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U.S. Industrial and Commercial Motor System Energy Consumption and Cost-Effective Savings

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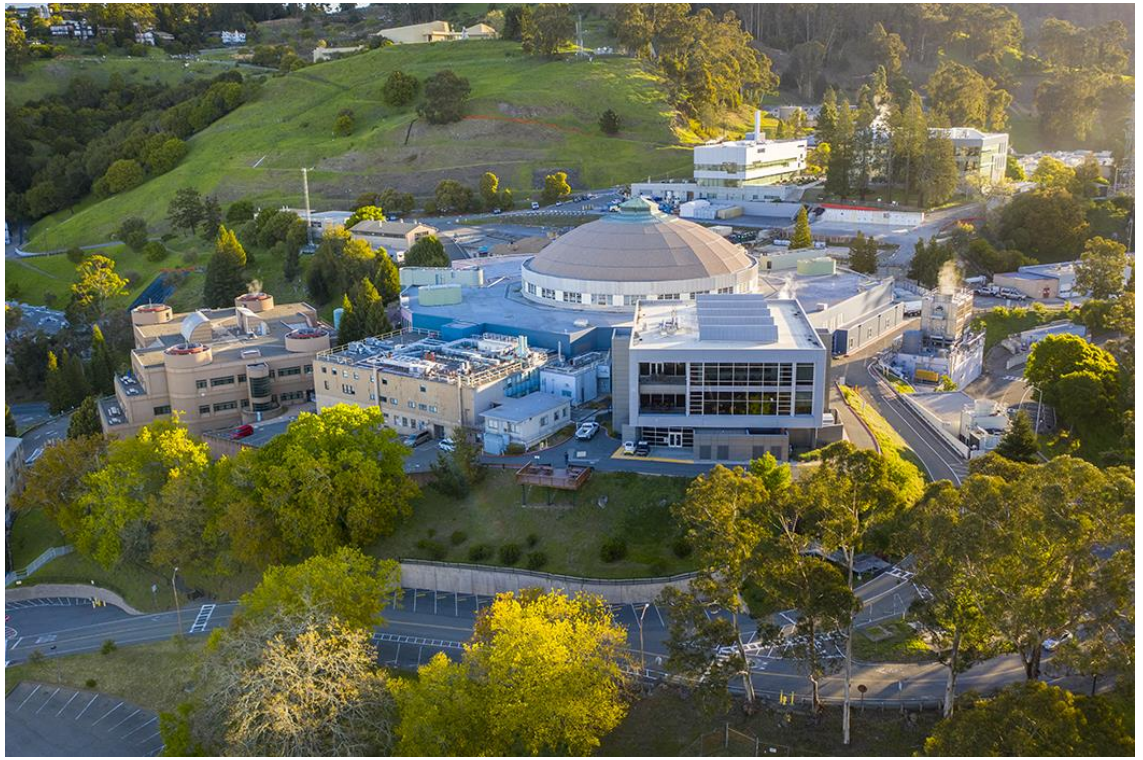
Outline

- Overview of U.S. Motor System Market Assessment
- Findings on installed based of U.S. industrial and commercial motor systems
- Analysis of energy efficiency technical potential



Project team

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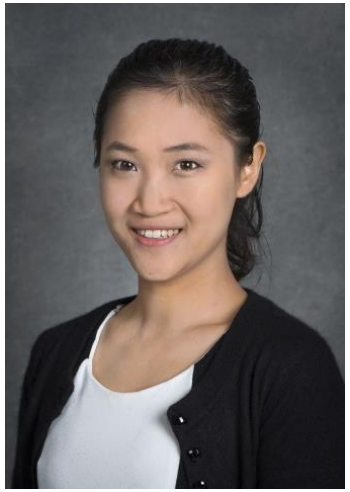

