# Carbon-Free Hydrogen and Renewable Electrification in High-Temperature Processes: Considerations to Decarbonize Industrial Sector

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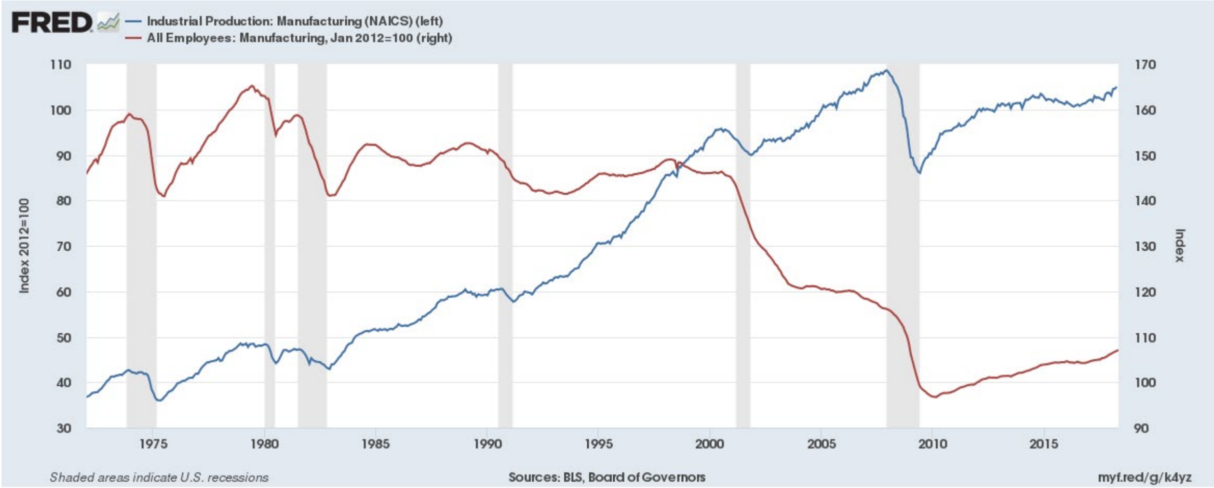
# Manufacturing Sector in Society

- Makes the Products (1/8) that are Consumed (2/3) by Economy
- Employs many People Directly -> Foundation of Standard of Living
- Employs Far More People Indirectly -> Services, IT, Finance, Logistics
- Foundation to National Security and Defense
- Energy Use in US Economy

- **Emits $CO_2$ as Green House Gas**




".. the promotion of domestic manufactures will, in my conception, be among the first consequences which may naturally be expected to flow from an energetic government"

- G. Washington (1789) in letter to Delaware Manufacturers Society

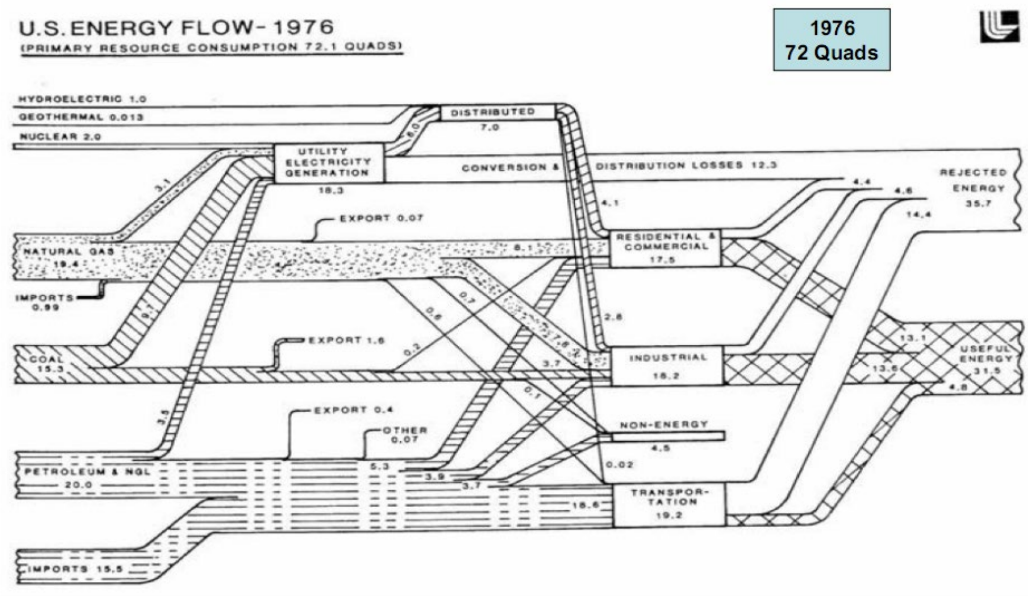
# 3 Decade Shift?

