OAK RIDGE National Laboratory

Energy Efficiency as a Foundational Technology Pillar for Industrial Decarbonization

Sachin Nimbalkar, PhD

Group Leader, Manufacturing Energy Efficiency
Research & Analysis Group

Oak Ridge National Laboratory

ORNL is managed by UT-Battelle LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

Acknowledgements

ORNL Co-authors and Contributors

- Senthil Sundaramoorthy, ORNL
- Chris Price, ORNL
- Dipti Kamath, ORNL
- Thomas Wenning, ORNL

DOE Advisors

- Joe Cresko, DOE IEDO
- John O'Neill, DOE IEDO

Industry's Significant Energy Demand and CO_2 Emissions

Industrial sector is comprised of
manufacturing | agriculture | mining | construction

ACCOUNTS FOR

33% of the nation's primary energy use

30% of CO_2 emissions

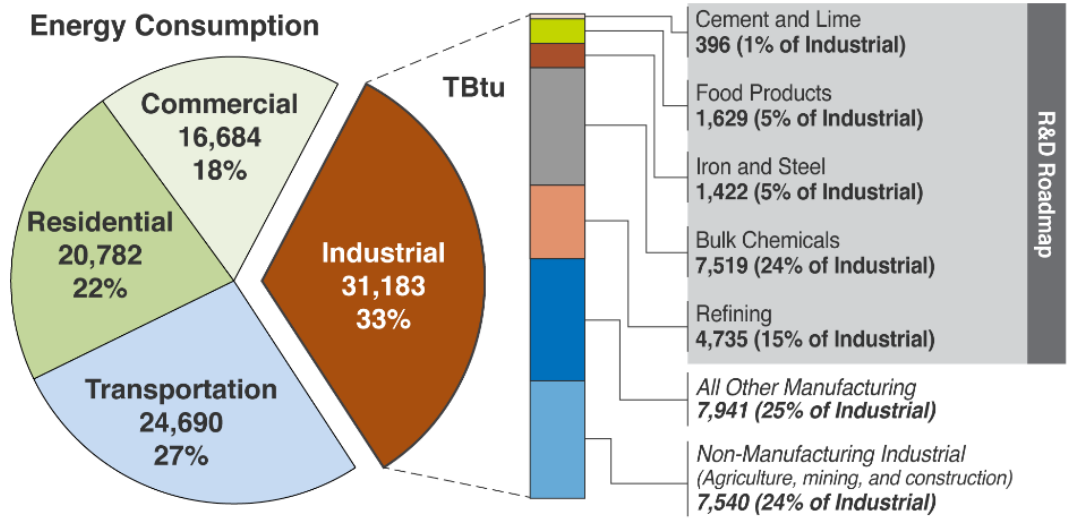
Anticipated industrial sector energy demand growth of 30% by 2050 may result in a

17% CO_2 emissions increase

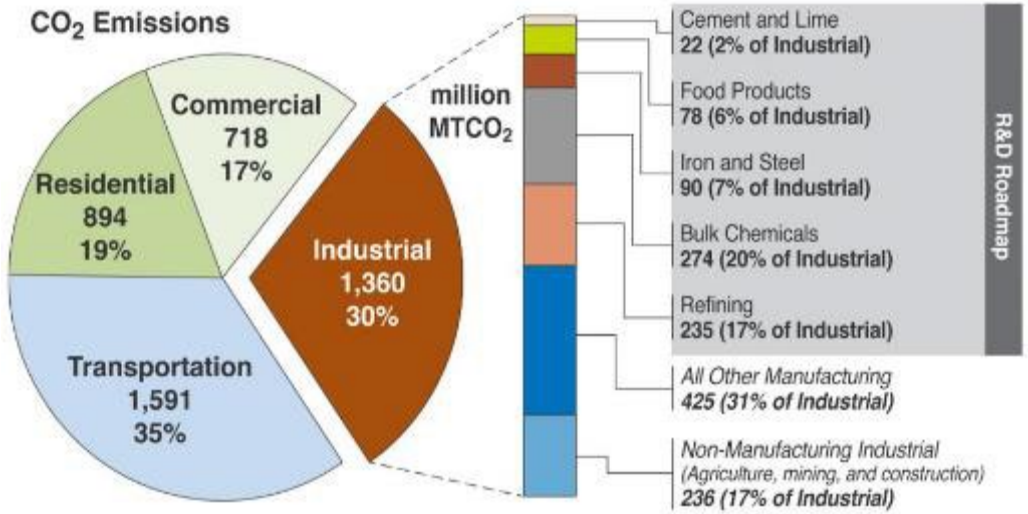
Technological advances in manufacturing will be critical to enabling decarbonization for other sectors.

Data source: Energy Information Administration (EIA) *Annual Energy Outlook 2021 with Projections to 2050*.

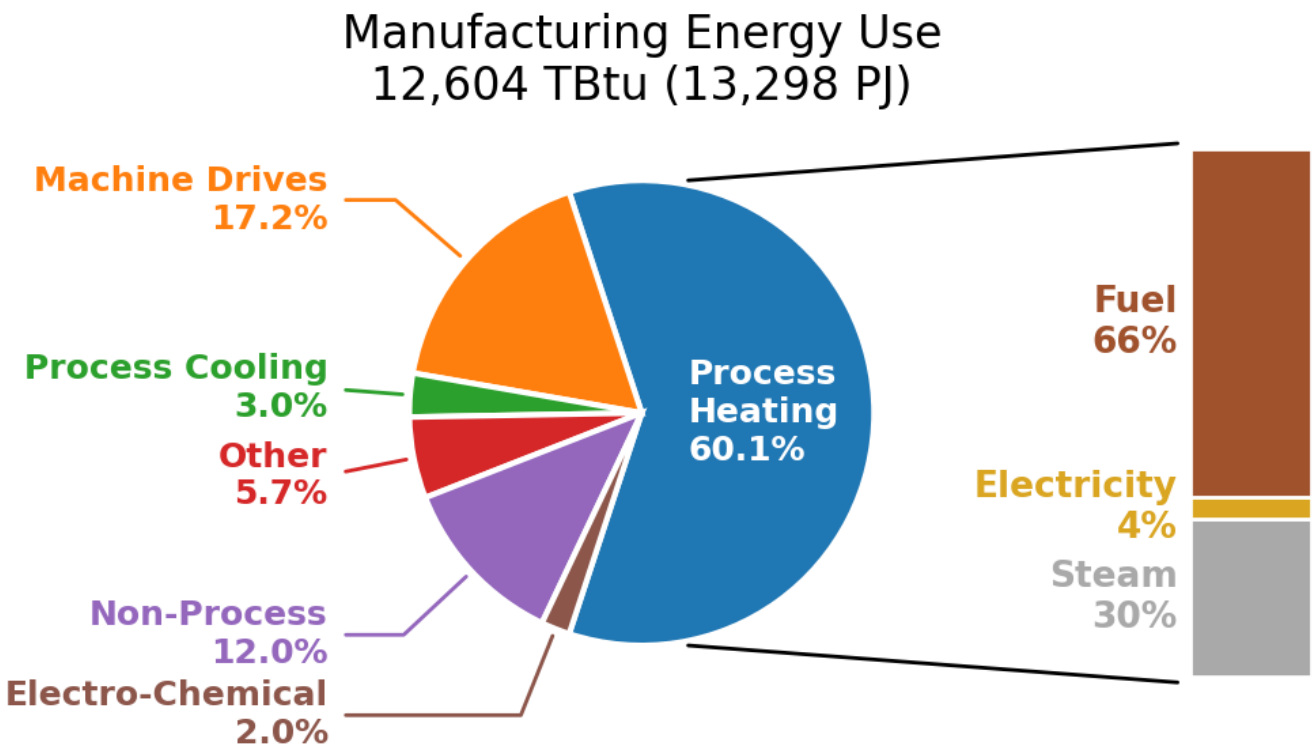
U.S. Energy Consumption by Sector and Subsector (2020)