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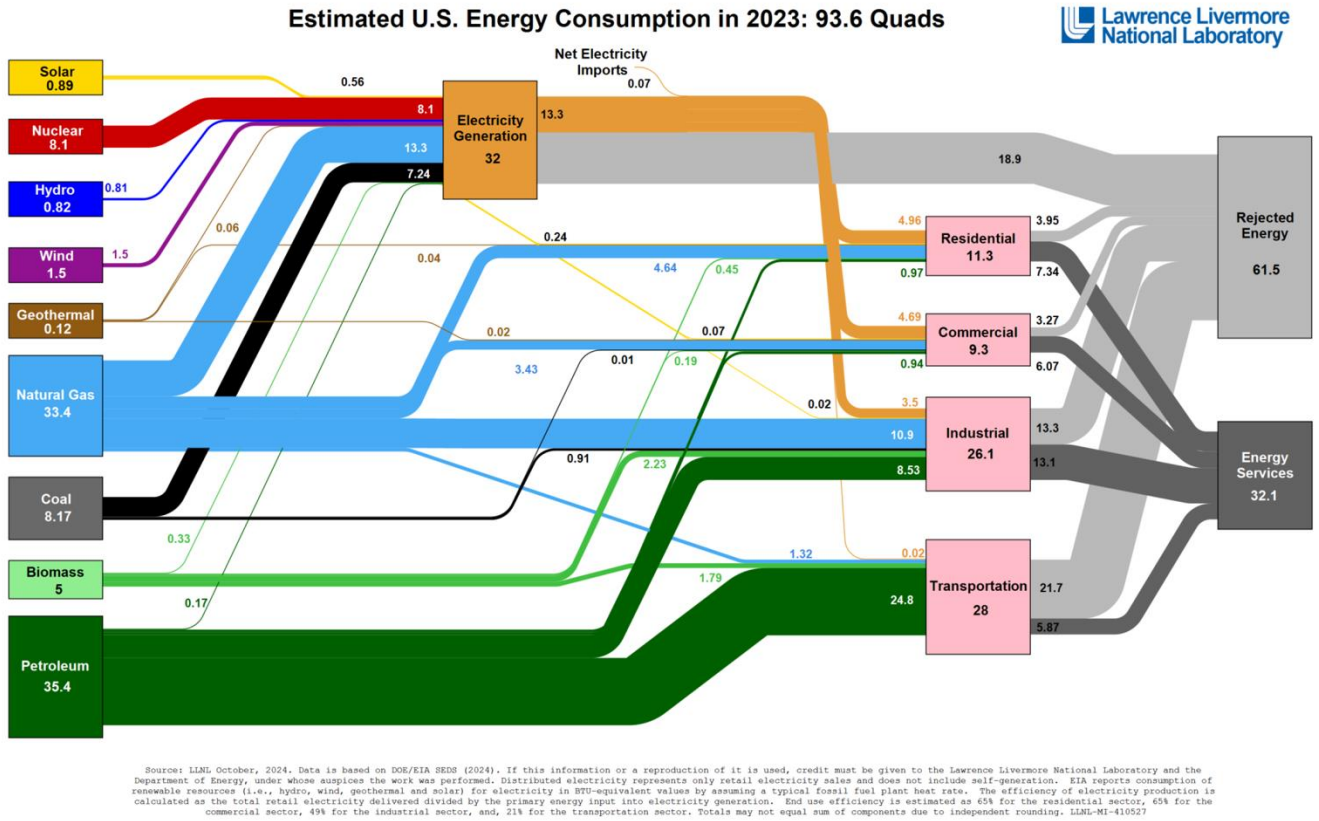
Terms of note

- Industrial – manufacturing, e.g., steel making, chemical production, semiconductor manufacturing, and municipal wastewater treatment facilities
- Commercial – non-residential buildings, e.g., hospitals, schools, office buildings
- Horsepower – unit of power in the imperial system equivalent to 0.746 kW
- Premium Efficiency – motor efficiency class equivalent to IE3
- Variable Frequency Drive (VFD) - electronic motor speed control
- Load factor – percent of full load of the end use demand