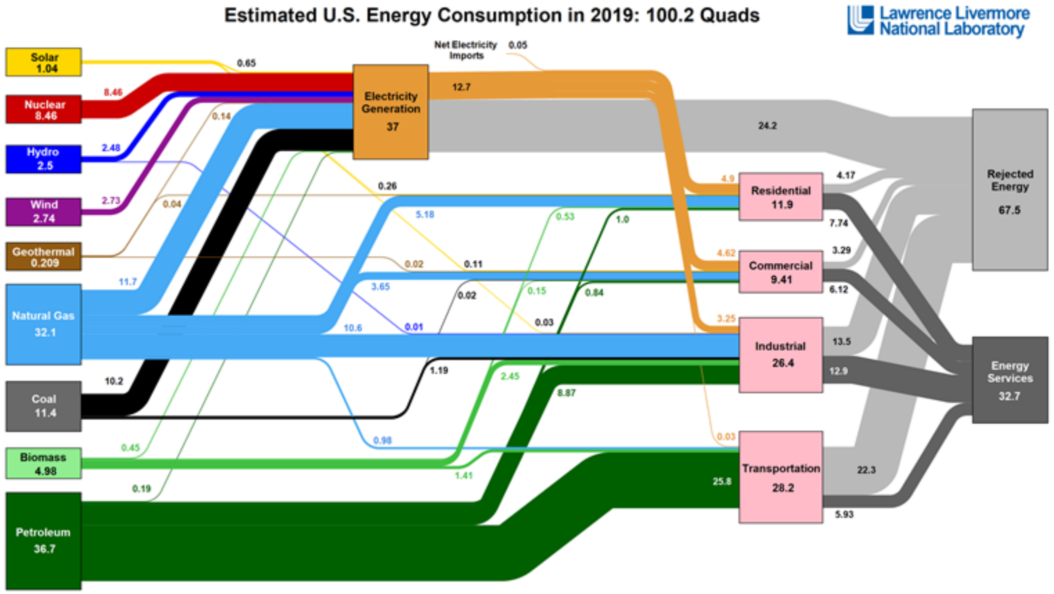
- **1976** 7.6Q Gas (42%)
  3.7Q Coal (21%)
  3.9Q(+3.7Q) Petroleum (22%)
  2.8Q Electricity (15%)
  18 Quad

Nominal Manf. Output: $580B

- **2019** 10.6Q Gas (40%)
  1.2Q Coal (5%)
  8.9Q Petroleum (33%)
  3.3Q Electricity (12%)
  2.6Q Biomass (10%)
  26.6 Quads