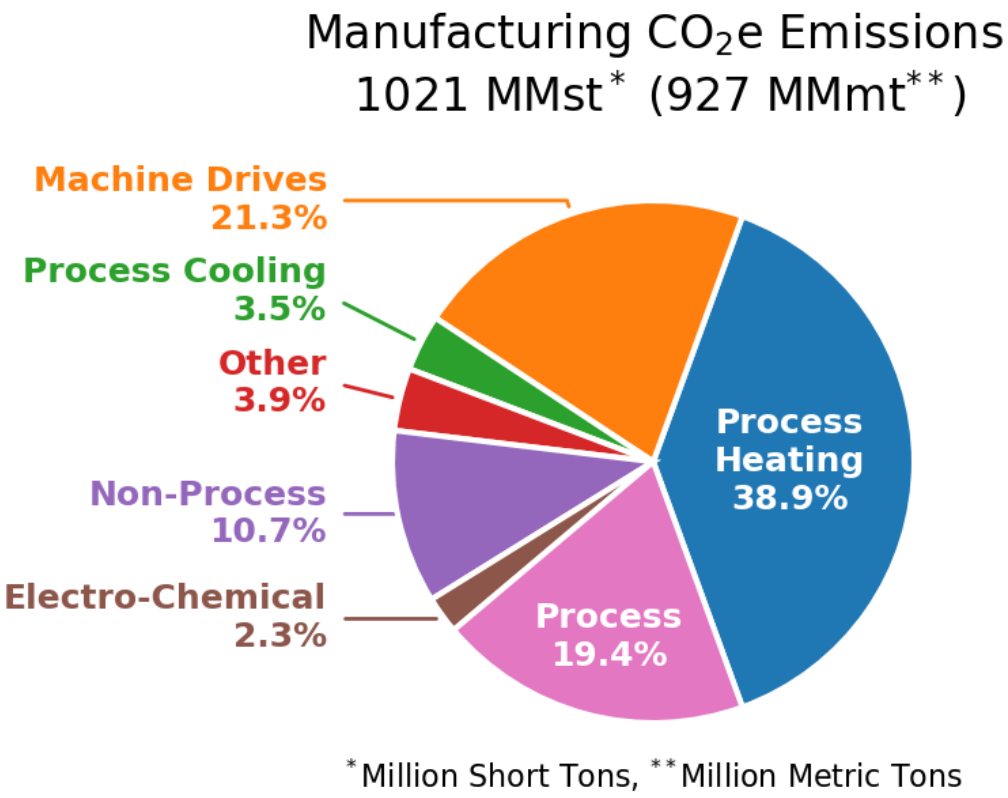


U.S. Energy-related CO_2 Emissions by Sector and



Energy Use and Emissions in Manufacturing Sector



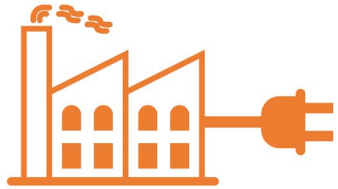


Source: DOE Energy Footprint Analysis based on Energy Information Administration's Manufacturing Energy Consumption Survey (MECS) data for 2018.

The Industrial Decarbonization Pillars

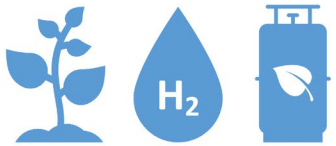
Energy Efficiency (near-term)

- Energy Management
- Adoption of Smart Manufacturing
- Improved Material and Process Efficiency
- Utilization of Combined Heat and Power



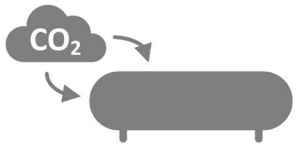
Industrial Electrification (mid- to long-term)

- Electrification of Process Heating
- Electrification of Space Heating
- Electrification of Hydrogen Production
- Development of Electrified Processes



Low-Carbon Fuels, Feedstocks, and Energy (mid- to long-term)

- Development of Carbon-Free Alternative Fuels
- Adoption of Low-Carbon Alternative Fuels
- Utilization of Low-Carbon Feedstock Materials
- Development of Biofuel Infrastructure



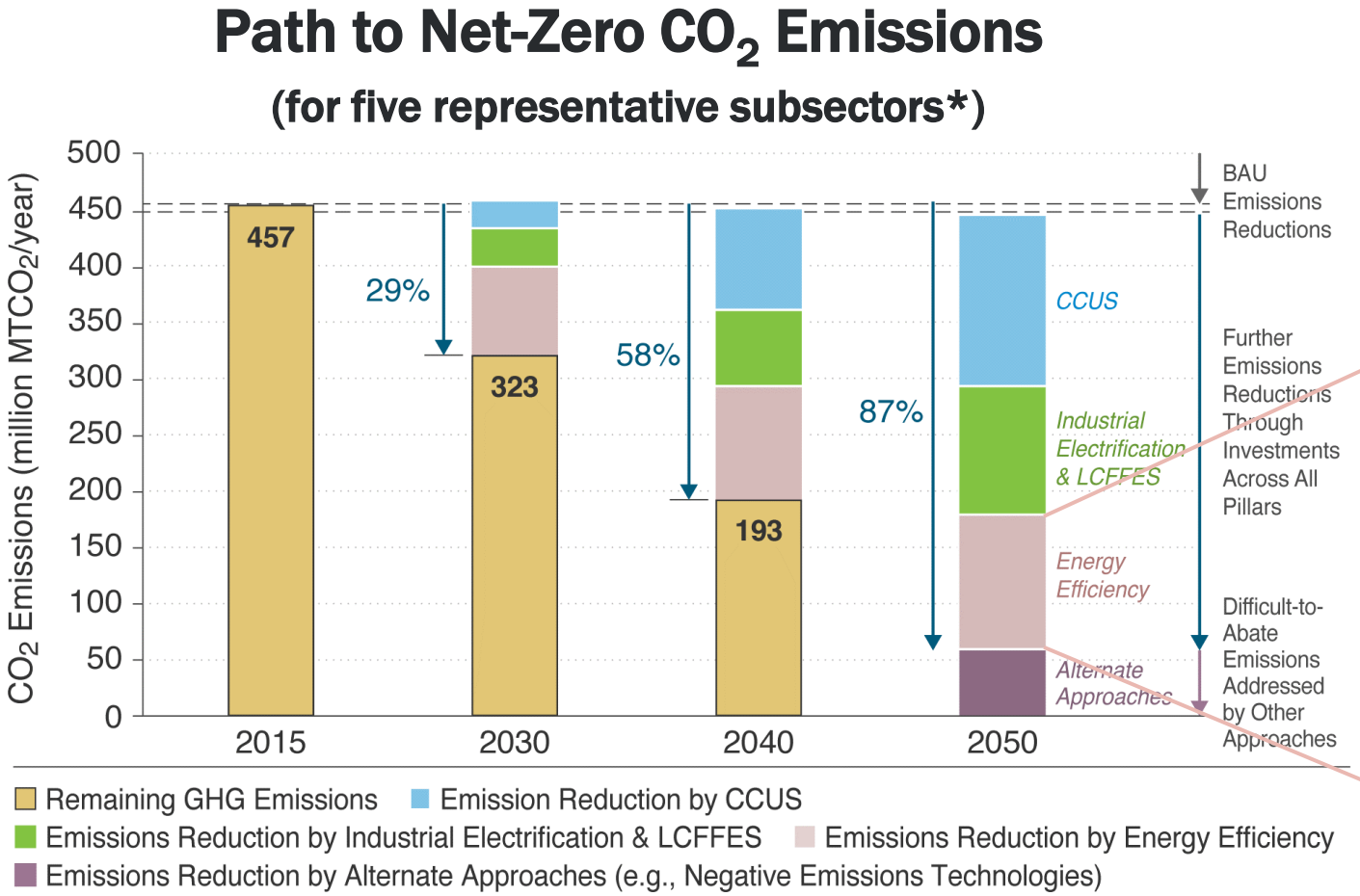
Carbon Capture, Utilization, and Storage (long-term)

