



20th Electroheat Symposium

“The Key to Heat Utilization – Heat Pumps and Electroheating: Innovation Toward Carbon Neutrality by 2050”



Perry Stephens, EPRI
Sr. Principal Technical Leader, Electrification &
End Use TSC Lead, Low Carbon Resources Initiative

October 20 – November 20, 2025
Japan Electro Heat Center – International Special Lecture

International Special Lecture



Perry D. Stephens, CEM

Electric Power Research Institute

- **Sr. Principle Technical Leader:** assists utilities to evaluate, develop and implement electric end-use technologies for residential, commercial, non-road mobility and industrial customer segments.
- **Co-lead, End-Use Technical Sub-Committee of the Low Carbon Resources Initiative (LCRI):** a collaborative effort with the GTI Energy and more than 50 sponsor companies and organizations aimed at advancing low-carbon fuel pathways on an economy-wide basis toward achievement of deep decarbonization goals.
- Previously worked for Duke Energy and The Timken Company and is considered an expert in manufacturing, thermal processing, energy efficiency, energy business strategies and engineering project management.
- Mr. Stephens is a Certified Energy Manager and holds a BSME from Rose-Hulman Institute of Technology in Terre Haute, IN and an MBA from Gardner-Webb University in Boiling Springs, NC.

The Electrification Pathway

A Key Pillar in US Industrial Decarbonization

This lecture will explore the role of heat pumps and electro-heating technologies in achieving carbon neutrality by 2050. Key topics include innovations in heat pump efficiency, advancements in electro-heating, and strategies for transitioning to low- and zero-carbon energy technologies. The symposium aims to provide insights into innovative heat utilization methods supporting global carbon reduction targets, emphasizing EPRI's research initiatives and collaborative efforts in electrification and low-carbon resources. Attendees will learn about the latest advancements in these technologies and practical solutions for achieving carbon neutrality, highlighting the importance of international collaboration and technology innovation.



EPRI and LCRI

EPRI

Leading Global Collaborative Energy R&D

EPRI is advancing energy technologies and informing decision-making through ~\$420M in collaborative annual research with more than 450 entities in 45 countries – spanning the production, delivery, and use of energy.

**Independent
Non-Profit
Collaborative**

www.EPRI.com



Low-Carbon Resources Initiative

FOCUS

Multiple options and solutions to establish viable low-carbon pathways

Technologies for hard-to-decarbonize areas of the energy economy

Affordable, reliable, and resilient integrated energy systems for the future

RESEARCH AREAS

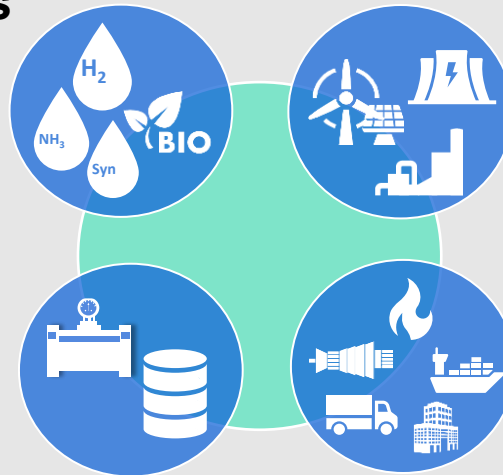
Hydrogen **Ammonia** **Synthetic/
Derivative Fuels** **Biofuels**

**Production
Pathways**

**Integrated
Energy
Systems**

**Storage &
Delivery**

**End Use
Applications**



VALUE

Independent, objective research leveraged by global engagement and collaboration

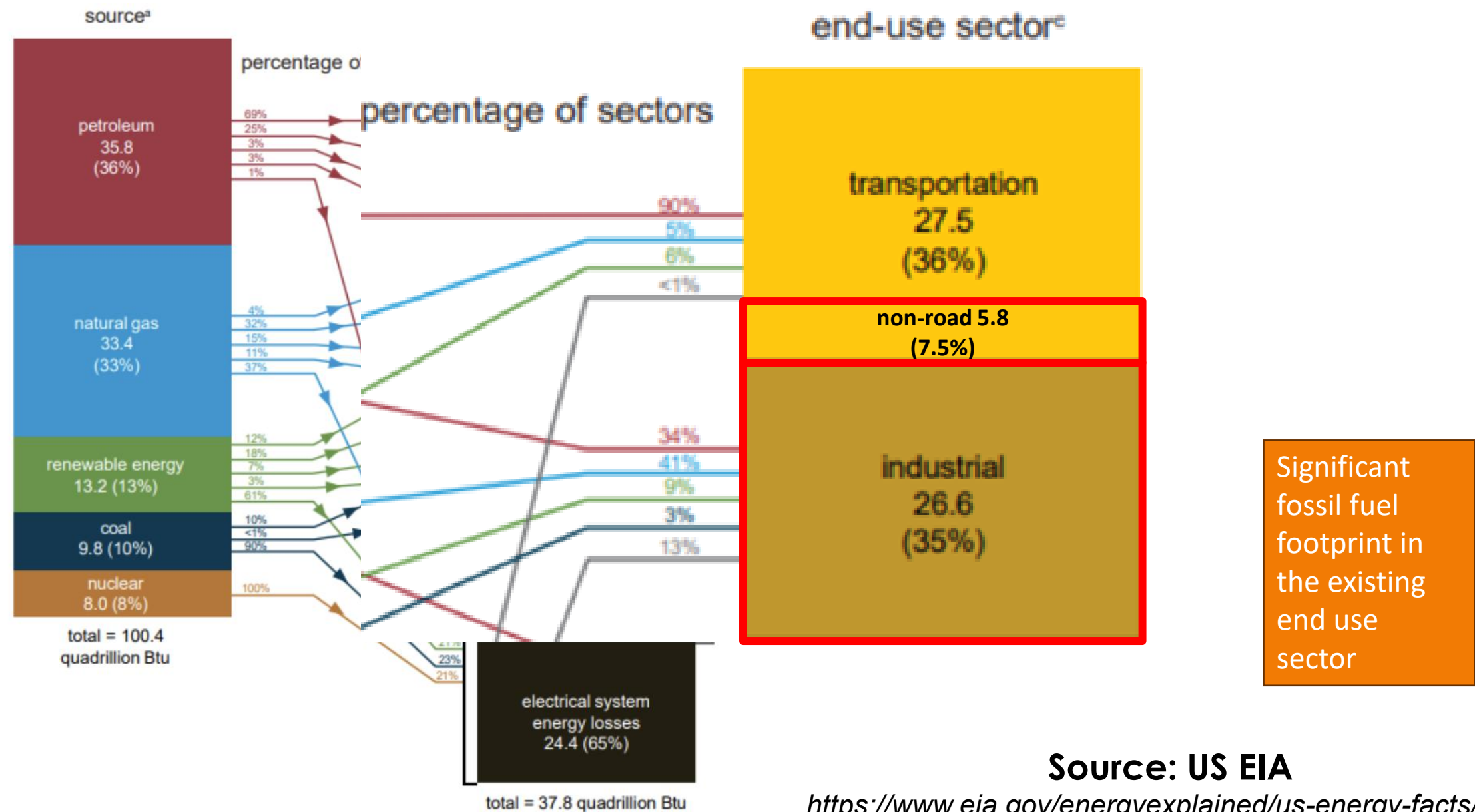
Comprehensive approach to low-carbon value chain and technology analyses

High-impact results from technology evaluations, and safety, environmental, and economic assessments



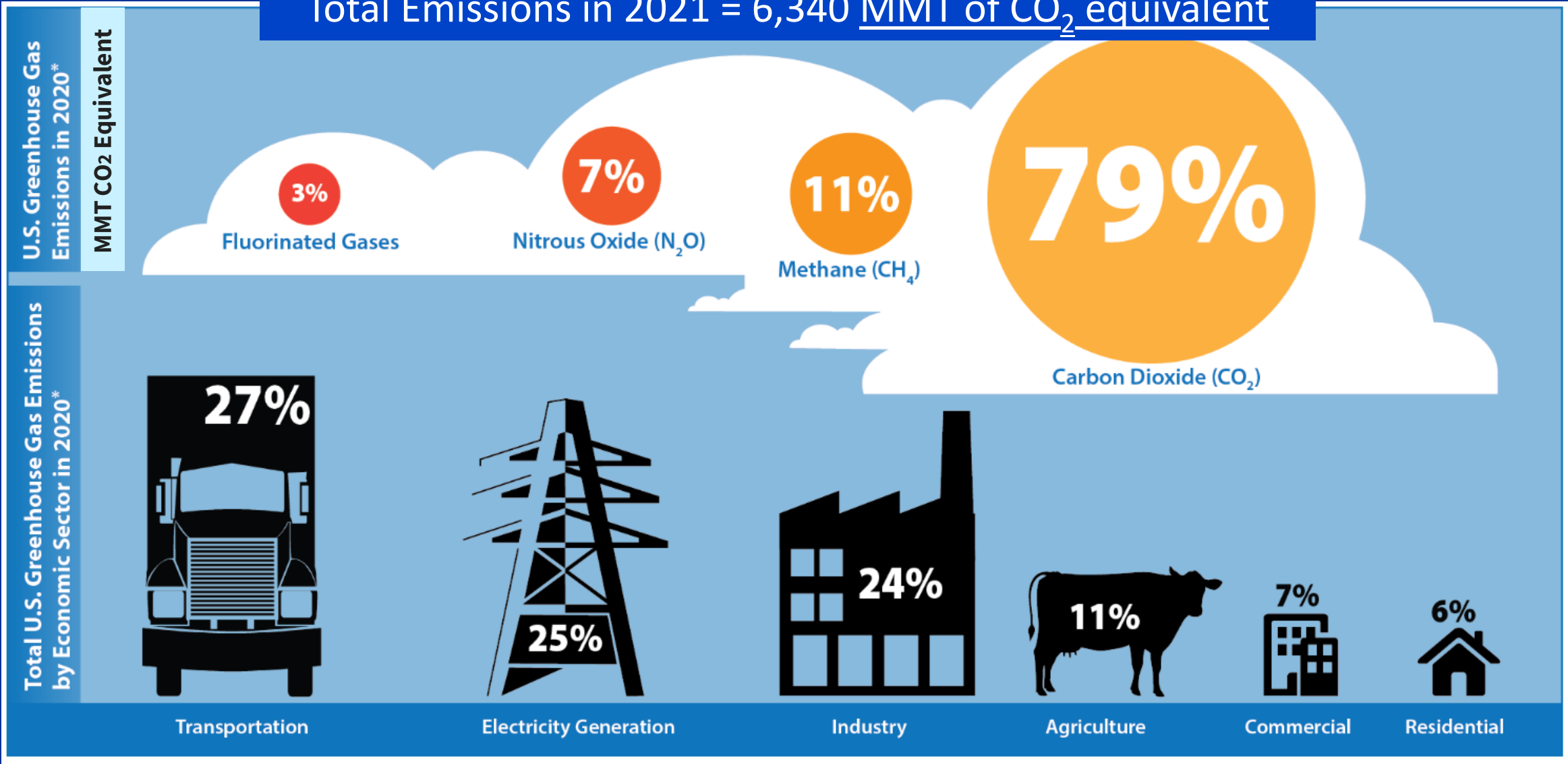
Economy-Wide Fossil Fuel Usage

U.S. energy consumption by source and sector, 2022



National Overall Greenhouse Gas Emissions by Economic Sector

Total Emissions in 2021 = 6,340 MMT of CO₂ equivalent

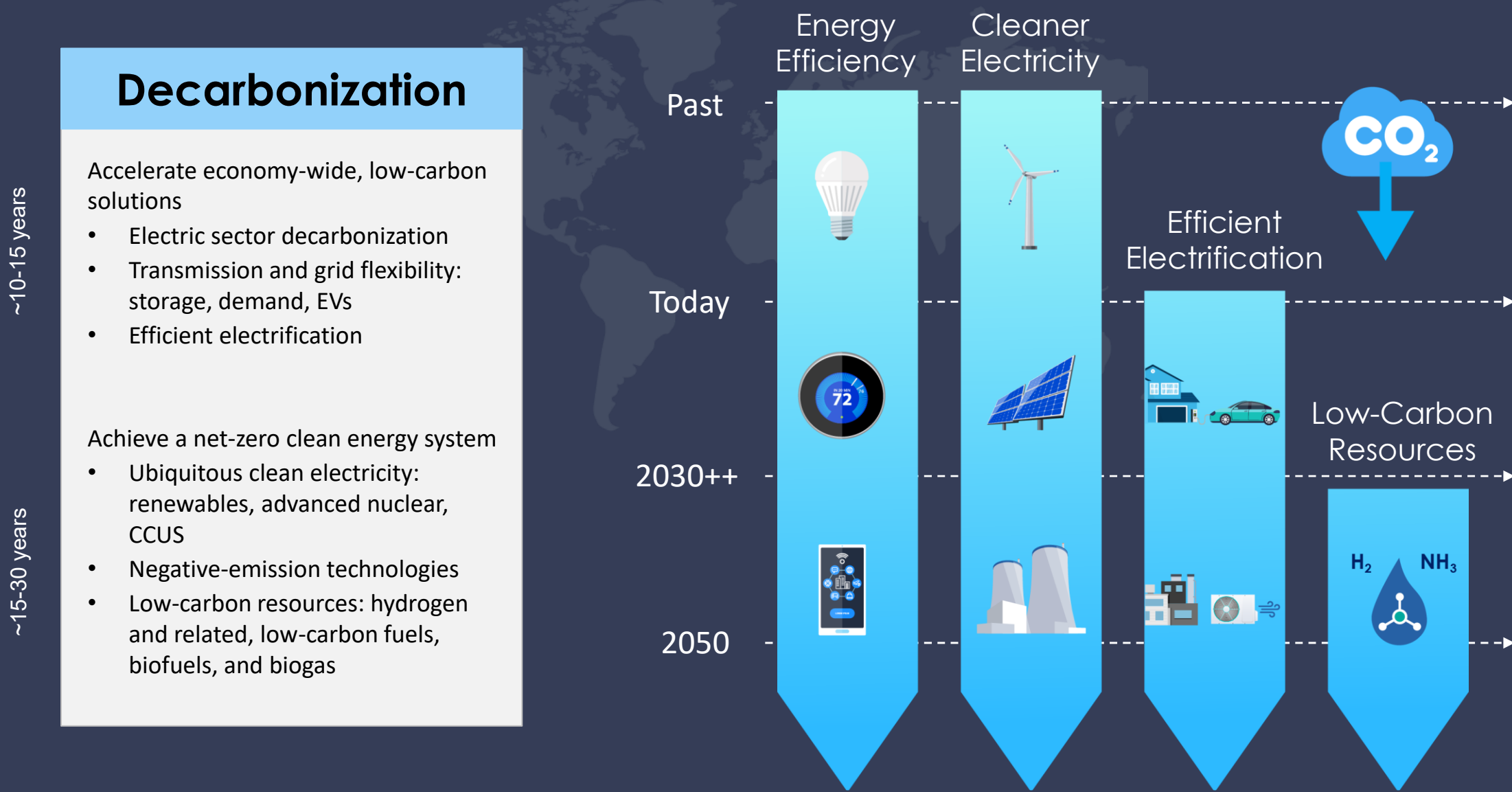


U.S. Environmental Protection Agency (EPA). Greenhouse Gas Inventory Data Explorer, 2023. <https://cfpub.epa.gov/ghgdata/inventoryexplorer/>.