Nominal Manf. Output: $ 2,335B




Energy Shown related to US Manufacturing Production, not Consumption

# Decarbonize Manufacturing: a Wicked Problem

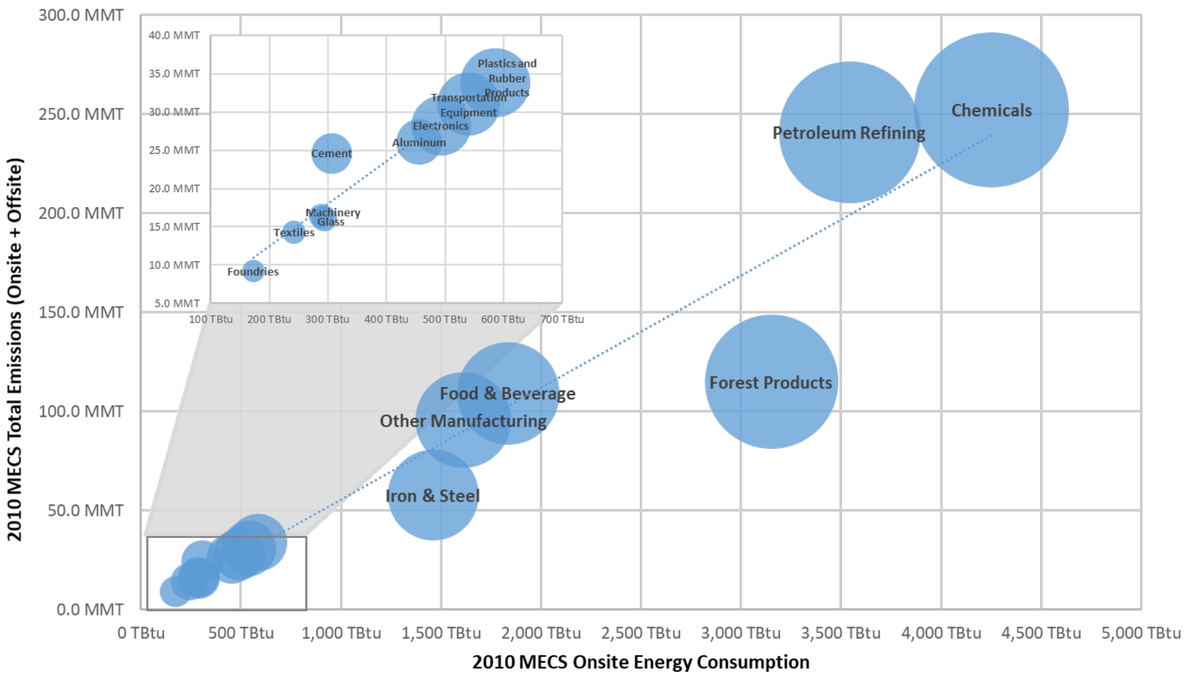
- A Lot of Trade-offs:
  None of them Really Good

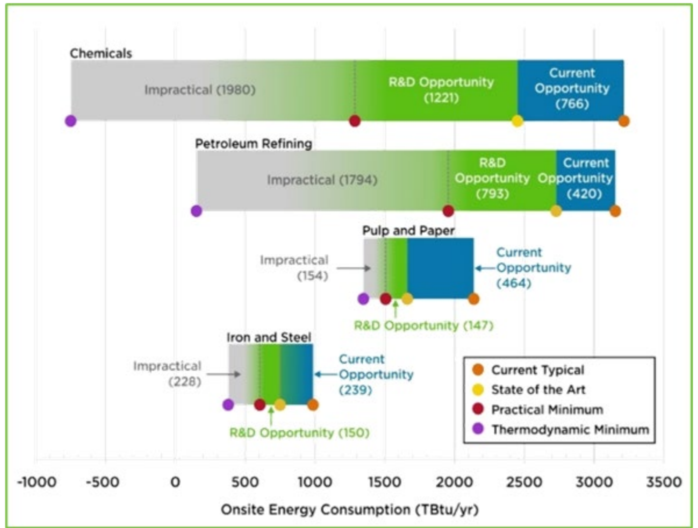
- Severe Cost to Doing Nothing:
  GHG Induced Climate Change

- Diversity of Root Challenges:
  No Apparent "Silver Bullet" Solution

- Fixed (but Growing) Financial Resources to Discover Solution

- Natural Tendency (and maybe Illusion) to:
  - Go "All in" on Most Promising Options
  - Establish a Single 'Cost Target' for Development