- Direct Air Carbon Capture
- Carbon Capture, Utilization, and Storage
- CO_2 Distribution Infrastructure
- Chemical Utilization

Energy efficiency advancements minimize industrial energy demand, directly reducing the GHG emissions associated with fossil fuel combustion.

Source: Industrial Decarbonization Roadmap; DOE/EE-2635; United States Department of Energy: Washington, DC, USA, 2022.

Energy Efficiency as a Foundational Technology Pillar



Energy Efficiency Pillar

1. Strategic Energy Management
2. System Efficiency
3. Smart Manufacturing
4. Materials and life cycle Efficiency
5. Combined Heat & Power

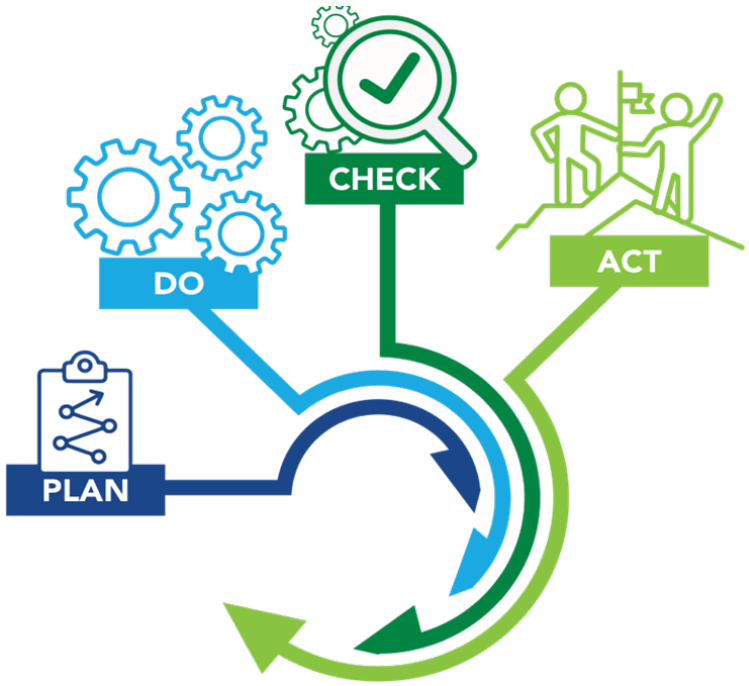
***Subsectors included in Roadmap analysis:** Iron & Steel, Petroleum Refining, Cement, select chemicals (ammonia, methanol, and benzene, toluene, and xylenes (BTX)), and select food & beverage products (beer, beet sugar, cane sugar, fluid milk, red meat, soybean oil, and wet corn milling).

Data source: Scenario modeling based on *Roadmap* findings (this study).

Source: Industrial Decarbonization Roadmap; DOE/EE-2635; United States Department of Energy: Washington, DC, USA, 2022.

Strategic Energy Management

- Energy Performance Improvement Platform
  - Energy efficiency is only one focus
  - Integrated demand side management (IDSM)
  - Resilience, security, demand, supply
  - Decarbonization
- Operational Excellence Program
  - Policies and procedures
  - Systematic approach
  - Change management
- Broader Organizational Framework
  - Energy management platform integrated into business systems
  - (Multinational) Corporate reporting, compliance, and alignment
  - Demonstrates action and commitment to long term success



A management system is:

✓ Say what you do
✓ Do what you say
✓ Prove it
✓ Improve it

EnMS Programs and Support of ISO 50001 Standard

SELF ATTEST

- Complete 25 steps in Navigator
- Self-attest to completion
- Report energy performance
- Recognition by DOE

Time required to complete: flexible

CERTIFY

- ANAB-accredited audit to certify to standard
- DOE support of US TAG/TC 301

Time required to complete: 12-18 months

VERIFY

- Requires ISO 50001 certification
- Robust M&V protocol
- 3rd party energy performance verification audit
- SEP 50001 Certification
- Professional certifications
- Elevated recognition by DOE