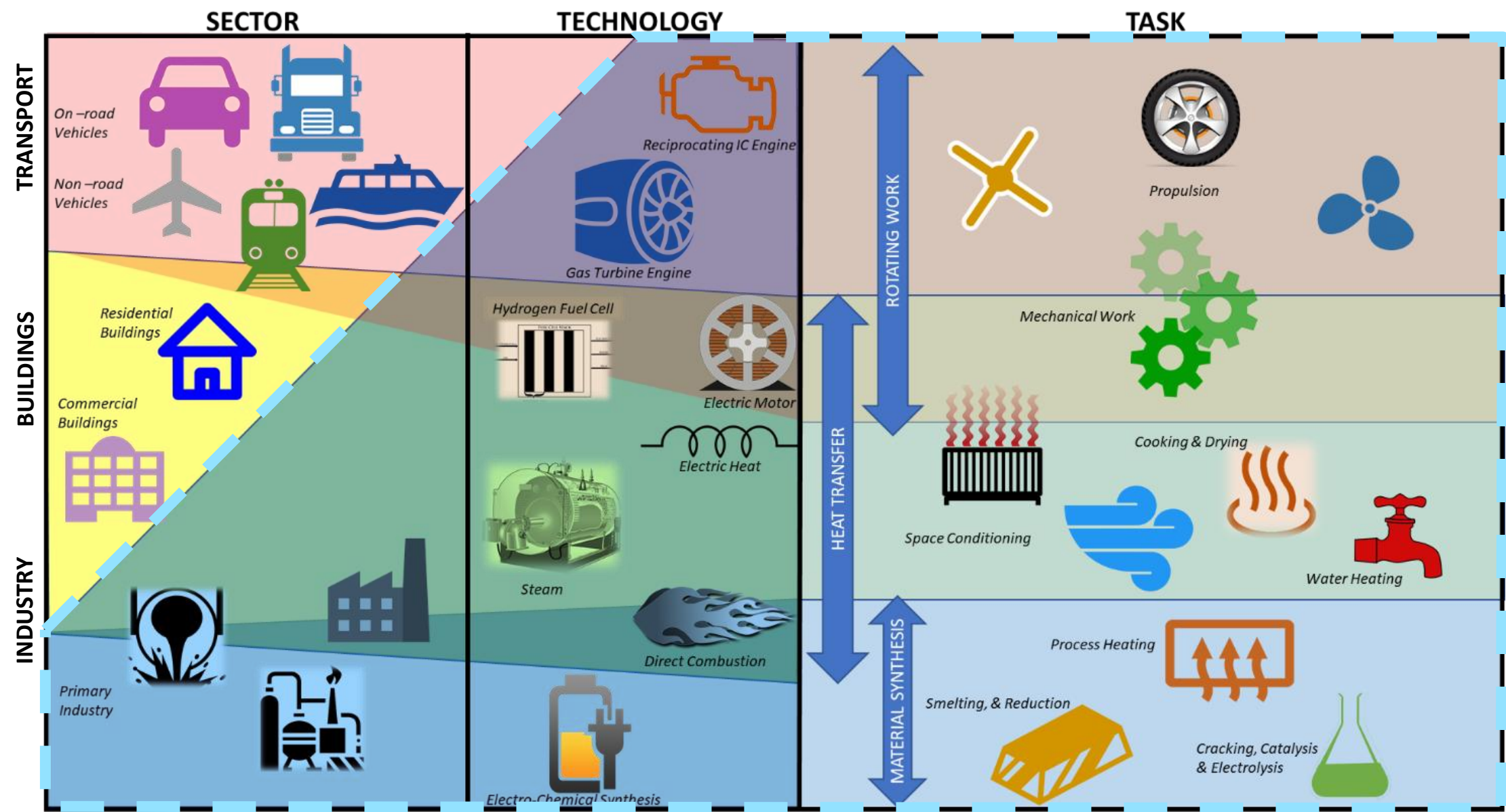


Decarbonization Pathways

Decarbonization Pathways Enabled by Innovation

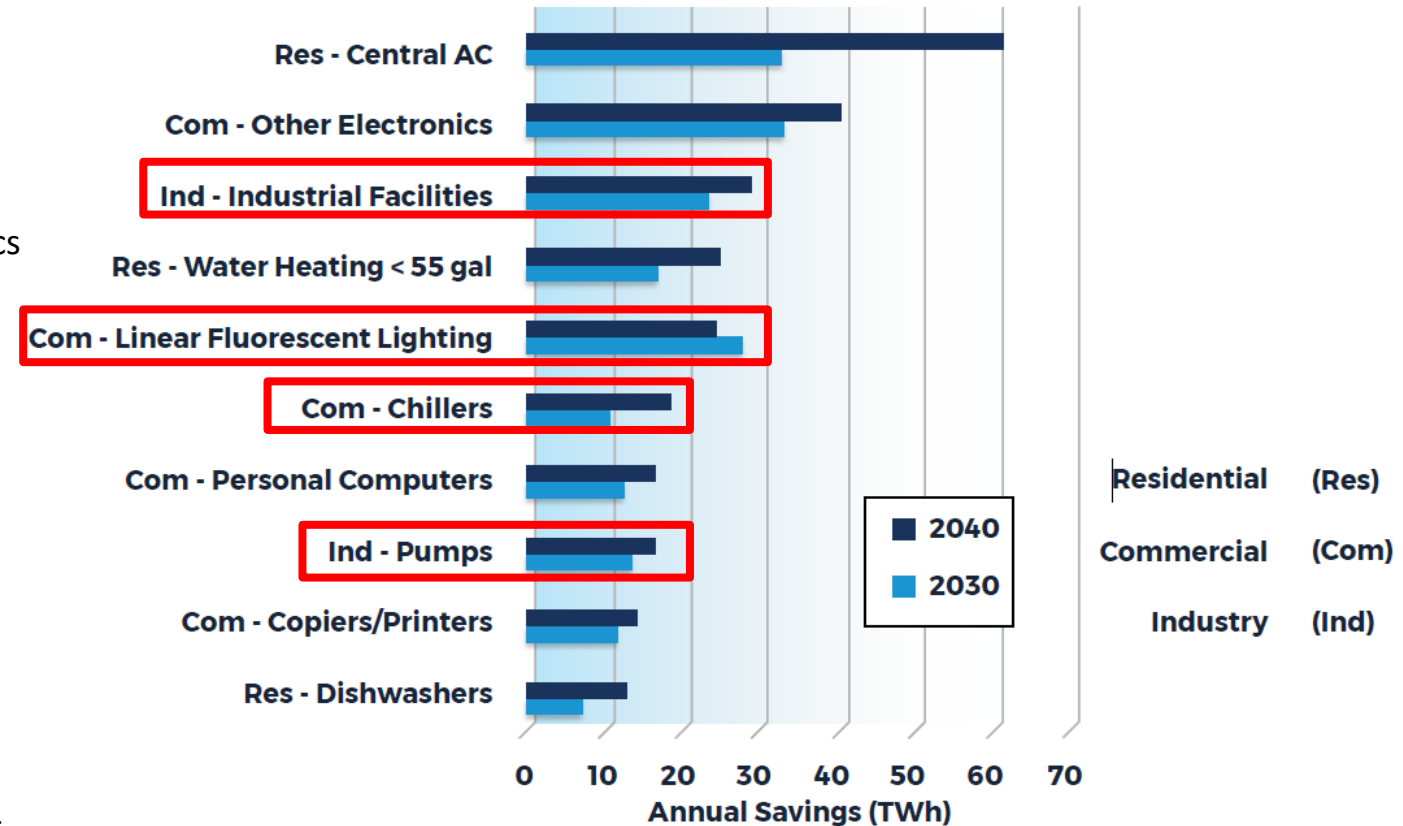


Overview of End-Use Devices



Historical Energy Efficiency – Electricity Consumption

- Most net-zero emission scenarios include greater energy efficiency across the economy
- Four waves of energy efficiency
 - Government standards
 - Utility programs
 - Technology spillovers from advances in consumer electronics
 - Intelligent automation
- Since 2005 electricity consumption has been reduced by >50 TWh
- Energy Recovery
- Waste heat recovery:
 - Create additional heat or reduce heat demand
 - Waste Heat Boiler
 - Regenerative burners
 - Generate electrical or mechanical power
 - Heat recovery steam generators
 - Thermal photovoltaic generator Solid-oxide electrolyzer cell pairing

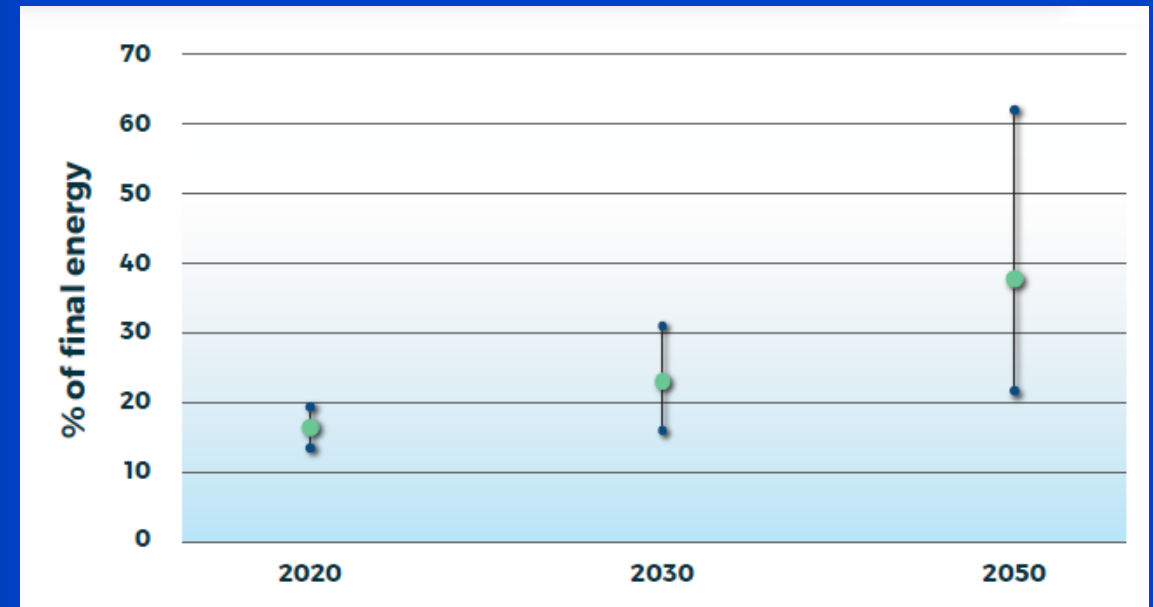


There's a large potential for U.S. Electricity Savings from Energy Efficiency Measures

Direct Electrification

- Early applications
 - Electric passenger vehicles
 - Can lower emissions even with fossil-based electricity
 - 2020: 2% of new passenger cars globally
 - 2030: Projected >50% of new passenger cars globally
 - Heat pumps: a solution to both heat and cool your homes and recover waste heat.
 - Residential sector: Projected >100 million households globally by 2030 instead of natural gas or oil
 - **Industrial sector: Projected ~33% of low temperature heat (<100°C) globally by 2030**

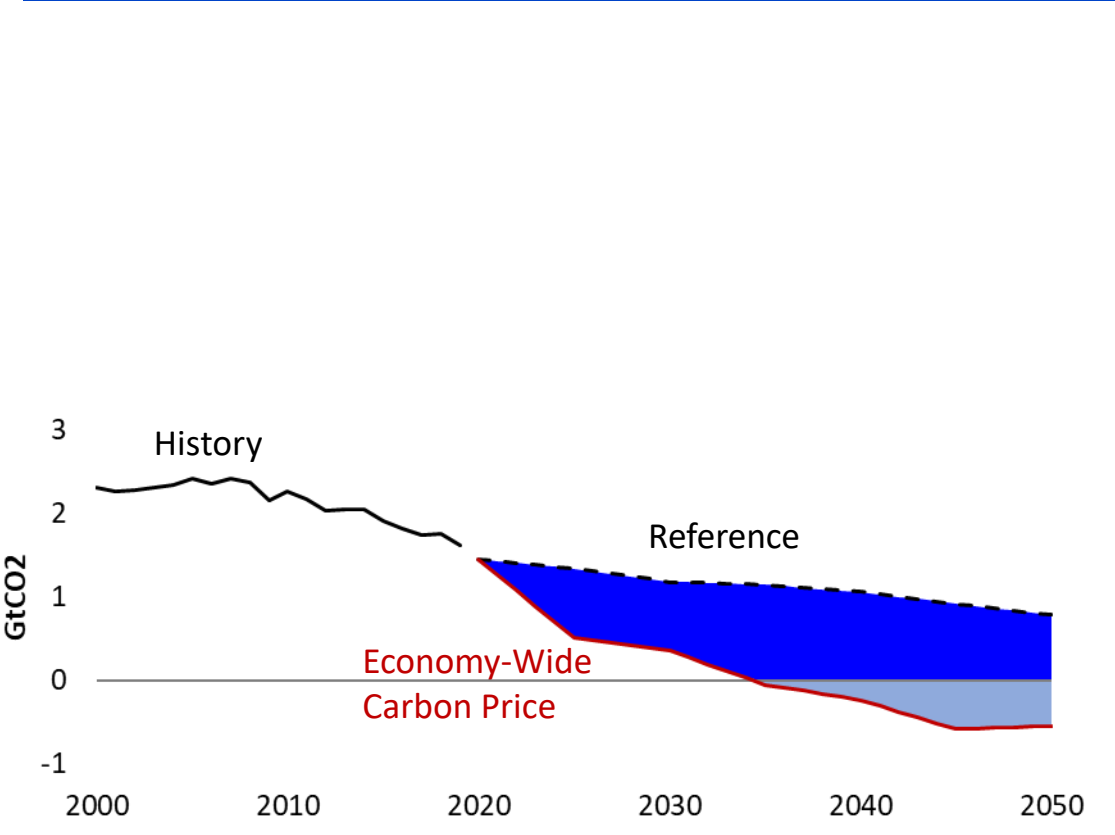
Projected Electricity Share of Global Final Energy Use in a Net-Zero Energy Future (IPCC 2018)



Direct Electrification

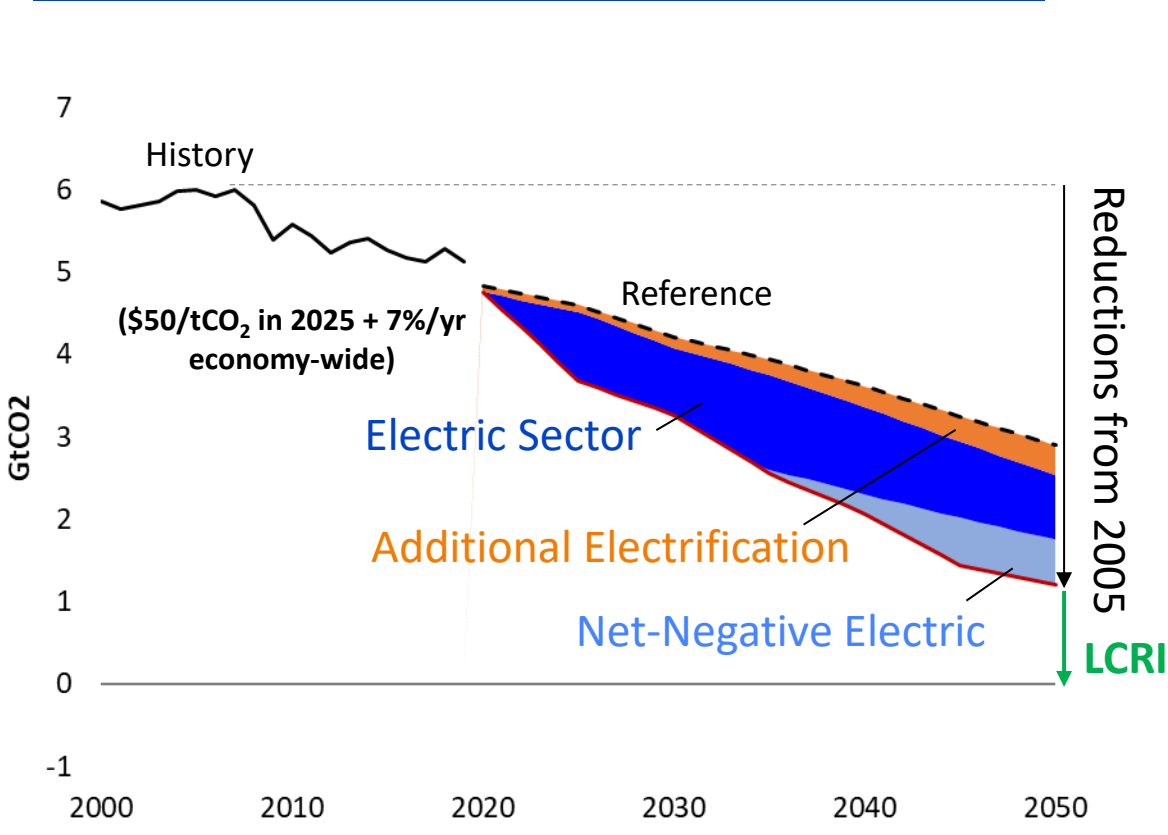
How does electric sector decarbonization contribute?

