- *Stabilize climate*
- *Reduce air and water pollutant discharges*
- *Water resource conservation*

- *Resource security (availability and accessibility)*
- *Reduce foreign dependence*
- *Maximize benefit of both fossil fuels and biomass energy crops*
- *Conservation of energy resources*