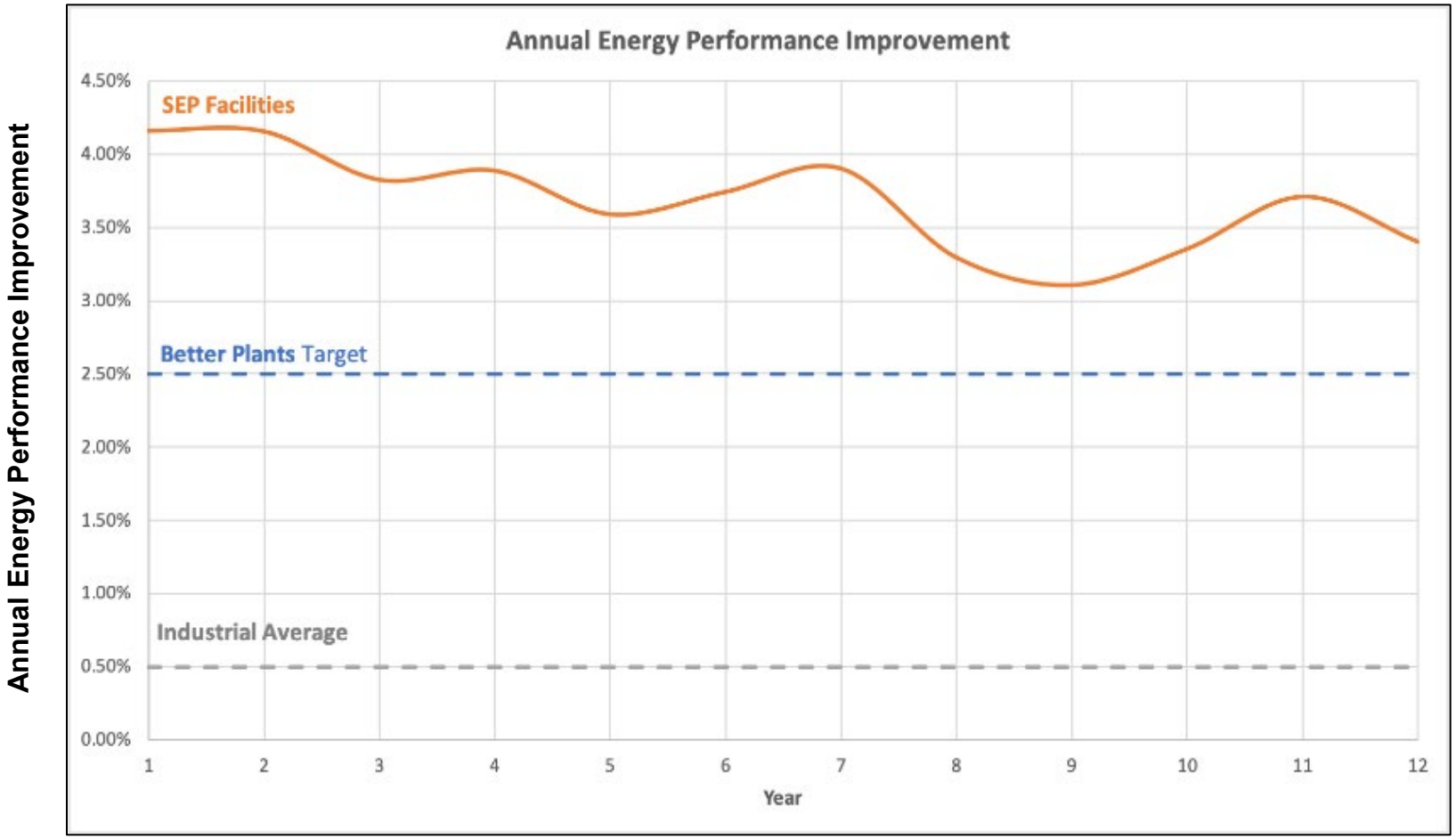
Time required to complete: 12-18 months

50001 Ready can be part of a Pathway toward ISO 50001 Certification and Validated Energy Savings in SEP

Superior Energy Performance 50001 Program

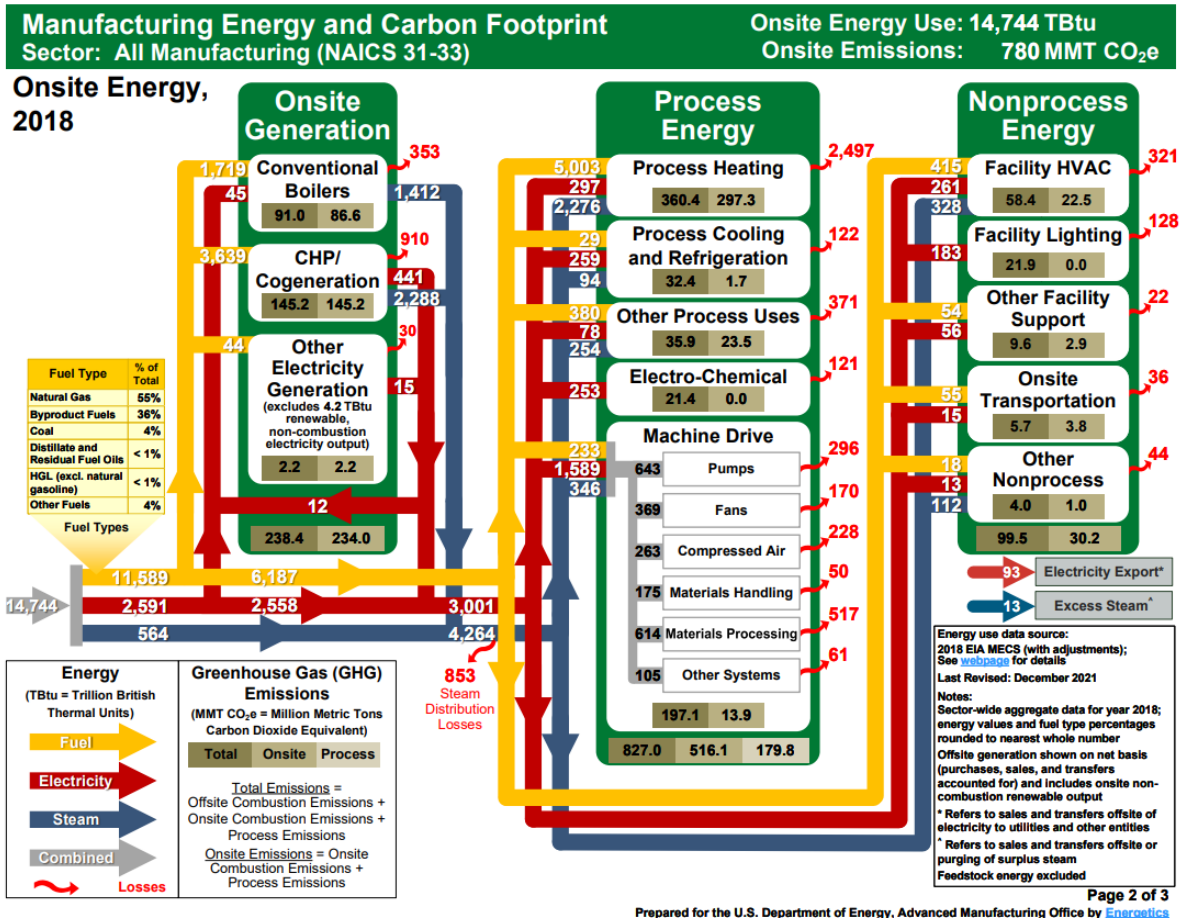
- Analysis of eleven years of SEP program participants' energy savings shows *a 4.2% improvement* across all facilities in the first year.
- By the 11th year, the facilities are still achieving a *3.4% year on year improvement* in energy performance.
- Far exceeds the average improvement in energy intensity across all of industry
  - 0.5%/year per EIA
  - 1.3%/year per IEA
- Journal article to publish in Sustainable Energy Technologies and Assessments in late 2023