Electric Sector CO₂ Emissions



With a harmonized economy-wide carbon price, bio-CCS drives electric sector emissions **net-negative**

Economy-Wide CO₂ Emissions



Economy-wide emissions fall to 80% below 2005 with net-negative electric sector emissions

Direct Electrification

Key Actions by 2030 in Electric Sector

-  ■ **Expand the grid** to maintain reliability with high wind and solar and electrification of other sectors
 - Ensure adequate backup capacity and load flexibility
 - Build associated transmission (intra-region essential, inter-regional valuable)
-  ■ **Extend and uprate existing nuclear and hydro**
-  ■ **Manage coal retirements** (community impacts, financial)
-  ■ **Add new natural gas capacity** to replace coal, balance renewables
-  ■ **Develop technologies for clean firm capacity (CCUS, advanced nuclear, clean hydrogen [AECs], long-duration storage)**

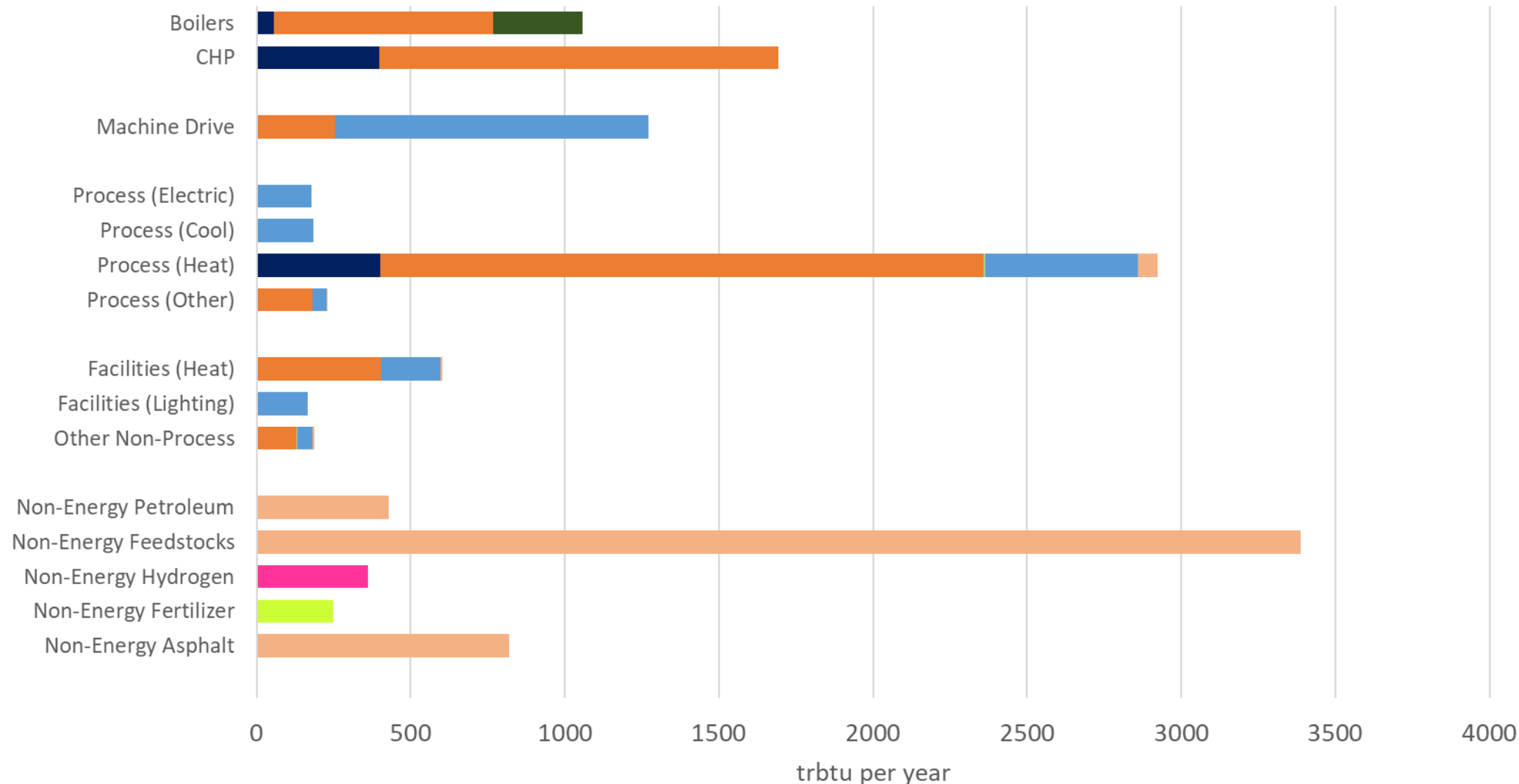
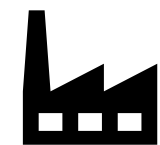
80% by 2030 target *requires* accelerated technology development and deployment



Industrial Electrification

Industry (Manufacturing)

Current U.S. Final Energy Use

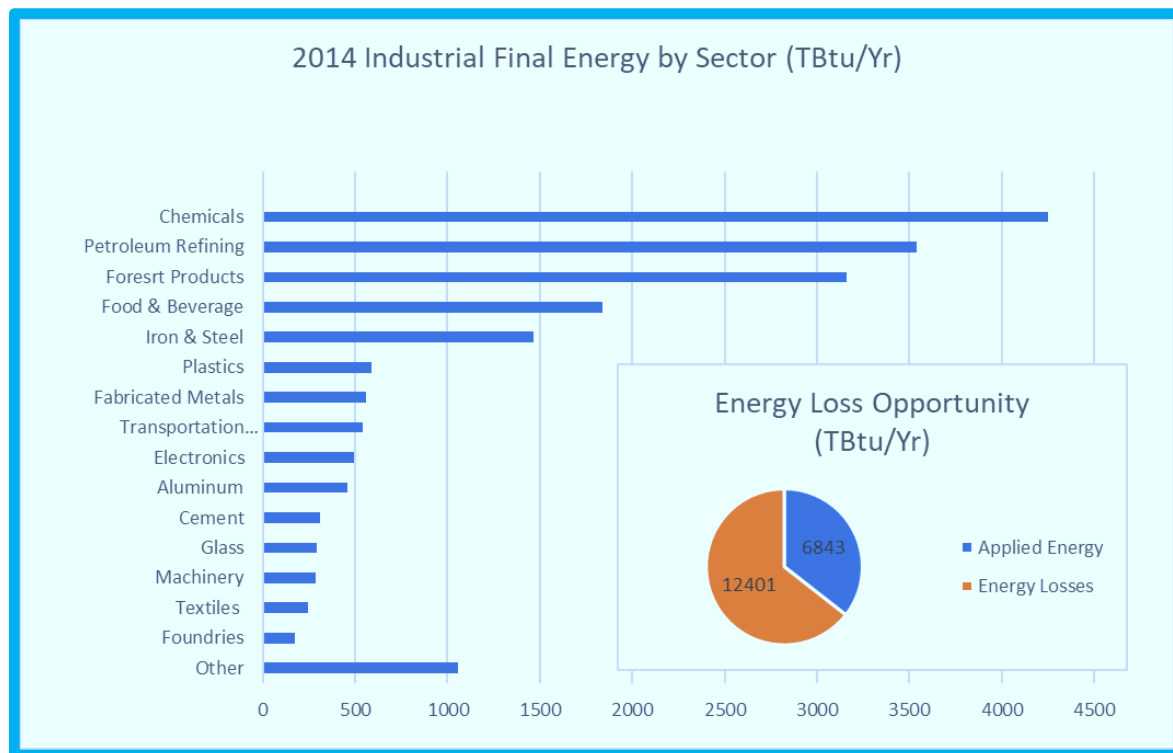


Source: LCRI Report <https://lcri-netzero.epri.com/> or [3002024882](https://www.epri.com/3002024882)

■ Coal/Coke ■ NG ■ Diesel ■ Electricity ■ Hydrogen ■ Biomass ■ Other HC ■ Ammonia

Industrial Sector

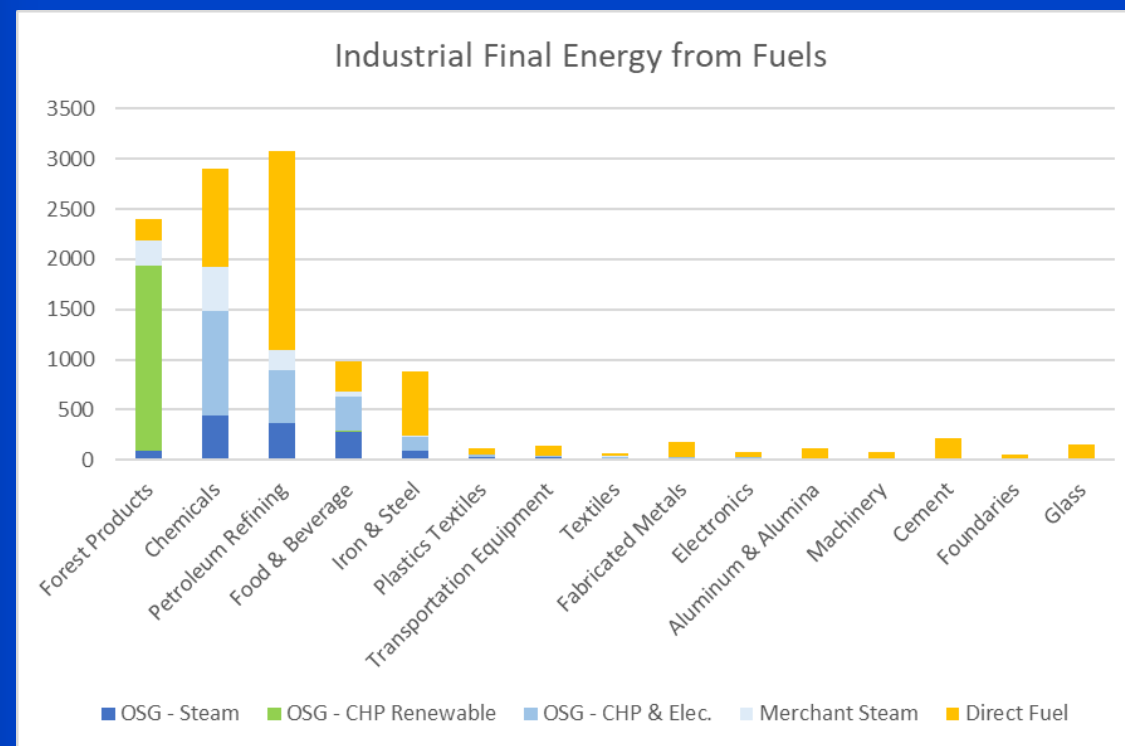
Review of U.S. Energy Consumption



US Industry Final Energy and Losses (TBtu/Yr)

- ~24% of the U.S. economy-wide energy consumption
- > 1/4 of all combustion related CO₂
- ~ 2/3 is wasted due to inefficiencies

Industrial Final Energy from Fuel Combustion (Tbtu/Yr)



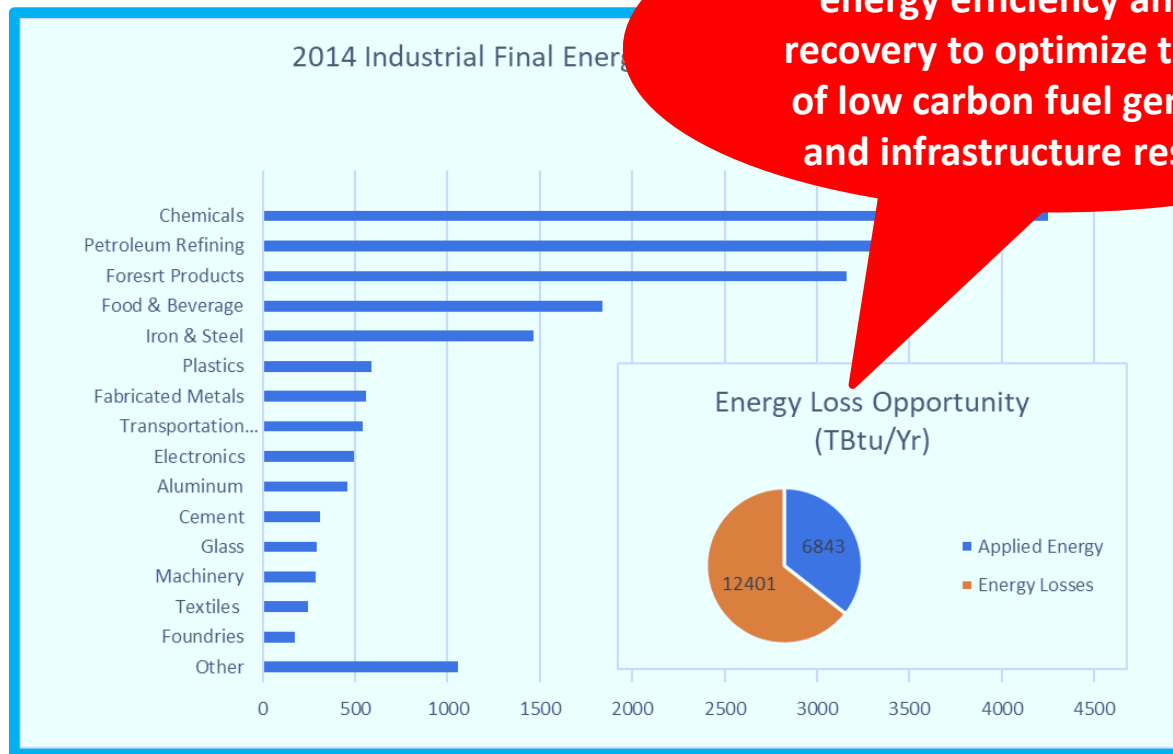
Industrial Energy by the Numbers:

- 79% - final energy from fossil fuel combustion
- 56% - direct process energy inputs
- 44% - feedstock for other chemical production

(Source: McKinsey 2020)

Industrial Sector

Review of U.S. Energy Consumption

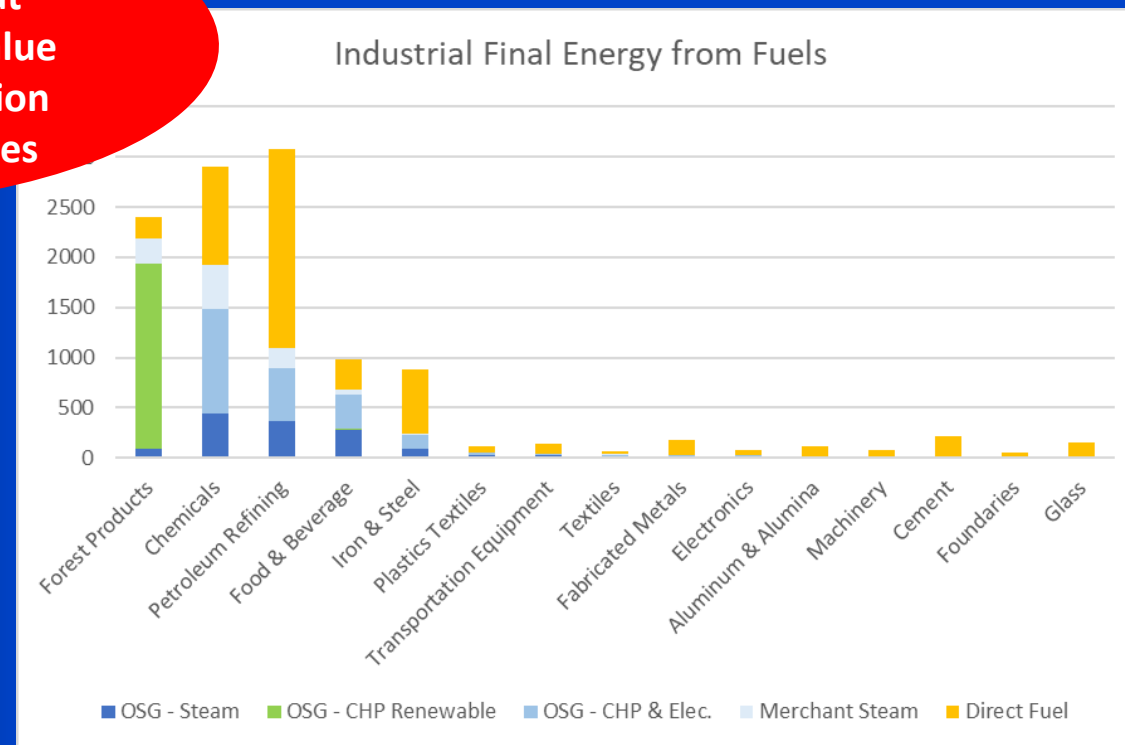


Suggests a need to maximize energy efficiency and heat recovery to optimize the value of low carbon fuel generation and infrastructure resources