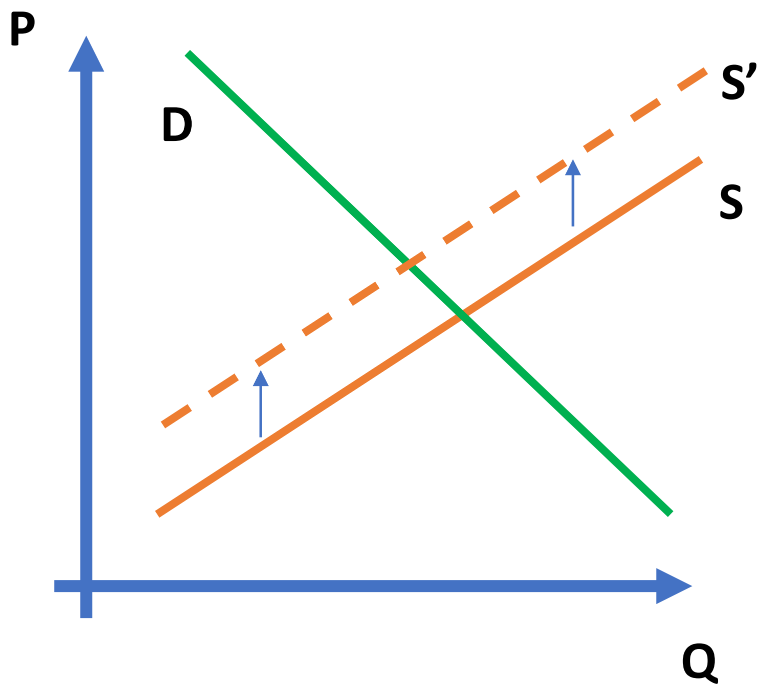


# Cost and Trade-off Economics Matter

- Commodity Prices:

| | |
|---|---|
| Pig Iron (Fe): | \$400-\$450/Tonne |
| Portland Cement (CaO): | \$50-\$75/Tonne |
| Ethylene ($C_2H_4$) | \$1000-\$1100/Tonne |
| Syngas ($CO+3H_2$): | \$500-\$550/Tonne |
| Separated Hydrogen: | \$1500 - \$2000 /Tonne |




- The Price is not a Fixed Target
  It is a sliding Value satisfying Quantity Demanded

- Increasing the Supplier Price Invariably Reduces Demand (and someone is potentially out of work)

- New Technical Solution Needs to "Cost Less" Than Existing Market
  - ideally subsidy free target, for establishing ultimate technical cost targets
  - even for least price-sensitive early demand segments, price increase drops margins

# Transformation Cost Parity Points

- Cost Cross-Over Parity:

  New / Increased Product Demand is Best Satisfied using the New Technology

- Transformation Cost Parity:

  Existing Product Demand is Best Satisfied by New Technology with All-in Cost less than Marginal Cost of Incumbent Tech

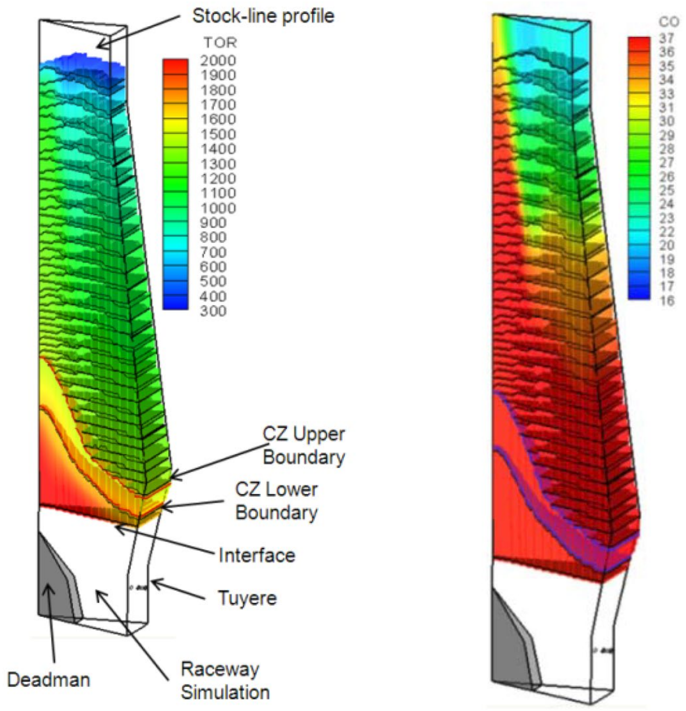
- Tear-Down Cost Parity:

  The Land is More Valuable for a New Use than Leaving Infrastructure Standing and Un-used

New Technology Needs to Pay Both Fixed (infrastructure) and Marginal (Operating) Costs

Incumbent Technology Need only Pay for Marginal (operating) costs, plus some Maintenance

# Key High Temperature Reactions




(a) Burden temperature (K) (b) Gas CO (v. %)

HPC Modelling of Blast Furnace
(Chenn, et.al. 2012)