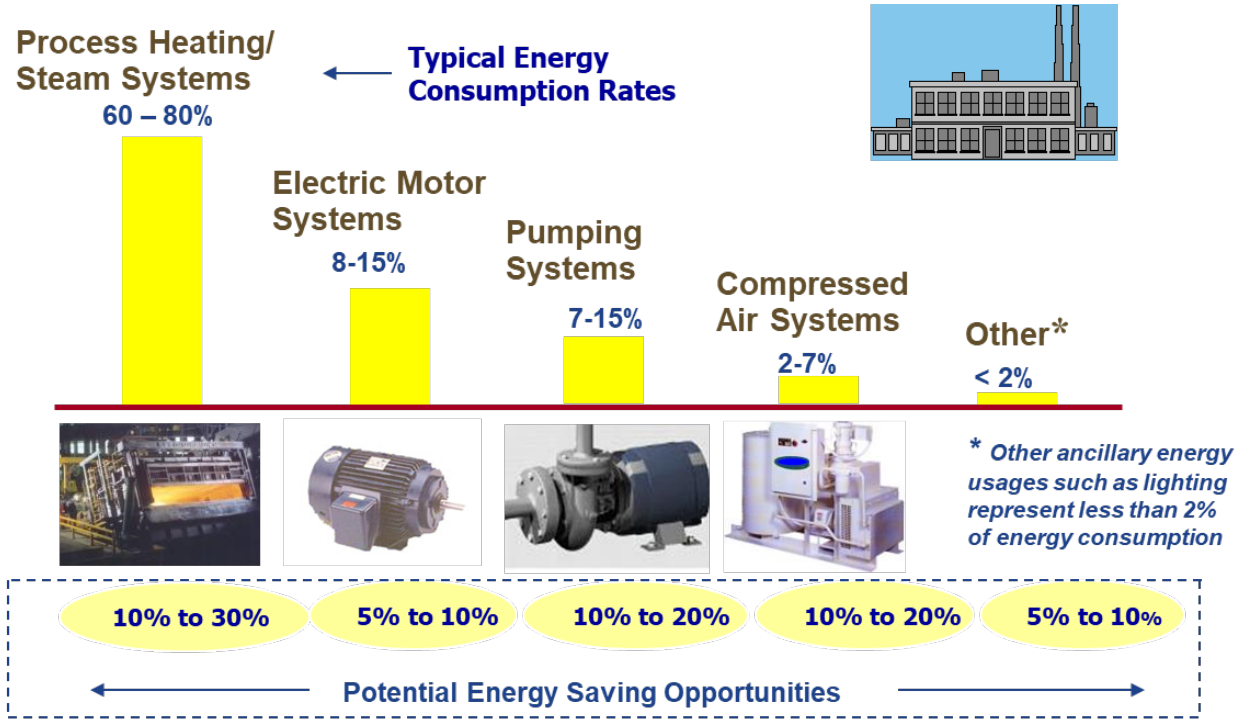
Research Findings: Energy Management Saves More Energy



2022 LBNL analysis

Energy Efficiency of Industrial Systems





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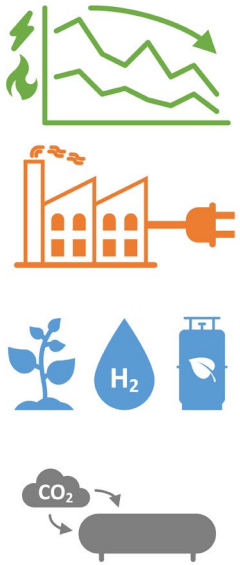
Smart Manufacturing Pathways for Industrial Decarbonization and Thermal Process Intensification

Industrial Decarbonization



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Thermal Process Intensification[2]

Low-Thermal Budget Transformative (mid- to long-term)
- Electrolysis and electrodialysis
- Microwave and radio frequency processing
- Drying via ultrasound processing and membrane separation
- Hydrogen-based production of ammonia, ethanol etc.

Alternative Thermal Processing (near- to mid-term)
- Electric, induction, and resistance heating
- Alternative liquid biofuels or biochemicals
- Hybrid fuel systems
- Solar thermal systems

Transformative Supplemental (near-term)
- Smart IoT devices for system optimization
- Smart manufacturing (e.g., artificial intelligence, digital twins, predictive process controls)
- Flexible, modular manufacturing and operations design

Waste Heat Management (near-term)
- High-temp heat pumps
- Thermal energy storage and waste heat to power
- Recuperators, regenerators, and economizers
- Thermoelectric devices, heat pipes, etc.

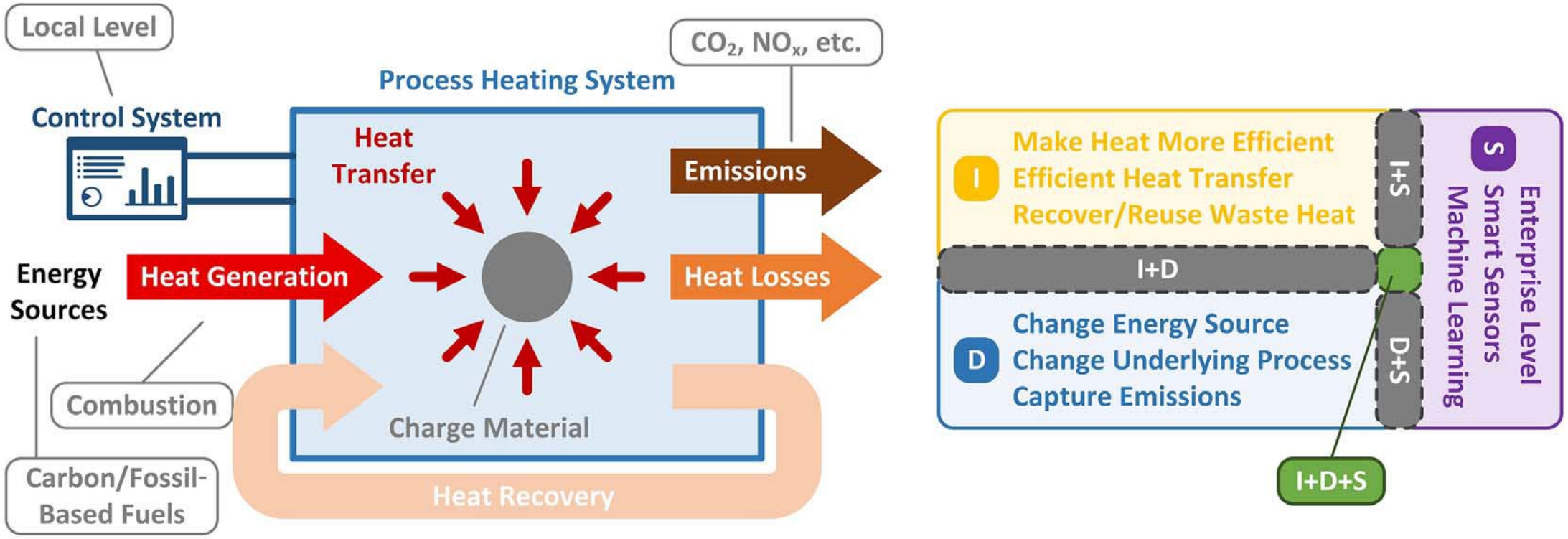
Thermal Process Intensification

Smart manufacturing pathways offer a way to both decarbonize and intensify existing processes while enabling continuous efficient operations and future implementation of new technologies.[1]

1 Price, C.R.; Nimbalkar, S.U.; Thirumaran, K.; Cresko, J. Smart Manufacturing Pathways for Industrial Decarbonization and Thermal Process Intensification. Smart Sustain. Manuf. Syst. 2023, 7, 41–53.
2 U.S. Department of Energy Advanced Manufacturing Office, Thermal Process Intensification: Transforming the Way Industry Uses Thermal Process Energy, May 2022, https://www.energy.gov/eere/amo/articles/thermal-process-intensificationtransforming-way-industry-uses-thermal-process