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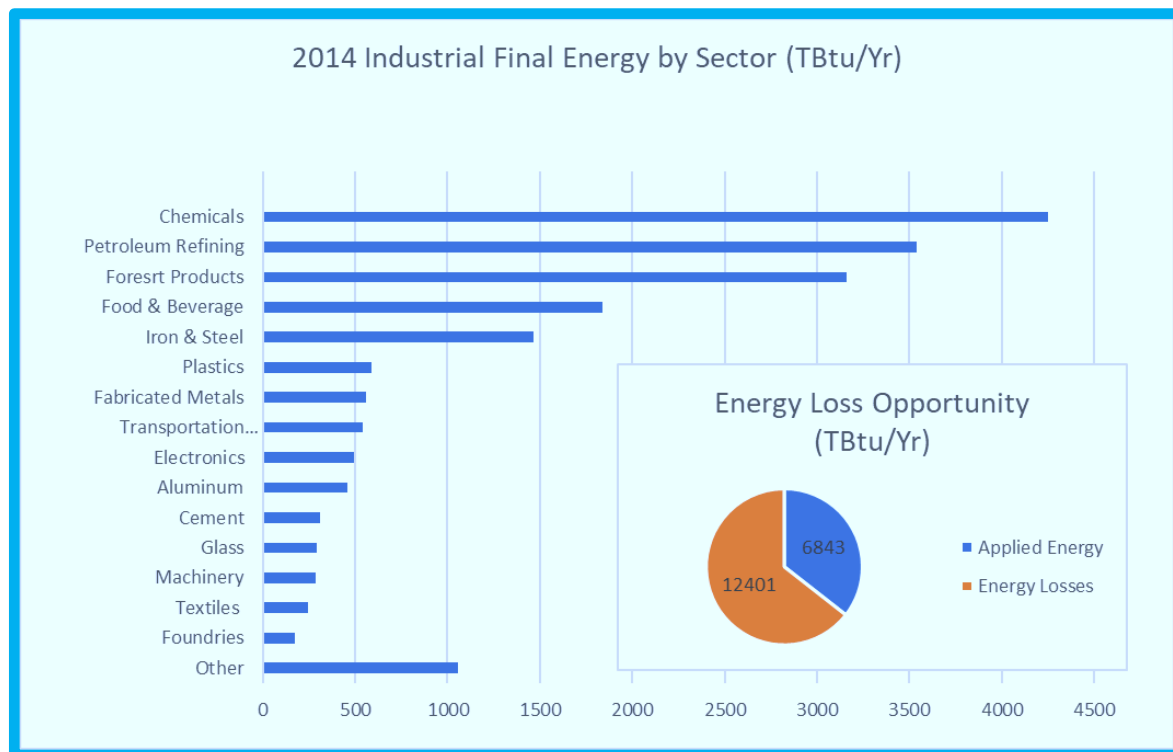
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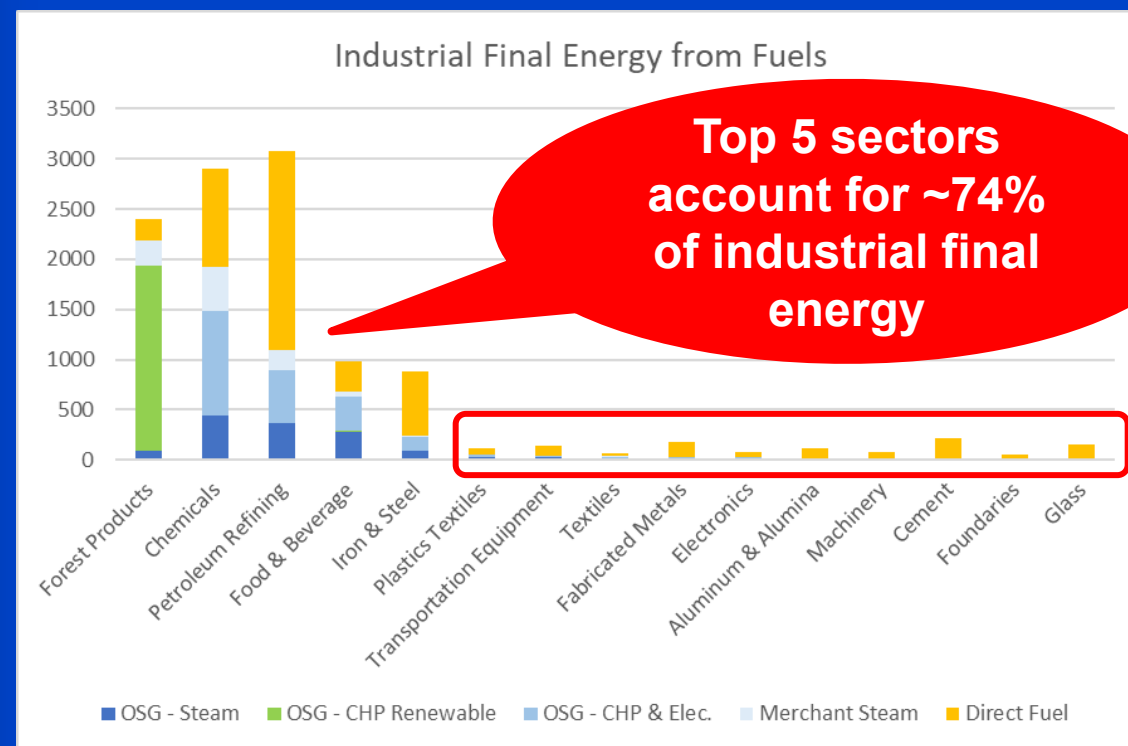
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(Source: McKinsey 2020)

Electrification End-Use Technologies



SECTORS

RESIDENTIAL

COMMERCIAL

INDUSTRIAL

TRANSPORTATION

Space Heating:
Air Source Heat Pumps
Ductless Split Heat Pumps
Cold Climate Heat Pumps

Water Heating:
Heat Pump Water Heaters

Cooking:
Induction Cooktops

....and more

Space Heating:
Rooftop Heat Pumps
VRF Heat Pumps

Water Heating:
Heat Pump Water Heaters

Cooking:
Electric Fryers
Griddles, Combi-Ovens

Others:
Infra Red Comfort Heaters
Pool Dehumidifiers

....and more

Electric Process Heating:
Resistance heating
Infrared Heating
Induction Melting
Radiofrequency drying
Ultraviolet Curing
Electric Arc Furnace

Steam Generation:
Electrode Boilers
Industrial Heat Pumps

Passenger EVs
Light, Medium & Heavy-Duty Vehicles
School Buses
Transit Buses

Forklifts
Electric Terminal Trucks

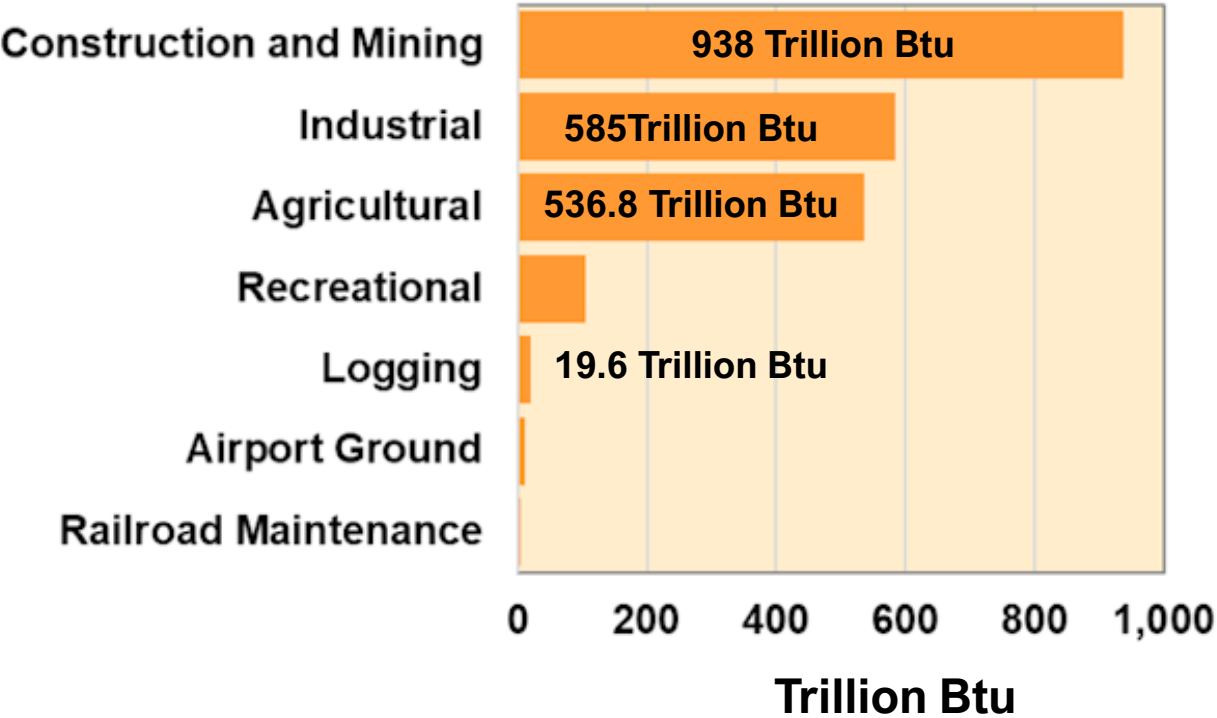
Airport Ground Support Equipment
Electric Golfcarts
....and more

END-
USES

Non-road Transportation Equipment Energy Use Breakdown

Category	Diesel	Gasoline	LPG	CNG	Total (Trillion Btu)
Agricultural Equipment	527.0	8.2	0	1.6	536.8
Airport Ground Equipment	10.4	0.3	0.2	-	10.8
Construction & Mining Equipment	913.7	21.7	2.5	0	938
Industrial Equipment	268.2	51.6	229.9	35.1	584.7
Logging Equipment	18.5	1.1	-	-	19.6
Railroad Maintenance Equipment	3.3	0.2	0	-	3.5
Recreational Equipment	1.8	103.2	0.1	-	105.2
Total	1,742.9	186.3	232.7	36.6	2198.5

Non-road Transportation Energy Use by Sector, 2019



Source: Environmental Protection Agency, MOVES 3.0.1

Industrial, Construction, Mining & Agriculture equipment account for 95% of the total non-road transportation sector energy use (2.08 Quads)

Major Opportunities in Non-Road Transportation



Electric & Autonomous Forklift



Autonomous Guided Vehicles



Grounds Maintenance



a



Terminal Truck



Personnel Cart



ASR



Electric Tuggers



Robotics and Drones



b

a) eTRU and b) Charger Port

Battery Electric Vehicles (BEVs) in the Mining Industry

To replace internal combustion engines BEVs must:

- Have long cycle lives
- Powerful discharge - Follow drive cycles
- Safely operable
- Cost competitive

Many companies have Mining BEVs in development...

- Caterpillar
- Epiroc
- LiuGong
- Liebherr
- Sandvik
- SANY

LiuGong



Sandvik



SANY



Caterpillar



Liebherr



Electric Cultivation/Utility Equipment

- John Deere – (Sustainable Energy Supply for Agricultural Machinery) SESAM prototype
 - 130 kW, standard tractor frame (108 kWh), regenerative braking, 4 hrs run time, 3 hrs charge time
- Monarch - Tractor
 - 70 hp, 10+ hrs operation, Autonomous, \$58K
- Solectrac – Compact electric tractor (CET)
 - Compact, 30 & 40 hp, 3-6 hr runtime, 22 kwh battery
 - 4 hr battery charge on 230 v. 30 amp
- Kubota
 - Concept, compact
- Case – IH (CNH)
 - Autonomous , Concept
- AGCO Fendt – e100 Vario
 - 100 hp, 80% charge in 40 min
- CLAAS
 - Diesel Hybrid, Autonomous
- SAME Deutz-Fahr
- New Holland - Autonomous