- Categorization of Reactions Impacting Technology Strategy
  - Give off Heat or Absorb Heat
  - Oxidative or Reductive
  - $CO_2$ Evolution in Process
  - $H_2$ Evolution in Process
  - Maximum Exterior Temperature (Radiative Losses)
  - Energy in Gas Mixture Separation Processes

- Major Reactions to Consider:
  - Iron in Steelmaking: $Fe_2O_3 + \frac{3}{2}C \rightarrow 2Fel + \frac{3}{2}CO_2$

    Blast Zone: 1600°C-1800°C
  - Cement Production: $CaMg(CO_3)_2 \rightarrow MgO + CO_2 + CaCO_3 \rightarrow CaO(with\ SiO_2) + MgO + 2CO_2$

    Kiln Sinter Temperature: 1400°C-1450°C
  - Ethylene Cracking: $C_2H_6 \rightarrow C_2H_4 + H_2$

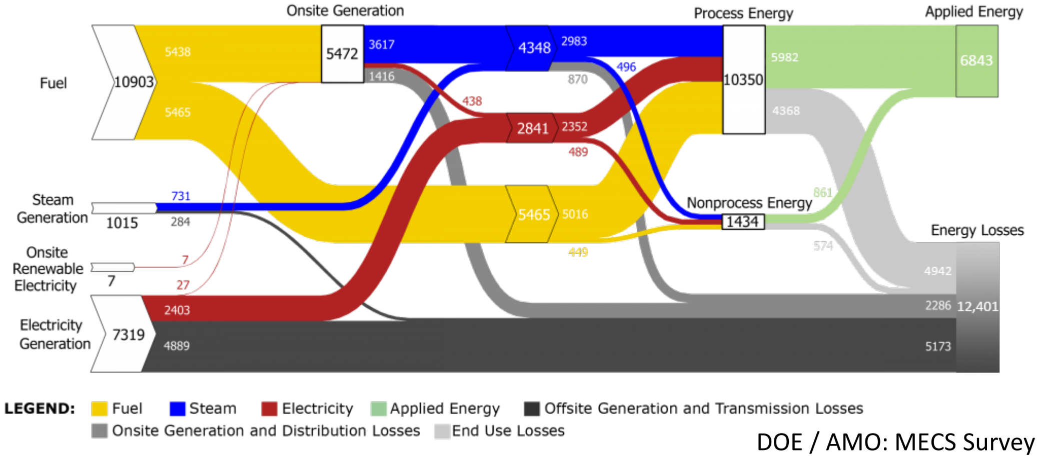
    Cracker Temperature: 800°C – 850°C
  - Methane Steam Reforming (to syngas): $CH_4 + H_20 \rightarrow CO + 3H_2$

    SMR Reaction Temperature: 900°C – 1000°C

# Pathways to Clean Sensible Heat (Electrified)

- Natural Gas to Heat (current bridge fuel approach)
- Natural Gas to Electricity to Heat (makes no sense)
- Renewable Electricity to Process Heat (only if cheap)
    - Intensified Heat: Put Heat only where/when needed