Pathways toward a smart (S), intensified (I), and decarbonized (D) system from the baseload (left) case

Implementation of SM in the manufacturing sector can enhance the performance of existing systems, improve equipment lifespan, reduce waste, and increase production yields

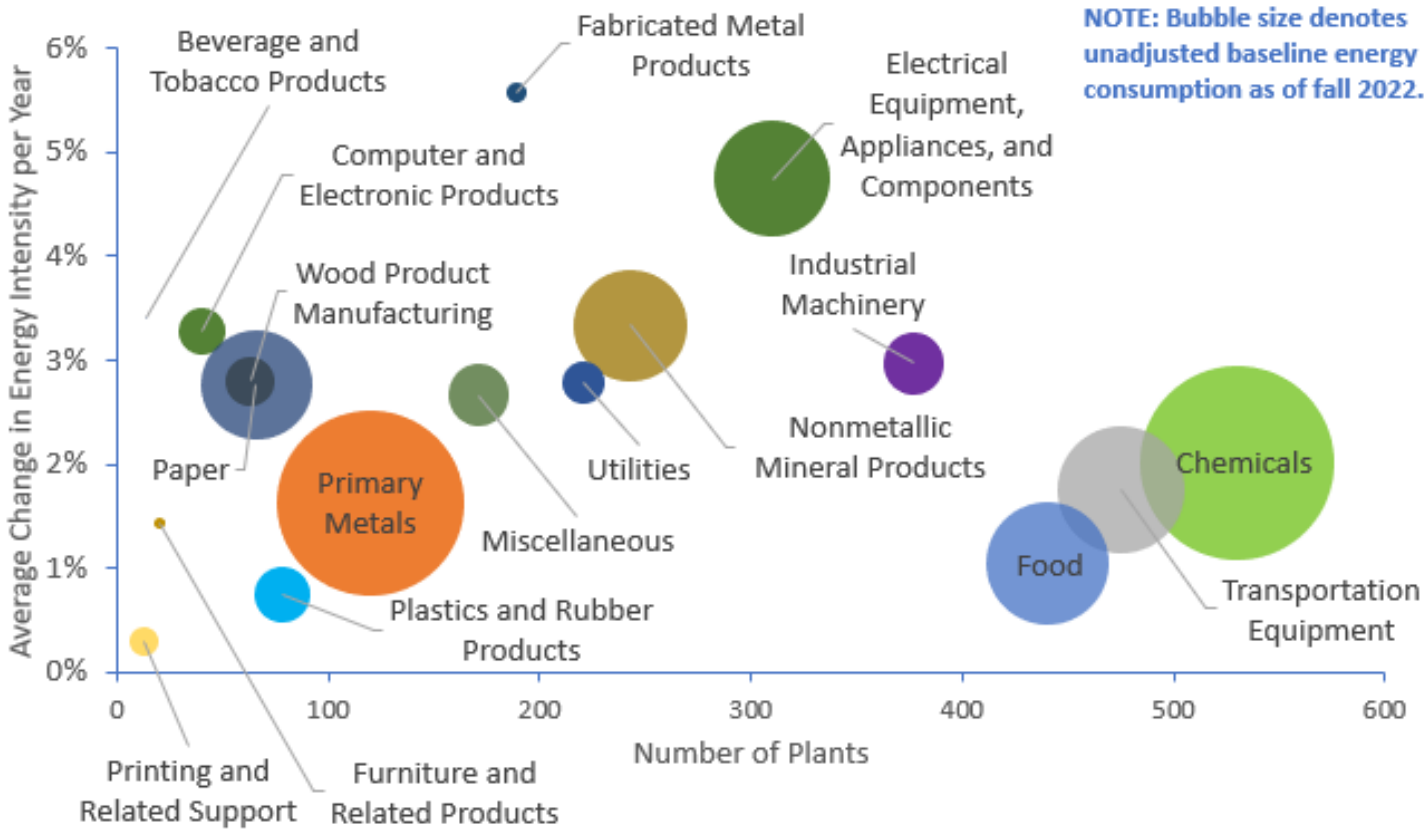


Source: Price, C.R.; Nimbalkar, S.U.; Thirumaran, K.; Cresko, J. Smart Manufacturing Pathways for Industrial Decarbonization and Thermal Process Intensification. Smart Sustain. Manuf. Syst. 2023, 7, 41–53.

Overall Impact of the Energy Efficiency Pillar – Results from DOE's Better Plants Partners

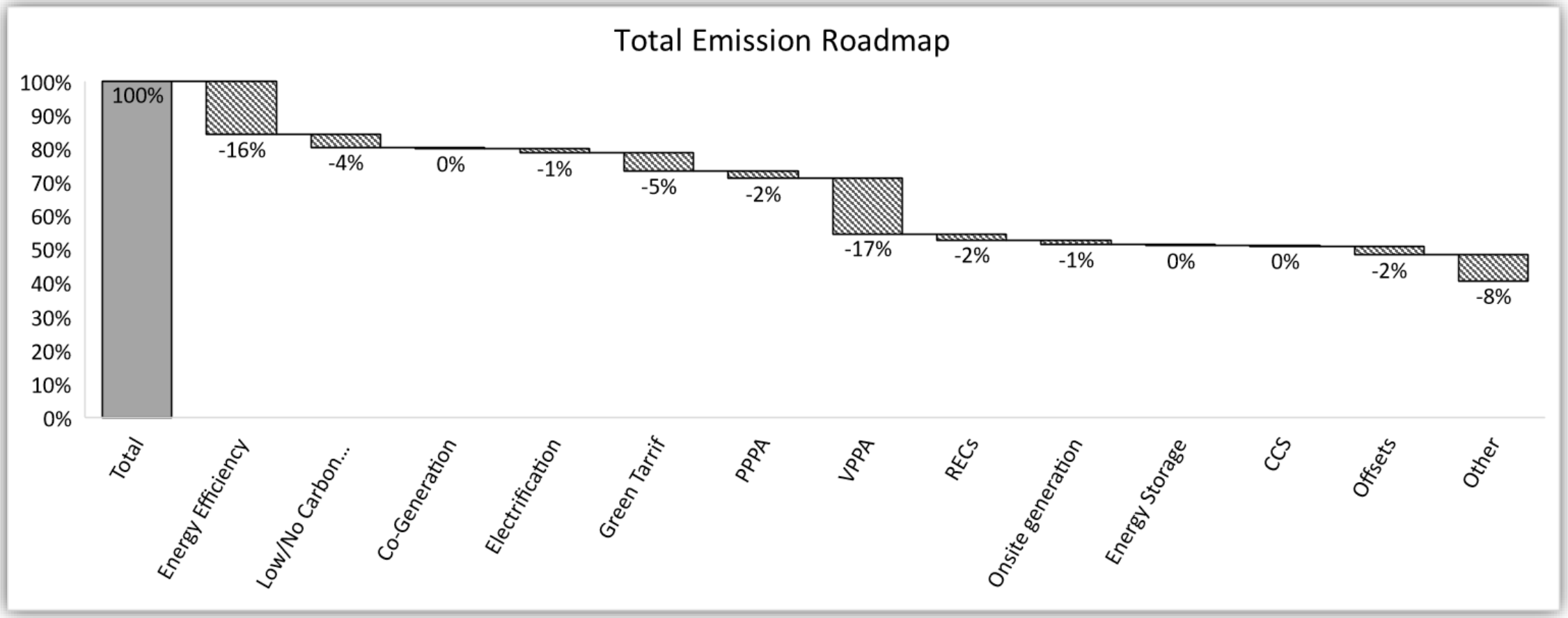
- Through the program, DOE supports 270+ partners (~3600 facilities), corresponding to 14% of the U.S. manufacturing footprint.
- Since 2010, these partners have reported savings of 2.2 QBtu of energy and $10.6 billion. This is equivalent to 131 MMT of CO2 emissions reductions(1).