Kuboto – Prototype Compact



<https://www.monarchtractor.com/all-electric.html>



Claas – Diesel Hybrid



John Deere SESAM



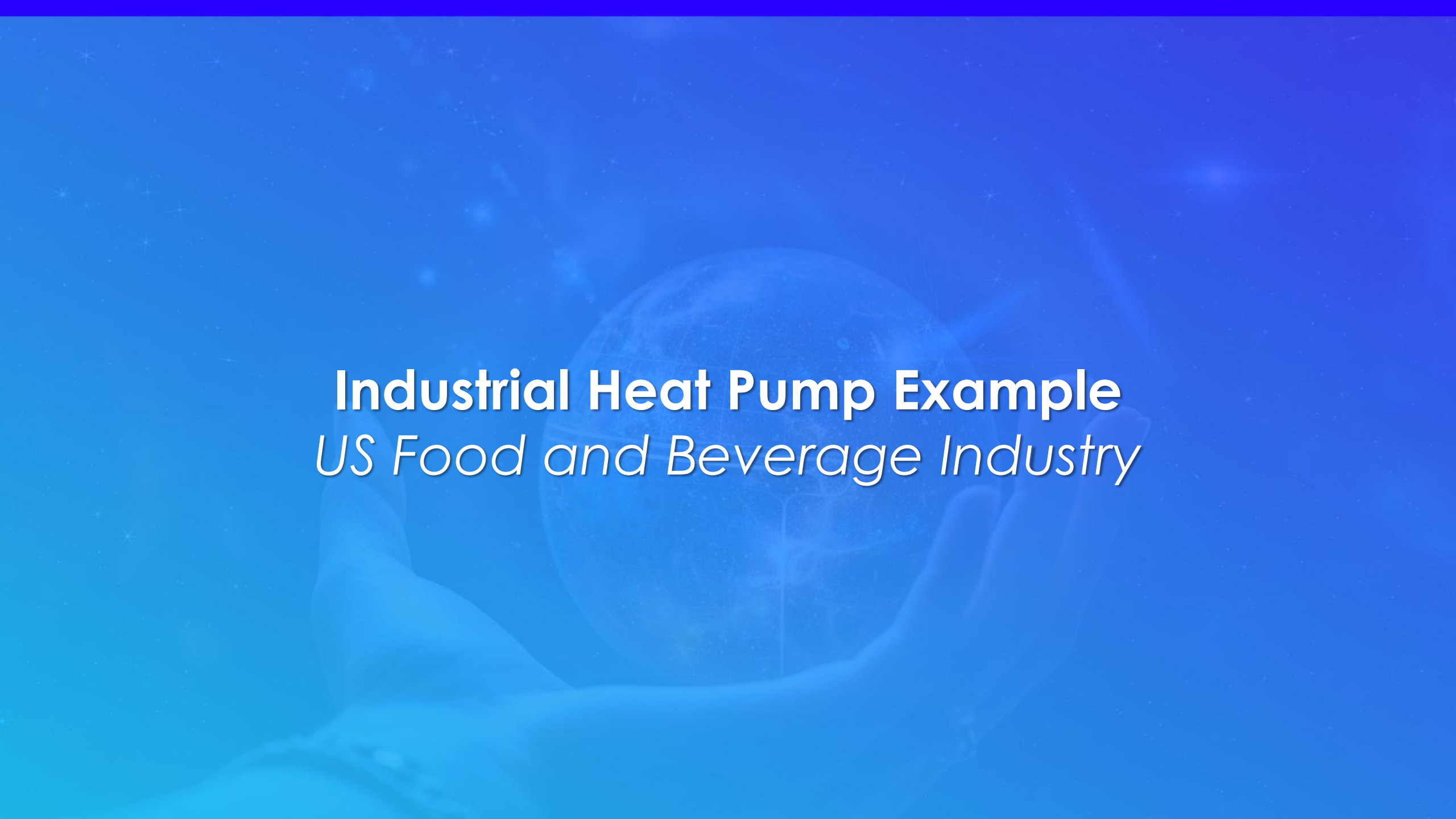
Case –IH Autonomous



<https://www.fendt.com/us/e100-vario>



Solectrac Compact



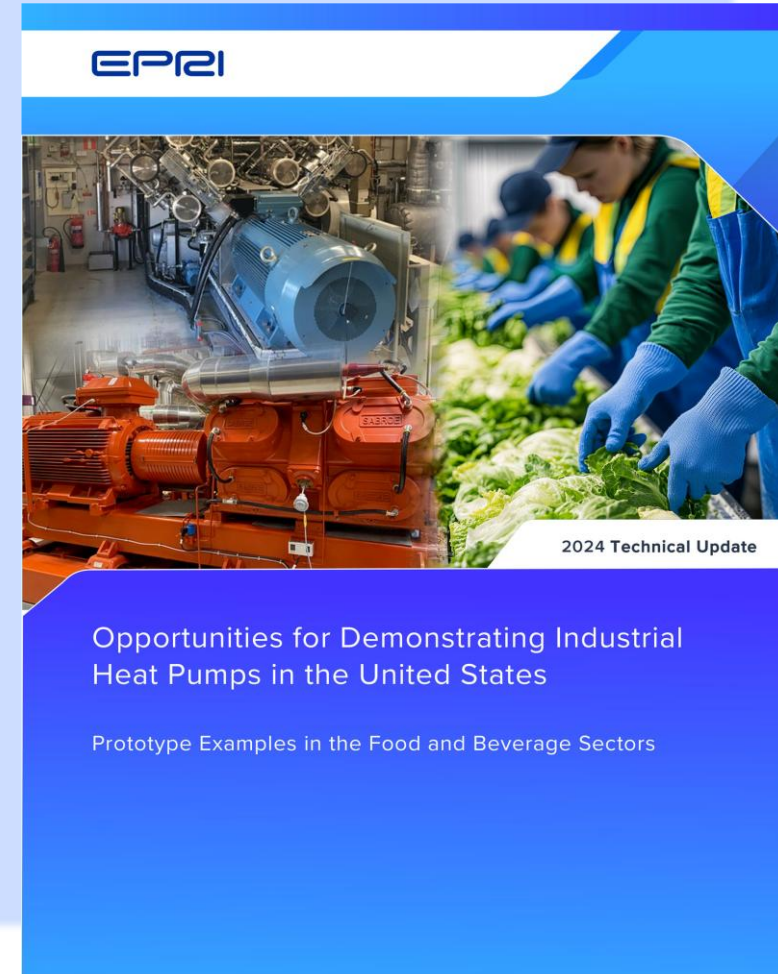
Industrial Heat Pump Example

US Food and Beverage Industry

EPRI Report

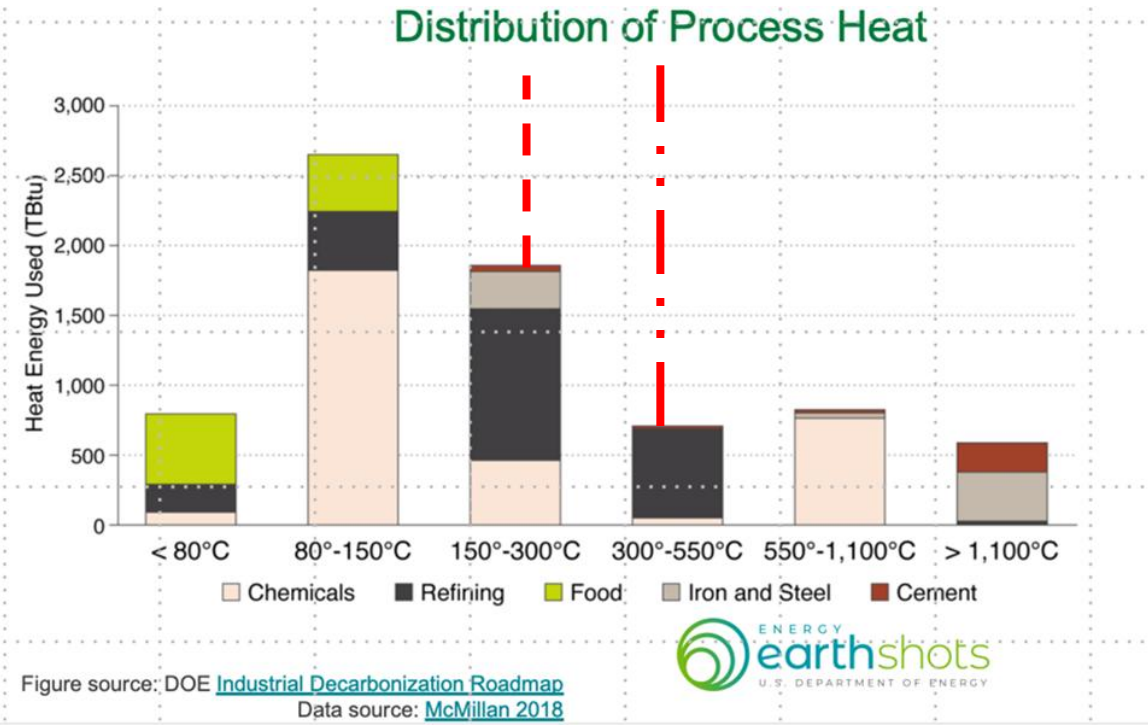
PID #3002031135

- Opportunities for Demonstrating Industrial Heat Pumps in the United States: Prototype Examples in the Food and Beverage Sectors
- Publicly available report



Process Heat Available for Industrial Heat Pumps

Process Heating Share of U.S. Manufacturing Energy Use and Temperature Heating Requirements by Sector (A. Shultz, DOE)



IHP Technology Readiness by Temperature Range (IEA, 2023)

Temperature Range (°F)	Technology Readiness Level (TRL)	Example Processes
< 175	TRL 11: Proof of market stability	Paper: De-inking Food: Concentration Chemicals: Bio-reactions
175 - 212	TRL 10: Commercial and competitive but large-scale deployment not yet achieved	Paper: Bleaching Food: Pasteurization Chemicals: Boiling
212 - 285	TRL 8-9: First-of-a-kind commercial applications in relevant environment	Paper: Drying Food: Evaporation Chemicals: Concentration
285 - 320	TRL 6-7: Pre-commercial demonstration	Paper: Pulp boiling Food: Drying Chemicals: Distillation Various industries: Steam production
320 - 390	TRL 8-9: First-of-a-kind commercial applications for small-scale MVR systems and heat transformers TRL 4-5: Early to large prototype	Various industries: High temperature steam production
> 390	TRL 4: Early prototype	Various industries: High temperature processes

Closed loop HTHP upper limit

Open loop HTHP upper limit

Five Prototypical F&B Processes Evaluated for IHP Opportunity

Subsector(s)	NAICS code	Energy Consumption (TBtu/yr)	# of Establishments	Top 10 states*
Fruit & Vegetable Canning	311421	64	568	CA, WA, NY, PA, TN, FL, OR, MI, NJ, CO
Animal Slaughtering & Processing	311611, 311612, 311613, 311615	170	3,088	NY, NC, PA, AR, IA, NE, CO, MO, MS, TN
Fluid Milk Manufacturing	311511	48	360	CA, NY, PA, WA, OH, MD, WI, FL, TX, VA
Bakeries	311811, 311812	52	8,147	NY, CA, OH, WA, NC, CA, CO, GA, FL, TX,
Breweries	312120	58	3,065	NY, CA, OH, WA, NC, CA, CO, GA, FL, TX
Total		375	14,303	

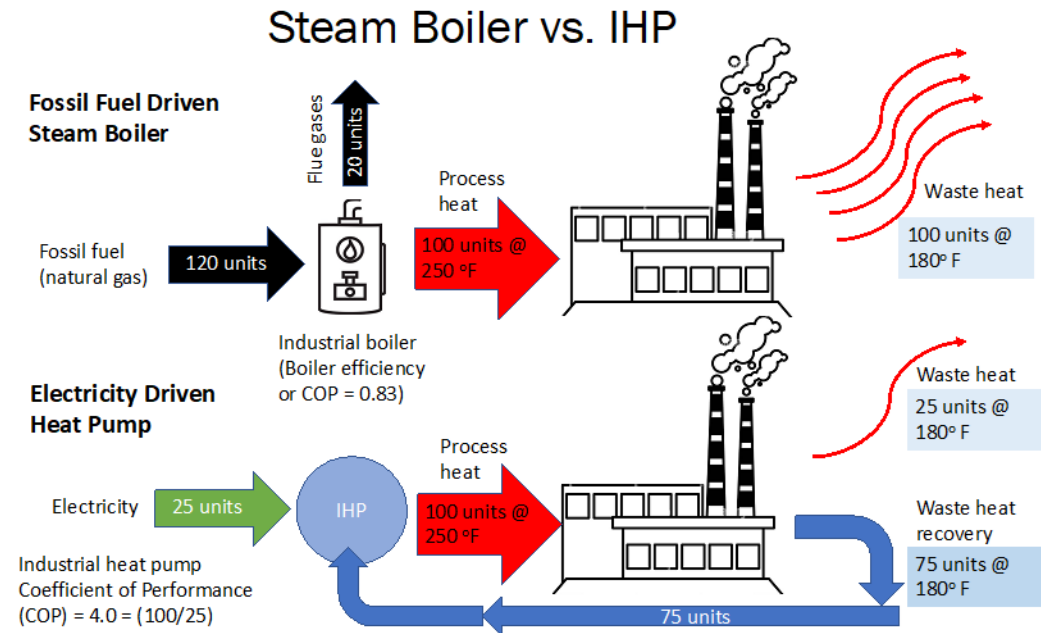
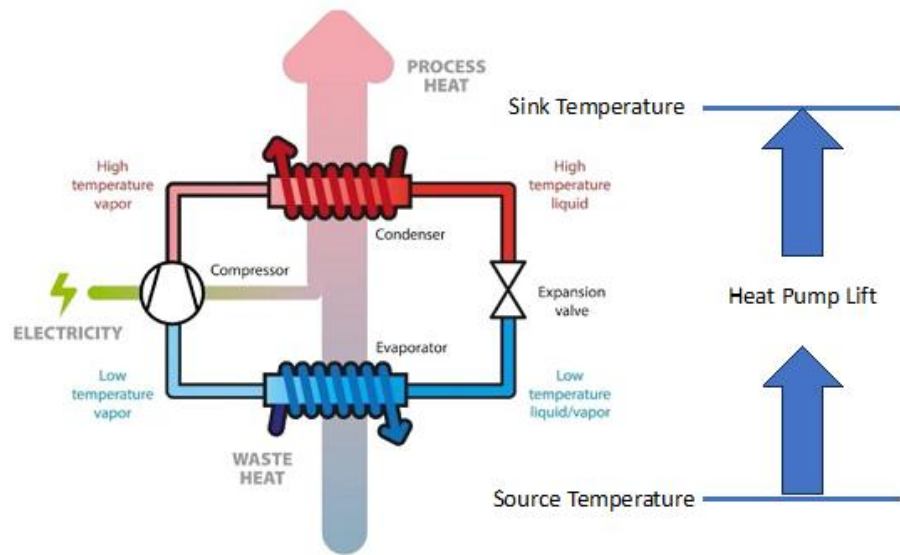
*Based on a combination carbon emission reduction potential and favorable Electric-Fuel Price ratio in state

Efficiency Impact of Vapor Compression Cycle

Understanding COP

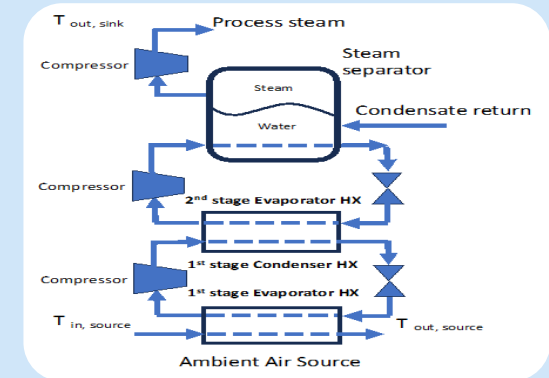
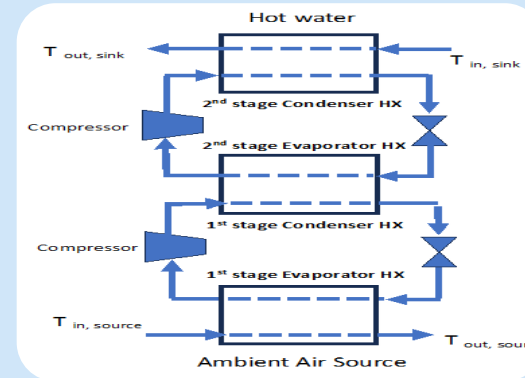
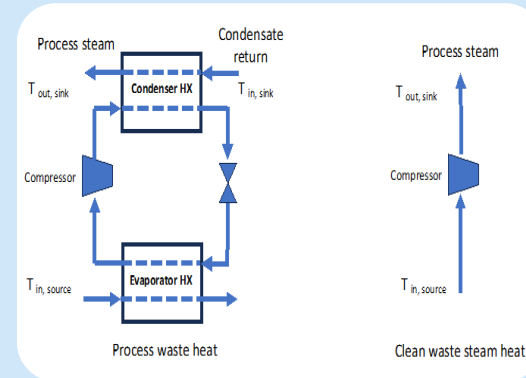
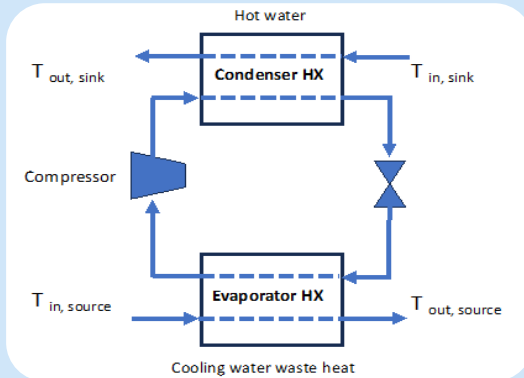
Mechanical vapor compression heat pump
(source: Zuhlsdorf, 2023)

Steam Boiler versus Industrial Heat Pump
Comparison Diagram (ACEEE 2023)



Coefficient of Performance = COP = Process heat delivered / electricity input

Types of Industrial Heat Pumps for Food & Beverage



Single Stage

- Mech. Vapor Comp. (MVC)
- Cooling Water Heat Rejection
- Fluid Heating

Single Stage

- Mech. Vapor Re-Comp. (MVR)
- Closed or Open Cycle
- Process Water Heat Recovery
- Steam Generation