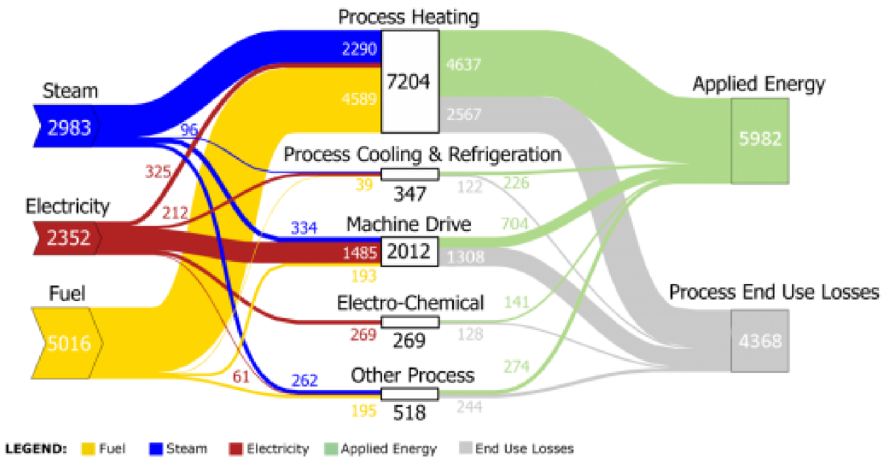
U.S. Manufacturing Sector (TBtu), 2010




DOE / AMO: MECS Survey

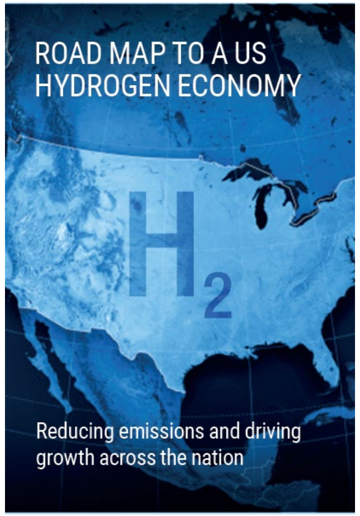
- Cost Parity:
    - Firm Renewable Electricity Is Less than Marginal Cost of Discovering Next Bit of Gas turned into Electricity (discounted for efficiency)
    - Drill Rig Count Drops when Gas less than $3.50 - $4.00/MBTU @ ~40% thermal to electrical conversion efficiency ~$15-20/MWh average 24/7/365 (storage + renewable total)
    - Key Challenges:
        * Storage plus Renewables Needs to be Dirt Cheap
        (about ~20% of where costs are in 2021)
        * Would Double Electricity Demand (and Infrastructure)
        * Cross-Over Point in Line-of-Sight in 2030 to 2035 if Present Innovation Driven Price trends Continue

Process Energy (TBtu), 2010



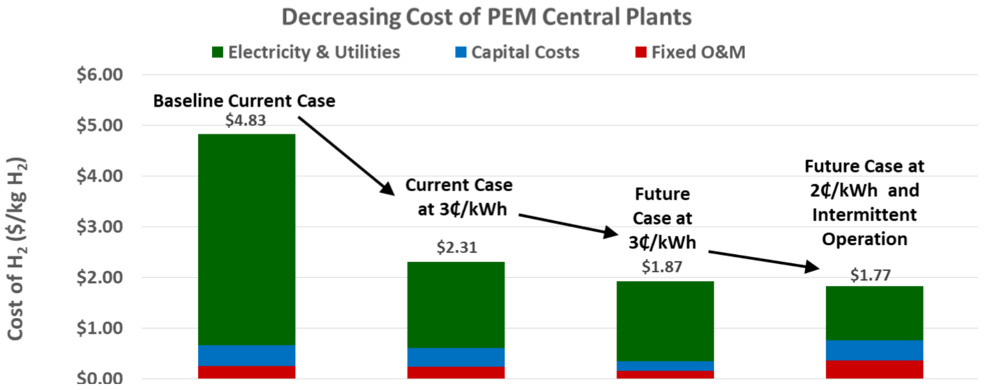
# Pathways to Clean Chemical Energy (Hydrogen)

- Plenty of Processes shown "Technically Possible" if we only had renewable Hydrogen less than SMR
- $1000 / Tonne ($1/kg) cost target 'fully deployed" would be aggressive, but beyond incremental improvement opportunity window for SMR + incremental improvement
- **Need: $1/kg by 2030 "Hydrogen Shot" focused on Carbon-Free Hydrogen to Decarbonize the Manufacturing Sector**
- Analogous to Sunshot, which at the time the solar community thought Sunshot was 'unreasonable' and 'naïve', but critics didn't have any physics reason why it would not work.
- If Exceed $1/kg Target, Impact and Adoption will be Greater




$1/kg Target for Industrial Uses Stated

Not a Lot of Specifics on How They Plan On Getting There




Feb 2020 DOE Hydrogen Program

# Discussion Points

- Trying to Find a Silver Bullet Solution is a Fools Mission: Competitive Portfolio Approach
- Have a Market Informed Set of Techno-Economic Targets

  US Chemicals Industry Spends ~$200B in Capital Investment per Year
- Establish a Technology Competition Between

  (a) Clean/Firm Renewables and (b) Clean Hydrogen
- For Persistently Hardest to Decarbonize GHG in Industry: Industrial Carbon Capture (plus, Utilization and Storage) with a Cost Structure Enabling Global Competitiveness
- Don’t be Afraid To Be “Unreasonable” in Techno-Economic Targets

# Thank You