Average energy intensity improvement in terms of no. of plants and program energy footprint for selected sectors(2)



(1) Better Plants 2022 Progress Update:: https://betterbuildingssolutioncenter.energy.gov/resources/2022-betterplants-progress-update
(2) Sundaramoorthy, S.; Kamath, D.; Nimbalkar, S.; Price, C.; Wenning, T.; Cresko, J. Energy Efficiency as a Foundational Technology Pillar for Industrial Decarbonization. Sustainability 2023, 15, 9487.

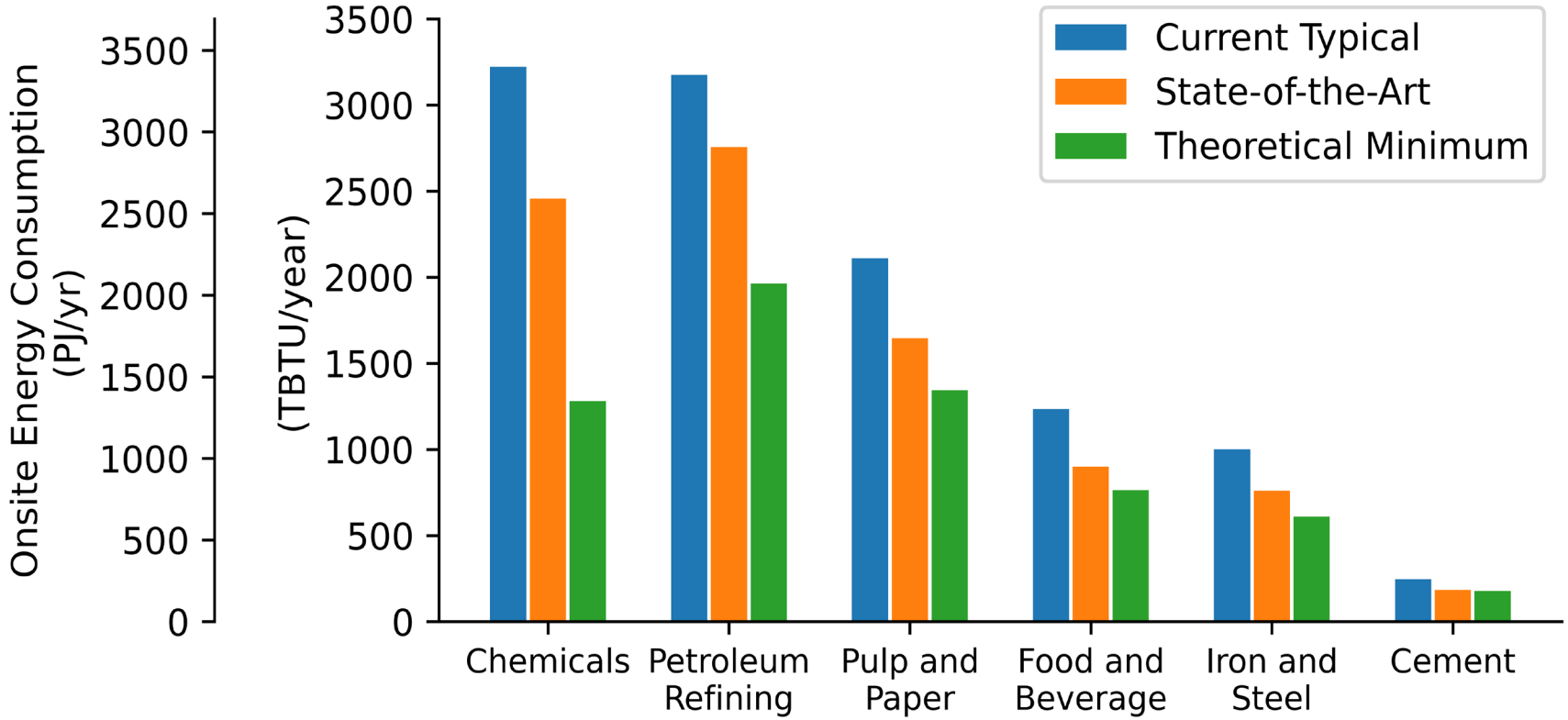
Lessons Learned from DOE's Low Carbon Pilot



This roadmap shows the pathways DOE's LCP partners are planning on undertaking for their 2030 or 2050 goal for their total GHG reduction

Energy Use of Select Energy and Carbon-Intensive Industries

- Energy efficiency technology pillar can achieve a significant reduction in energy consumption and corresponding energy-related CO2 emissions by reducing current typical energy intensities to state-of-the-art energy intensities.



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Summary of Select Studies on the Industrial Decarbonization through Energy Efficiency

Reference	Origin	Baseline Year	Target Year	Energy Savings	Emissions Reduction by Energy Efficiency Pillar	Savings Type	Sector	Pillars/Pathways Addressed
Nadel and Ungar, 2019	United States	2019	2050	6.25 quads (6.6 EJ)	244 MMT	Energy use/CO_2 emissions	Industrial	Energy efficiency
WSP et al., 2015	United Kingdom	2012	2050	—	23–59 MMT	CO_2 emissions	Industrial (energy-intensive)	Multiple pillars; energy efficiency contributing 12.8–23% reduction
ClimateWorks Australia, 2014	Australia	2010	2050	40%	—	Energy intensity	Industrial	Energy efficiency
European Commission, 2018	Europe	2015	2050	25%	259 MMT CO_2e (53% from baseline)	Energy use/CO_2 emissions	Industrial	Energy efficiency
Hasanbeigi et al., 2019	United States	2040 Business as usual	2040 advanced technology deployment	—	0.54 MMT CO_2 per year (5% from baseline)	CO_2 emissions	Cement	WHR to power and other emerging technologies and measures
McKane and Hasanbeigi, 2010, 2011	United States, Canada, European Union, Thailand, Vietnam, and Brazil	2008	—	173–234 TWh/year (28% to 38%)	—	Energy use	Industrial	Motor systems (pumping, compressed air, and fans)
Whitlock et al., 2020	United States		2050	—	15% from baseline	CO_2 emissions	Industrial	Multiple pillars considered
de Pee et al., 2018a	Global	2014	2050	—	15–20% from baseline	CO_2 emissions	Industrial	Multiple pillars considered

Source: Sundaramoorthy, S.; Kamath, D.; Nimbalkar, S.; Price, C.; Wenning, T.; Cresko, J. Energy Efficiency as a Foundational Technology Pillar for Industrial Decarbonization. Sustainability 2023, 15, 9487.