Two Stage

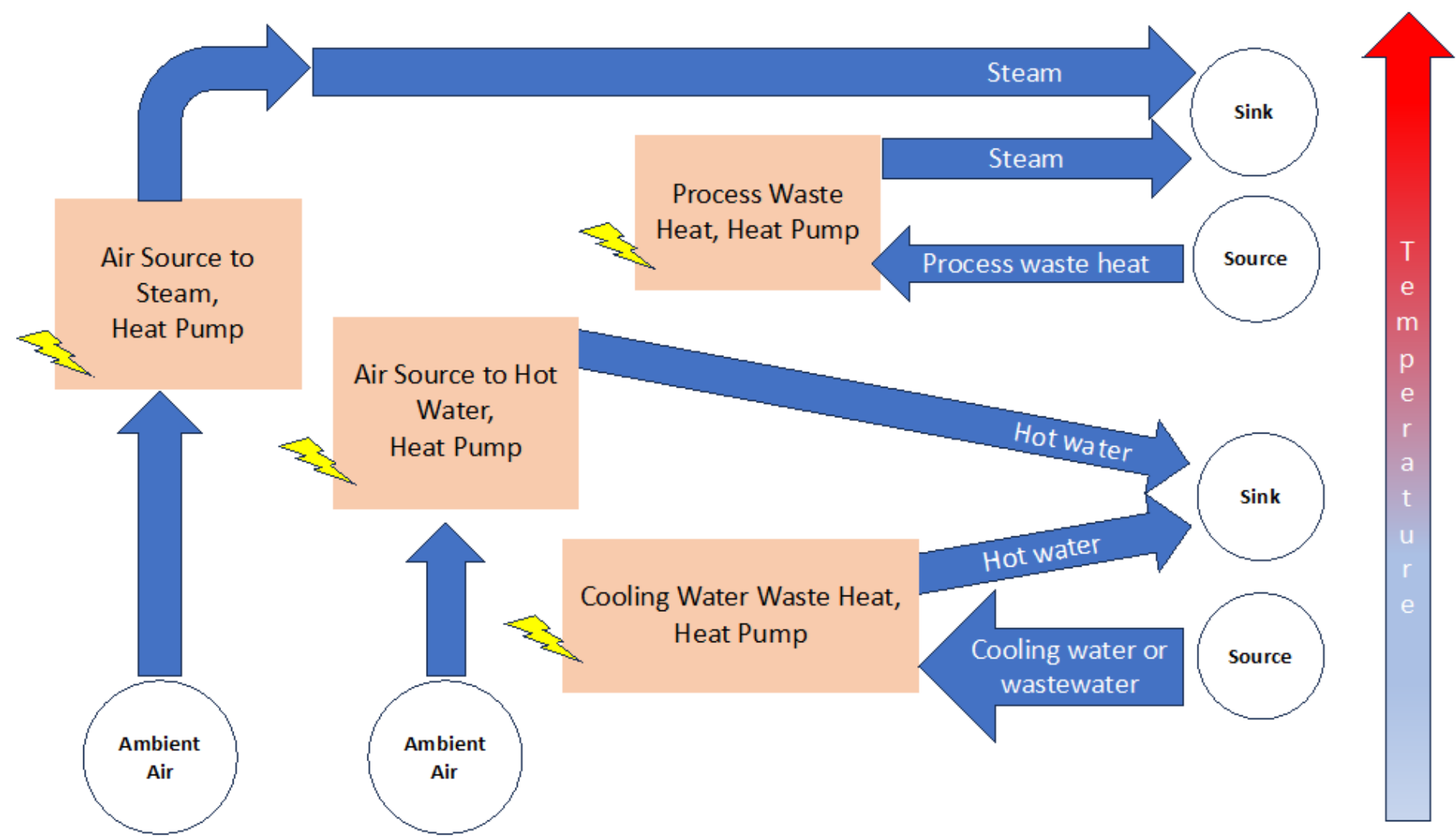
- Mech. Vapor Comp. (MVC)
- Air Sourced Heat Supply
- Fluid Heating up to 140 °F

Three Stage

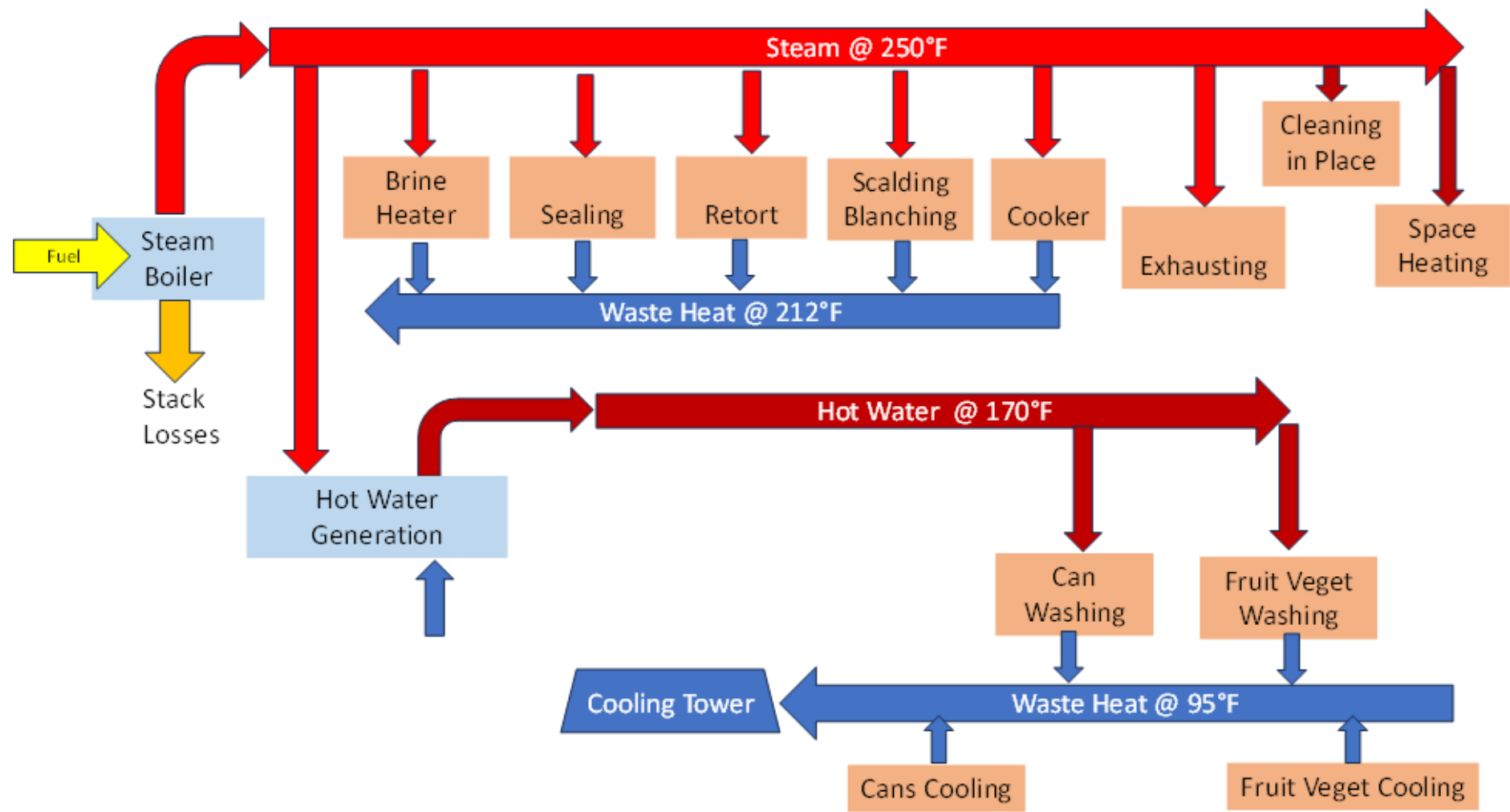
- 2 Stage Mech. Vapor Comp. (MVC)
- 1 Stage Steam Comp
- Air Sourced Heat Supply
- Steam Generation

For steam temperatures > 250°F and lift < 35°F a thermal vapor recompression (TVR) may be an option

Four heat pump types: from heat sources to heat sinks

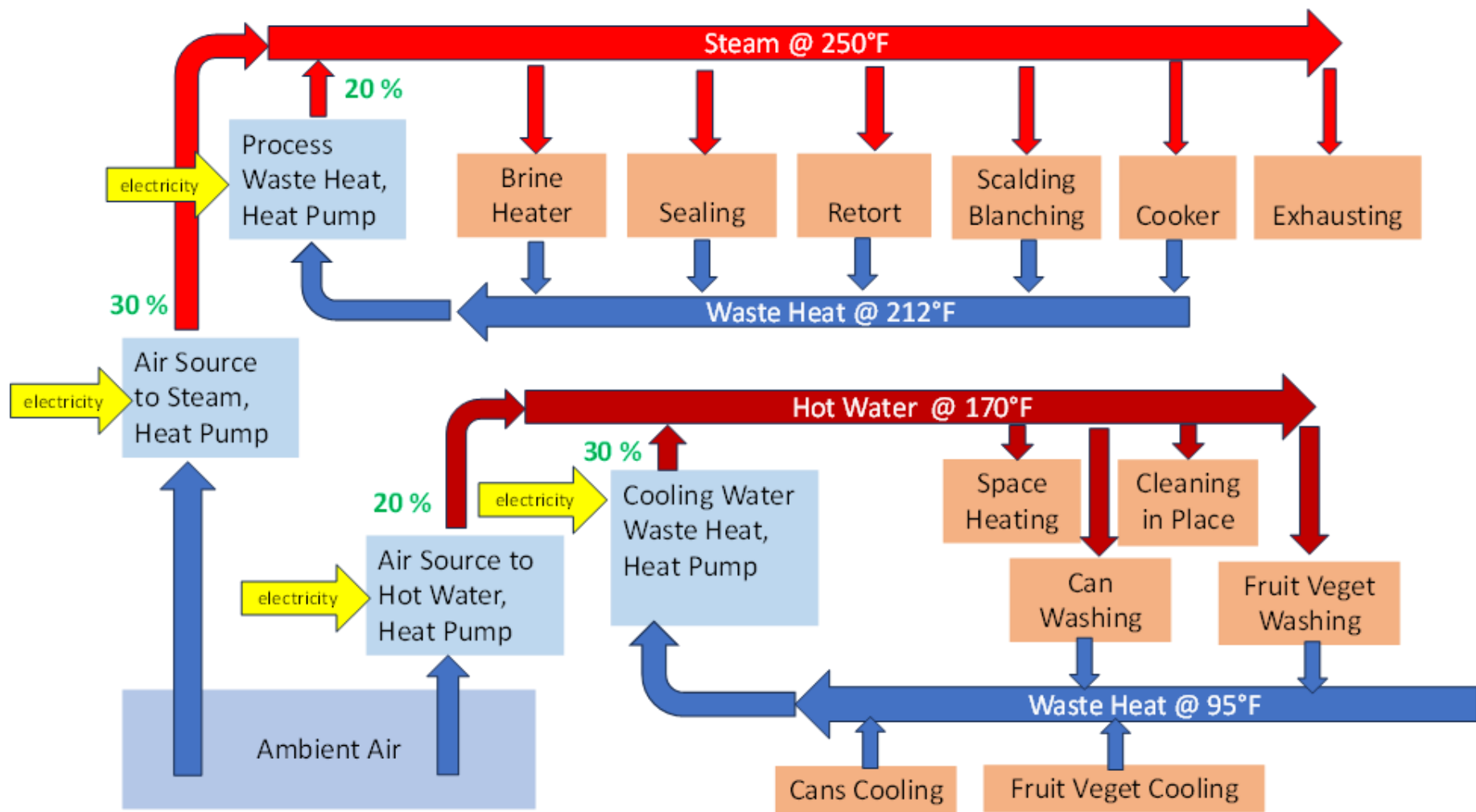


Baseline Boiler Fruit & Vegetable Canning Process



66 MMBtu/hr process demand 26 MMBtu/hr waste heat

Industrial Heat Pump Fruit & Vegetable Canning Concept



18.3 MMBtu/hr of 26 MMBtu/hr waste heat recovered (70%)

US Energy and Carbon Emissions Reductions Opportunity

Wide-spread Industrial HP Adoption in Food & Beverage Sector

	Fruit & Vegetable Canning	Animal Slaughter & Meat Processing	Fluid Milk Manufacturing	Breweries	Bakeries	Total 5 subsectors
Total establishments (small/large)	568 (531/37)	3,088 (2,914/179)	360 (351/9)	2,728 (2,686/42)	8,147 (8,147/0)	14,891 (14,629/267)
Site fuel savings (TBtu/yr)	64	145	27	25	18	278
Site Electricity Increase (MM-kWh/yr)	4,287	7,092	1,606	1,274	989	15,249
Site Electricity Demand Increase (MW)	86	887	201	159	124	1456
Net carbon emission reduction – US grid average carbon intensity, 2021 – million tons / year	1.9	5.3	0.7	0.9	0.6	9.4
Net carbon emission reduction – Future net zero grid – million tons / year	2.3	8.3	1.5	1.4	1.0	14.5

Technical potential assuming full deployment in 5 select Food and Beverage sectors.

Regional Economic Comparisons with Electricity/Fuel Price Spread

	Fruit & Vegetable Canning	Animal Slaughter & Meat Processing	Fluid Milk Manufacturer	Breweries	Bakeries	Total 5 subsectors
Scenario 1, Heat pump economics across U.S. for Five F&B subsector low E/F Price (E/F = 2.0)						
Capital cost investment, \$ billion	\$4.9	\$7.1	\$1.6	\$1.2	\$1.4	\$16.2
Electricity cost, million/yr	\$264	\$437	\$99	\$79	\$61	\$941
Net operating cost savings, \$ million/yr	\$551	\$1,490	\$250	\$248	\$163	\$2,701
Simple payback - aggregate for subsector, years	8.9	4.7	6.3	4.8	8.9	6.0
Scenario 2, Heat pump economics across U.S. for Five F&B subsector average E/F Price (E/F = 3.3)						
Capital cost investment, \$ billion	\$4.9	\$7.1	\$1.6	\$1.2	\$1.4	\$16.2
Electricity cost, \$ million/yr	\$356	\$590	\$133	\$106	\$82	\$1,269
Net operating cost savings, \$ million/yr	\$338	\$1,064	\$165	\$174	\$108	\$1,851
Simple payback - aggregate for subsector, years	14.5	6.6	9.6	6.8	13.3	8.7
Scenario 3, Heat pump economics across U.S. for Five F&B subsector with RNG purchase (E/F = 1.0)						
Capital cost investment, \$ billion	\$4.9	\$7.1	\$1.6	\$1.2	\$1.4	\$16.2
Electricity cost, \$ million/yr	\$356	\$590	\$133	\$106	\$82	\$1,269
Net operating cost savings, \$ million/yr	\$1,467	\$3,621	\$636	\$607	\$420	\$6,752
Simple payback, years	3.3	1.9	2.5	2.0	3.4	2.4

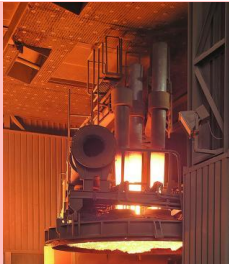
Electrification Technologies by Energy Uses

Resistance

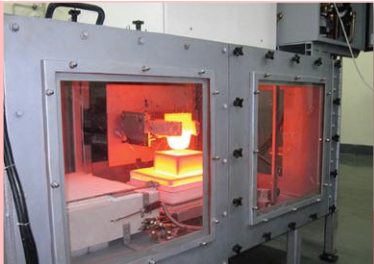
Electro-Magnetic

Ancillary

Melting



Electric Arc Furnace



Resistance Melting



Induction Melting



Logistics

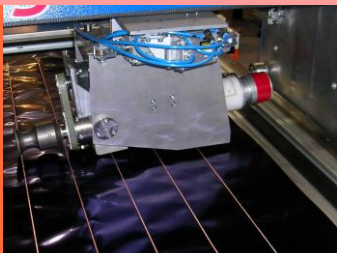
Heating



Convection Furnace



Radio Frq.



Ultrasonics



UV Curing



Induction Htg



Infrared Heating

Steam



Electrode Boiler



MV Boiler



Heat Trace



Heat Recovery HP/Chiller

Industrial Direct Electrification Measures

NAICS Description	Infrared Curing and Drying	Induction Surface Heat Treating	Induction Melting	Resistance Heating	Resistance Melting	RF/Ultraviolet Curing	Industrial Heat Pump/ Chiller
311: Food Manufacturing	✓	✓		✓		✓	✓
312: Beverage and Tobacco Product Manufacturing		✓		✓		✓	✓
313: Textile Mills	✓					✓	✓
314: Textile Product Mills	✓	✓					✓
315: Apparel Manufacturing	✓						
316: Leather and Allied Product Manufacturing	✓					✓	
321: Wood Product Manufacturing	✓					✓	✓
322: Paper Manufacturing	✓					✓	✓
323: Printing and Related Support Activities	✓					✓	
324: Petroleum and Coal Products Manufacturing				✓			✓
325: Chemical Manufacturing				✓		✓	✓
326: Plastics and Rubber Products Manufacturing		✓		✓			✓
327: Nonmetallic Mineral Product Manufacturing	✓				✓		✓
331: Primary Metal Manufacturing	✓		✓		✓		✓
332: Fabricated Metal Product Manufacturing	✓	✓		✓			✓
333: Machinery Manufacturing	✓	✓		✓			
334: Computer and Electronic Product Manufacturing	✓	✓		✓			
335: Electrical Equipment, Appliance, and Component Manufacturing	✓	✓		✓		✓	
336: Transportation Equipment Manufacturing	✓	✓		✓		✓	
337: Furniture and Related Product Manufacturing	✓	✓		✓		✓	
339: Miscellaneous Manufacturing	✓			✓		✓	

Non-Energy Drivers (Benefits)

- Lean Manufacturing
 - Productivity
 - Product Quality (Scrap & Repair)
 - Delivery
 - Process Flexibility
 - Inventory
 - Single piece flow
 - Up-time
- Labor Cost
- Raw Material Costs
- Capital (Equipment & Inventory)
- MRO, Consumables & Tooling Costs
- Product Features & New Products
- Health & Safety
- Environmental
- Brand Enhancement

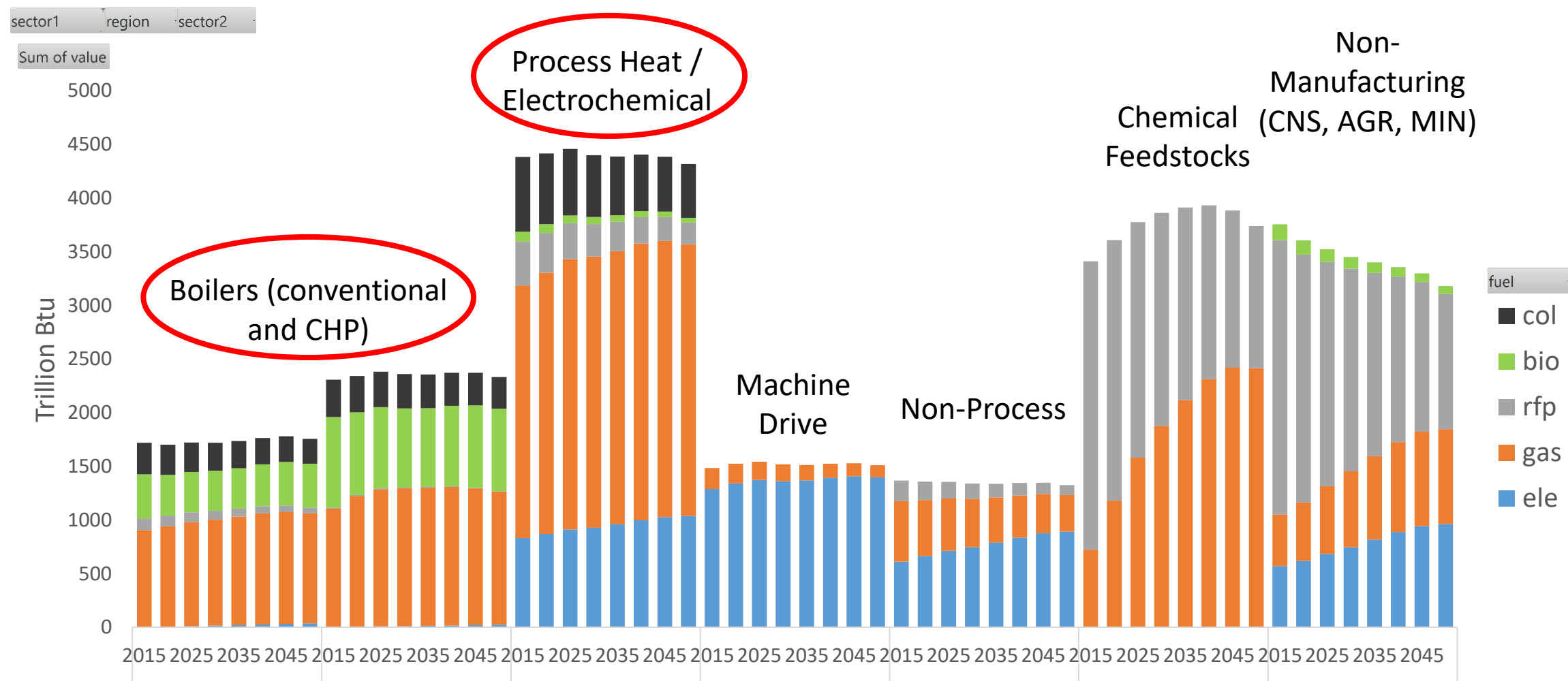




Industrial Decarbonization Strategy

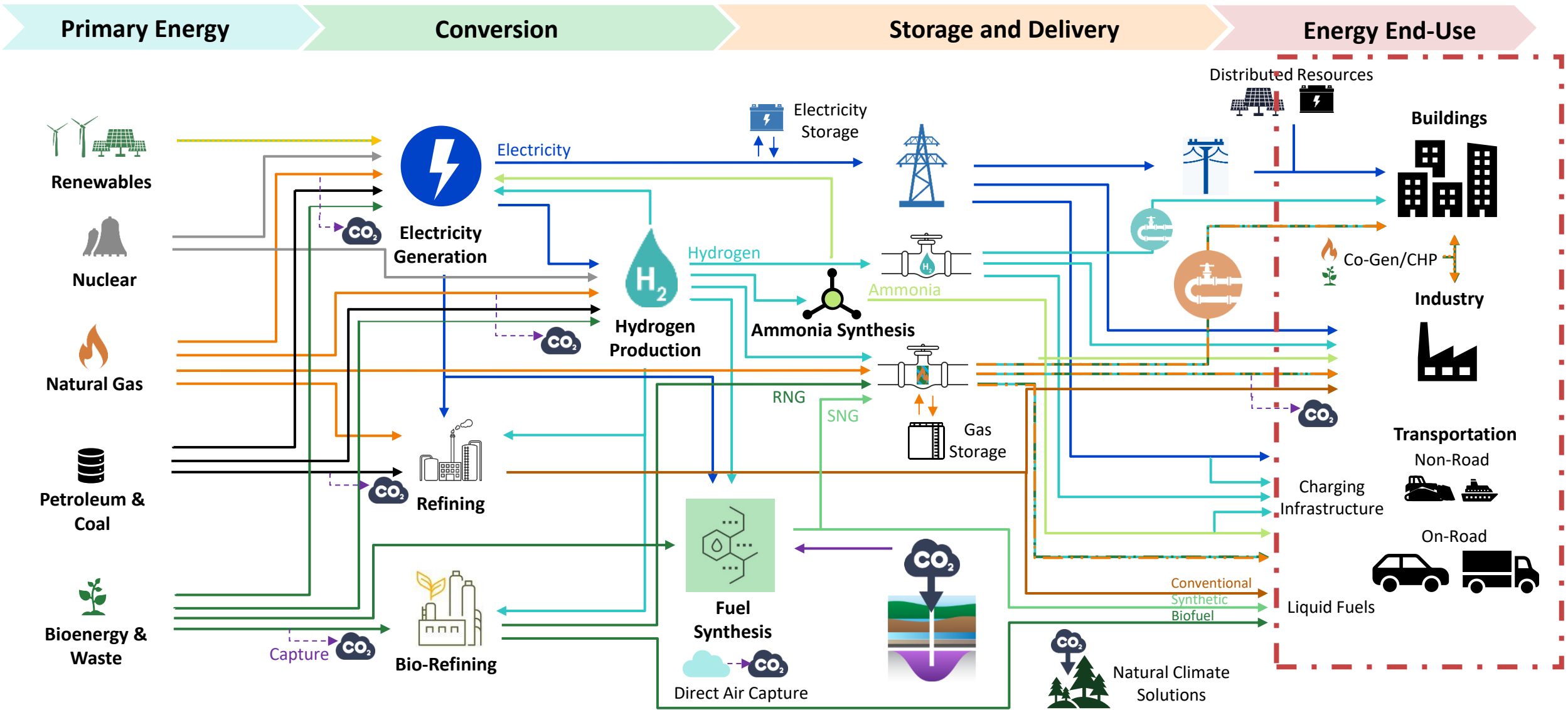
Indirect Electrification

EPRI National Electrification Assessment (2018)



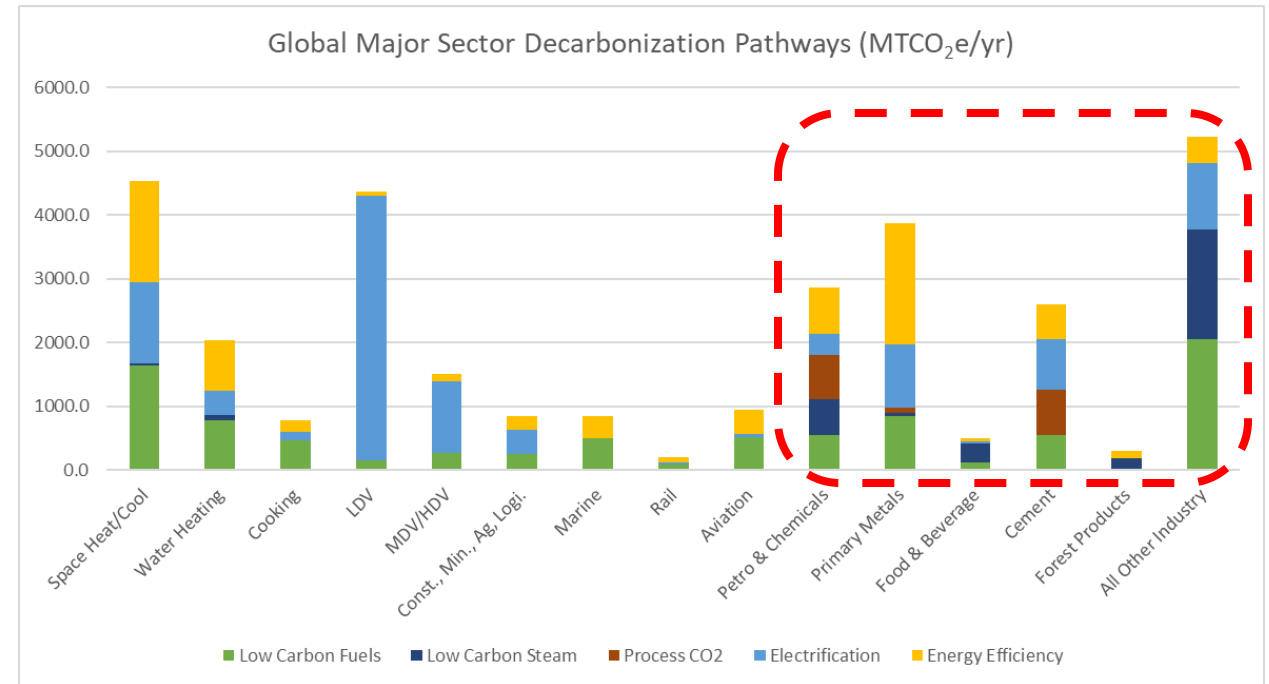
US REGEN Model Indicated Limited Electrification of Process Heat

Energy End Uses in Context



Industrial Decarbonization Pillars

- **Pillar 1: Energy Efficiency/Process Intensification**
 - Better Plants Strategies
 - ISO 50001
 - Advanced Waste Heat Recovery
 - Industrial Heat Pumps
 - Thermodynamic Cycles
 - Thermal/Thermo-chemical Energy Storage & Requalification
 - Oxy Firing
- **Pillar 2: Direct Electrification**
 - Electric Material Movement
 - Electric/Electrode Boilers
 - Electromagnetic Spectrum (Heating)
 - Advanced Membrane Separation
 - Inductive Thermal Catalysis
- **Pillar 3: Process Redesign (Process Emissions CCUS)**
- **Pillar 4: Indirect Electrification (Difficult to Electrify) through Alternate Energy Carriers.**



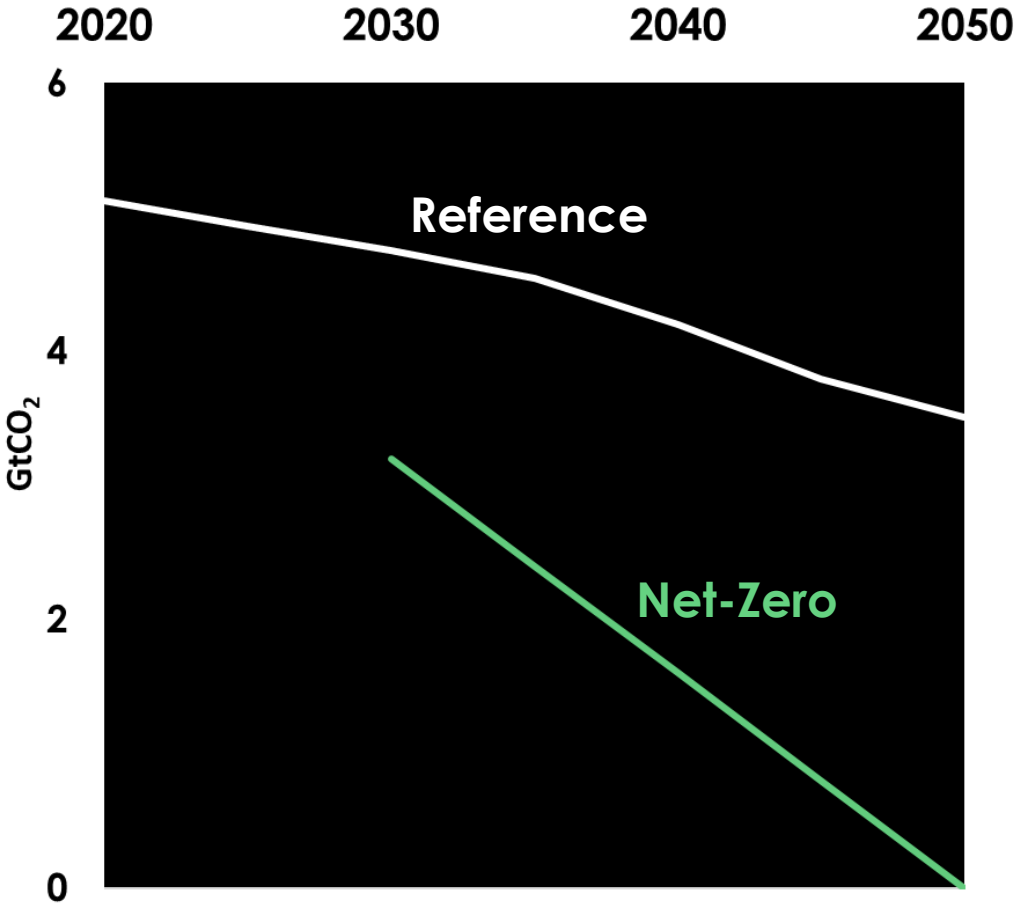


Low Carbon Resources Initiative

LCRI NET-ZERO 2050

Full report available at lcri-netzero.epri.com

Reference with no new carbon policy, continued technology improvements



Net-Zero by 2050 with three core sensitivities around CCS, gas, bioenergy

	All Options	Higher Fuel Cost	Limited Options
Geologic Storage of CO ₂	Lower Costs	Higher Costs	Not Available
Natural Gas Supply Costs	Lower Costs	Higher Costs	Lower Costs
Bioenergy Feedstock Supply	Full	Energy Crops Limited	Energy Crops Limited