Specific Strategies for the Six Energy-Intensive Industries

Energy Efficiency Pillar	Iron and Steel	Chemical	Food and Beverage	Petroleum Refining	Pulp and Paper	Cement
Strategic energy management	Commitment, identification, and implementation of energy efficiency projects, tracking energy and carbon efficiency performance, ISO 50,001, and energy management information systems					
System efficiency	Process heating, compressed air, pumps, and fans	Steam, process heating and cooling, compressed air, pumps, and fans	Steam, process heating and cooling, compressed air, pumps, fans, non-thermal drying, and dewatering	Steam, process heating and cooling, compressed air, pumps, and fans	Steam, process heating and cooling, compressed air, pumps, fans, efficient dispersers, refiners, and grinders	Process heating, compressed air, pumps, and fans; efficient grinding technologies (e.g., high-pressure grinding rolls, vertical roller mills in place of ball mills
Materials and life cycle efficiency	Top pressure recovery turbine, coke dry quenching, BOF gas recovery, improving semi-manufacturing yields, scrap reduction of end-use goods by improved manufacturing techniques (e.g., AM)	Energy, system, and material efficiency (e.g., recycling and waste minimization)	Food waste reduction	Desulfurization using clean hydrogen; efficient use of low-carbon energy sources	Innovative drying techniques, increased use of recycled pulp, biogas production from effluent, and black liquor gasification	High-efficiency clinker cooling and grinding; innovative chemistry (blended cement and low-carbon binders), and clinker substitutes (fly ash, ground granulated BF slag, etc.) wastes (oils and solvents) as alternative fuels in kilns
Smart manufacturing	Shortened smelting time and enhanced smelting efficiency using automated detection of molten steel components, blowing controls, and component analysis; digital twin	Smart manufacturing using data mining and modeling to develop dynamic target values for energy consumption; digital twin	Automation and smart manufacturing (soft or virtual software sensors to augment physical data points and enable control of nonstandard process variables), and precise measurement/control of steam energy; digital twin	Digital twin	Automation and smart manufacturing, such as cleaner automation; digital twin	Upgraded cement process controls to lower firing temperatures and times; digital twin
Combined heat and power	Waste heat management (reduce, recover, and recycle)	Combined heat and power; waste heat to power	Waste heat recovery	Waste heat recovery	Waste heat recovery; combined heat and power	

Source: Sundaramoorthy, S.; Kamath, D.; Nimbalkar, S.; Price, C.; Wenning, T.; Cresko, J. Energy Efficiency as a Foundational Technology Pillar for Industrial Decarbonization. Sustainability 2023, 15, 9487.

RD&D Needs for Energy Efficiency

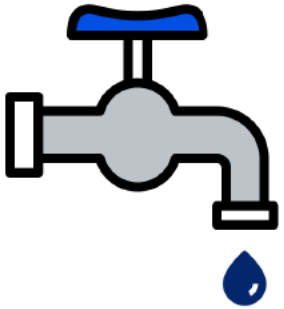
- To improve the efficiency of **process heating, steam, and motor systems** – the largest end-uses of energy in the industrial sector.
- **Smart manufacturing and advanced data analytics** to unlock energy efficiency opportunities at every level of system integration: equipment, facility, and supply chain.

- Research to address **big data challenges** related to data quality, storage, and computing; **advanced analytical tools** are needed to process the data and improve cybersecurity.
- Demonstrations of **plant automation systems** that provide real-time energy performance data.
- **Data integration to facilitate utility efficiency programs** that reward manufacturers for energy saved rather than equipment installed.

DOE's Better Plants Program

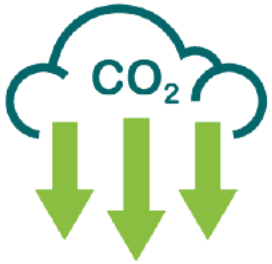
- The Better Plants Program partners with leading manufacturers and water utilities to **improve energy efficiency and competitiveness in the industrial sector, saving money in the process**.
- Through Better Plants, partners voluntarily set a specific goal, typically to reduce energy intensity by **25% over a 10-year period** across all their U.S. operations.

Increased Energy Productivity



Water Savings

Waste Reduction



Carbon Reduction

All Better Plants Partners

Better Plants®
U.S. DEPARTMENT OF ENERGY

U.S. DEPARTMENT OF ENERGY

Better Climate Challenge

Better Climate CHALLENGE
U.S. DEPARTMENT OF ENERGY

Portfolio-wide reduction in GHG emissions of *at least* 50% in 10 years

- Reduction includes Scope 1 & 2 emissions
- RECs allowed; No offsets
- Baseline up to 5-years back from join date
- Encouraged to establish an absolute target, but intensity-based targets will be accepted
- Pursue an energy efficiency target that will contribute towards the 50% emissions reduction. This target is intended to encourage prioritizing energy efficiency when pursuing a decarbonization plan.
- Goals less than 50% will be considered for energy-intensive sectors

Better Climate Challenge – Industrial Partners

Why Companies Join Better Plants or Better Climate Challenge

Industry Leadership

Developing Innovative, Replicable Solutions with Market Leaders

- National Recognition
- Peer to Peer Networking
- Better Building Solutions Center

Technical Assistance Resources

Making Energy Efficient Investments Easier

- Tools for Energy & Carbon Management
- Financing Navigator
- Diagnostic Equipment Program

Emerging Technologies

Innovation to Drive Savings

- DOE National Labs
- Advanced Technology Field Validation

Workforce Development

Helping You Meet Your Challenges of Today, and Tomorrow

- In-Plant Trainings
- Fundamentals of Energy Management and Decarbonization Trainings
- Industrial Assessment Centers

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Questions

Sachin Nimbalkar, PhD

Email: nimbalkarsu@ornl.gov

Phone: 865.576.3590

Energy Efficiency as a Foundational Technology Pillar

Energy efficiency is the foundational, cross-cutting decarbonization strategy—and remains the most cost-effective option for GHG reductions.

Pillar 1

97% of industrial sector CO_2 emissions (and 63% of GHG emissions overall) are associated with fossil fuel combustion for energy, with a majority attributed to process heating, steam, and motor-driven systems.

Process Heating and Steam	Motor-Driven Systems	Process Cooling	Electro-Chemical Processing	Other Process Uses	Non-Process Uses
42% of industrial combustion emissions	**28%** of industrial combustion emissions	**4%** of industrial combustion emissions	**4%** of industrial combustion emissions	**7%** of industrial combustion emissions	**15%** of industrial combustion emissions

Data sources: U.S. EPA *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2019*; DOE *Manufacturing Energy and Carbon Footprint*, based on EIA Manufacturing Energy Consumption Survey (MECS) data for 2014.

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Source: Industrial Decarbonization Roadmap; DOE/EE-2635; United States Department of Energy: Washington, DC, USA, 2022.