Electricity Supply and Demand

2020

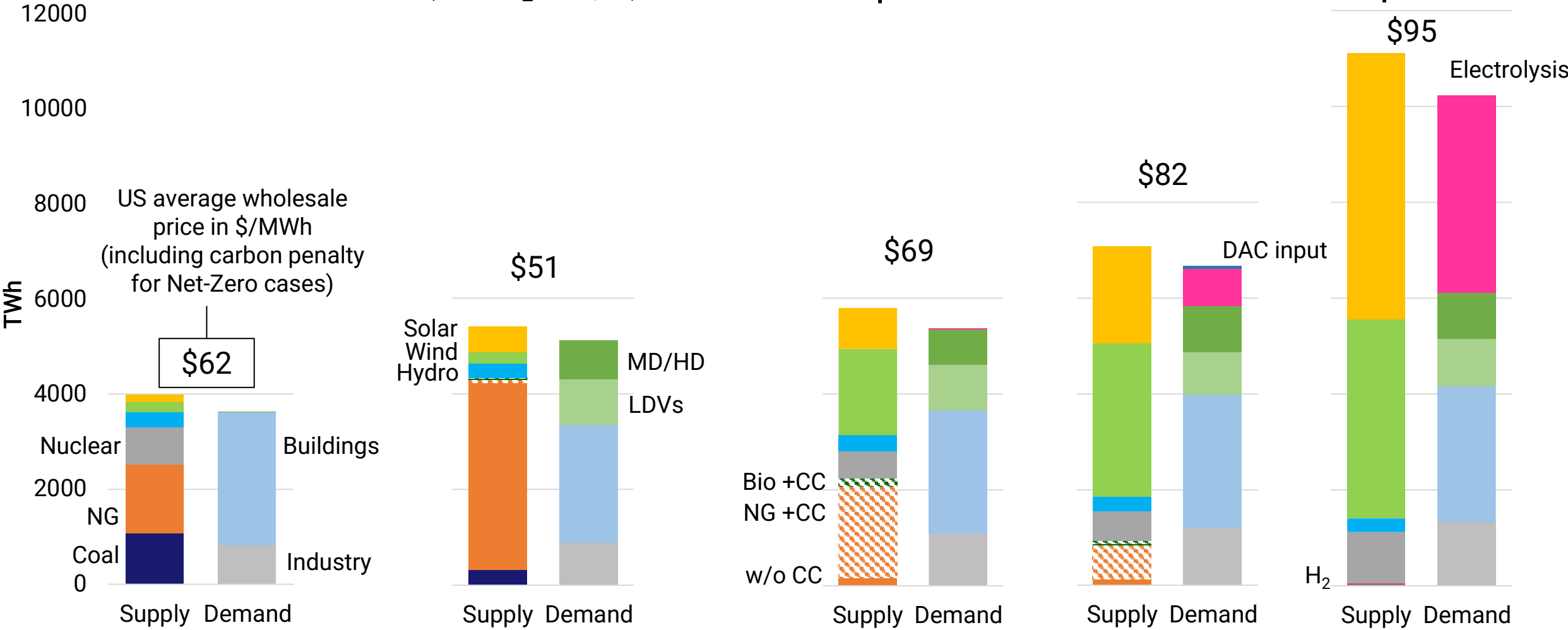
2050 Reference
(No CO₂ Target)

2050 Net-Zero

All
Options

Higher Fuel
Cost

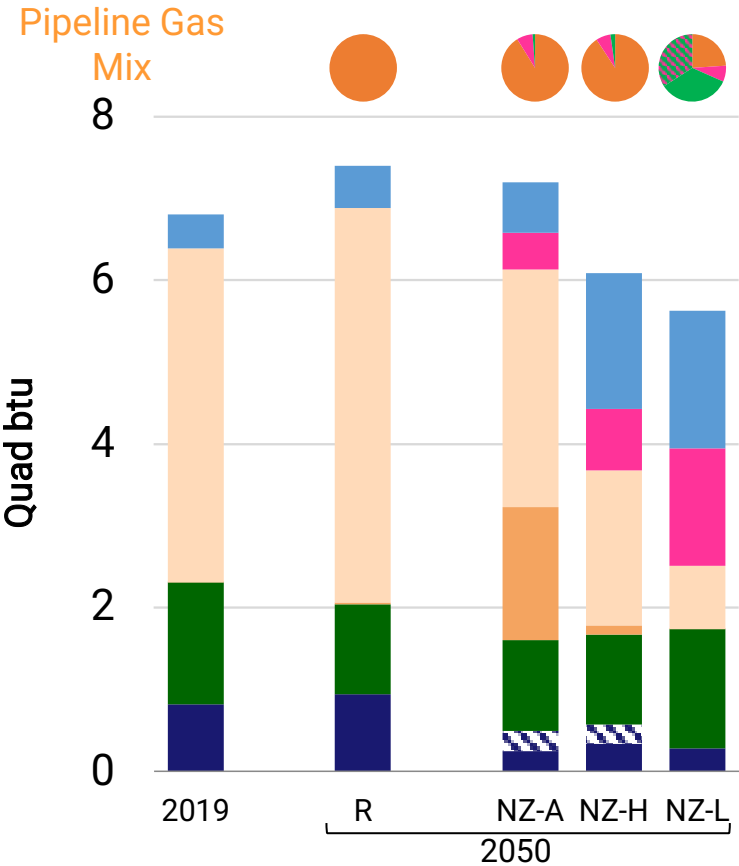
Limited
Options



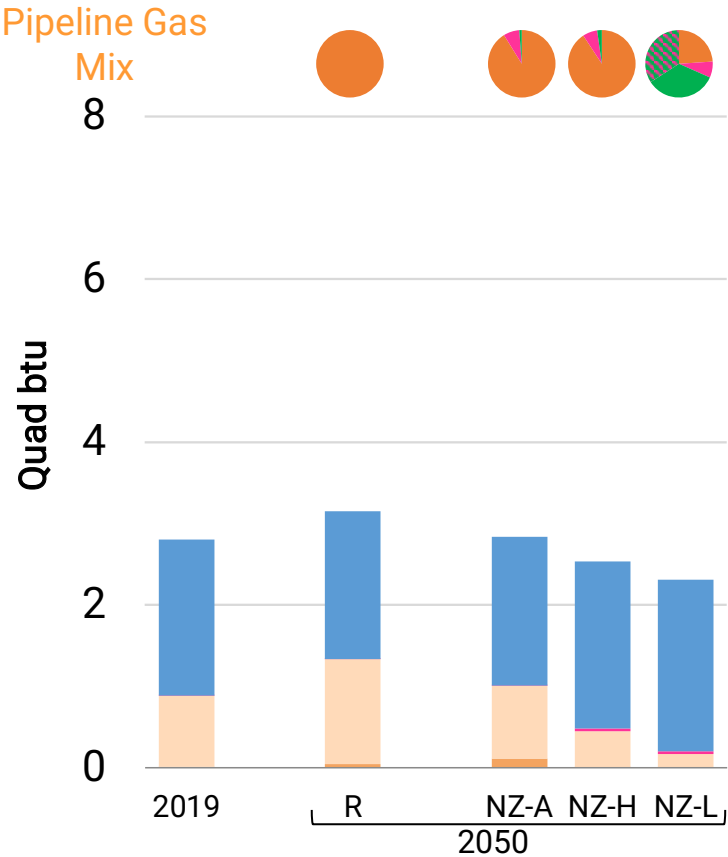
Industry Final Energy Use

Manufacturing

Process Heat/Steam



Other Manufacturing



Other manufacturing:

- Machine drive
- Electrochemical processes
- Process cooling
- Facilities HVAC, lighting

■ Coal ▨ Coal+CC ■ Biomass ■ Liquid Fuels
■ Pipeline Gas ■ Hydrogen ■ Electricity

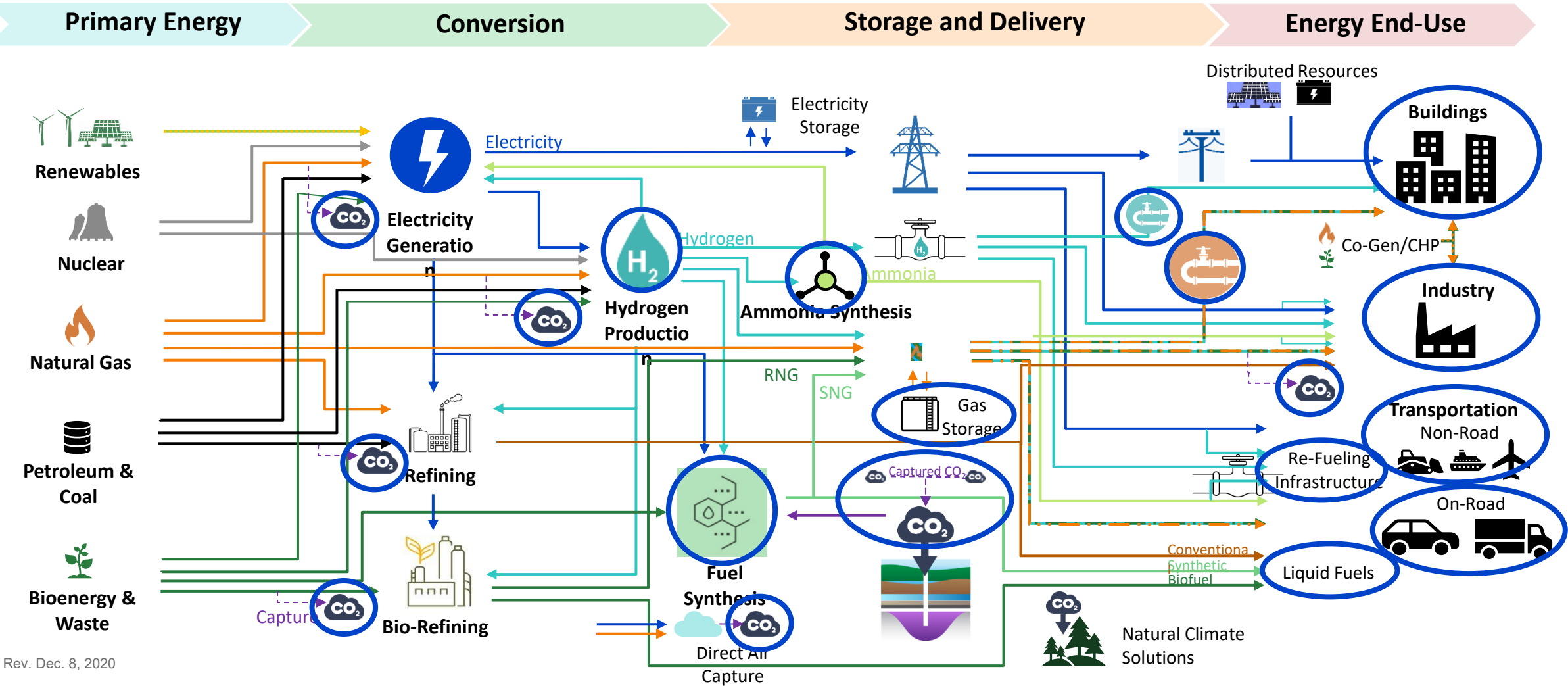
R Reference
NZ-A Net-Zero All Options

NZ-H Net-Zero Higher Fuel Cost
NZ-L Net-Zero Limited Options



LCRI/Electrification NEXUS

Electricity in a Low-Carbon Energy Ecosystem



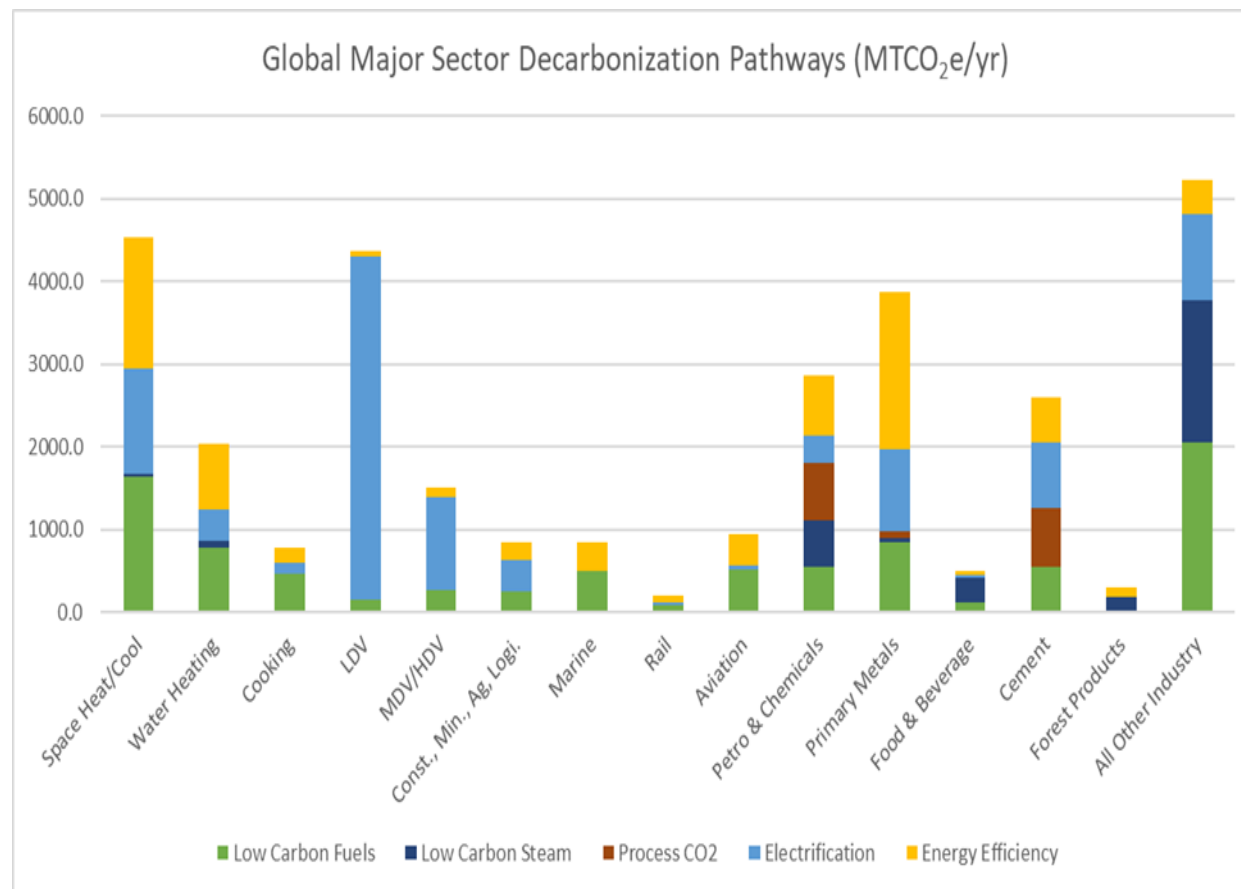
Rev. Dec. 8, 2020

Circles indicate points of new electric demand

Low Carbon Resources Initiative (LCRI)/Electrification Nexus

Where do LCRI and Electrification Interests Align?

- Low Carbon Fuel Electric Technology Opportunities
 - **Water Electrolysis of Hydrogen**
 - Water Treatment
 - Electrolyzers
 - Compression/Liquifaction
 - **Renewable/Synthetic Fuels Production (CCUS)**
 - Biomass Harvest/Transport/Prep
 - CO₂ Capture, Compression and Transport
 - Synthetic Fuel Refining
 - **Transport and Storage**
 - AEC Compression/Pumping/Refrigeration
 - **Power Generation Fuels**
 - SMR of H₂ + CO₂ Capture, Compression
 - **Environmental Aspects & Safety Mitigation Controls**
 - **End Use Final Energy – Direct Electrification**
 - Buildings
 - On Road Transport
 - Non-Road Transport
 - Industry



Most Low Carbon Resource Pathways will Require Electric Power



TOGETHER...SHAPING THE FUTURE OF ENERGY®