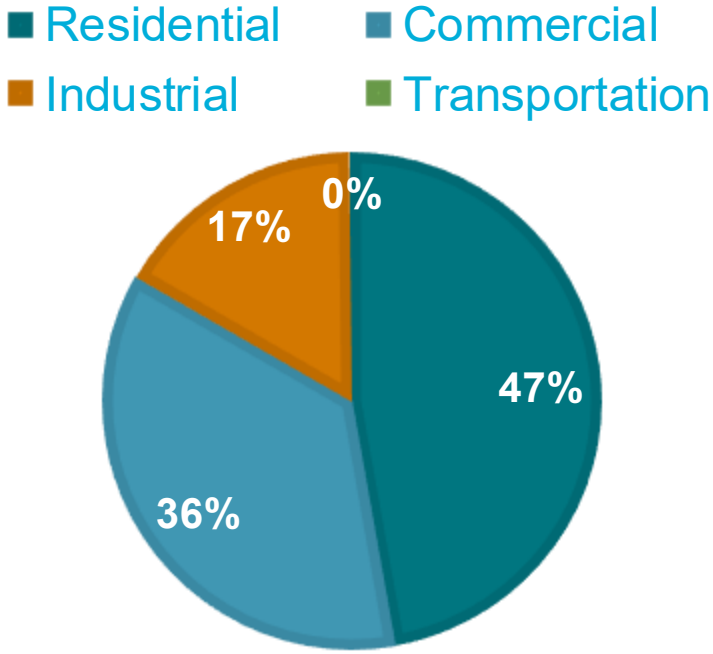
Electricity in the U.S. energy economy

Reducing electricity consumption is key to reducing energy costs in U.S. industrial and commercial facilities



Electricity generation accounted for 34% of U.S. energy consumption with 30% going to industrial and commercial facilities in 2023. Source: Lawrence Livermore National Laboratory

ELECTRICITY SALES BY SECTOR (2023)



Total electricity sales in the US in 2023 was $491B with industrial and commercial facilities bearing 53% of these costs, or $260B. Source: US DOE EIA

Introduction to Motor System Market Assessment

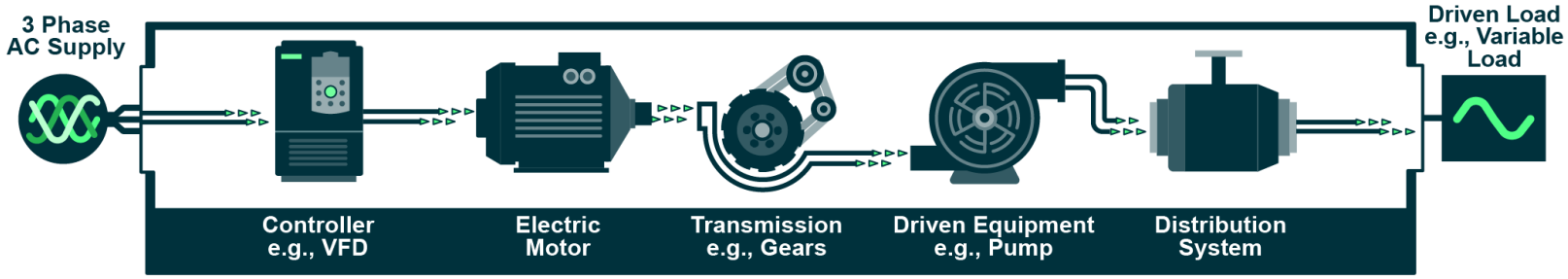
- In 1998, USDOE published a comprehensive assessment of industrial motors and motor-driven systems, based on an extensive survey conducted in 1997
- In 1999, DOE published a similar but less comprehensive assessment of commercial motors and drives.
- "United States Industrial Electric Motor Systems Market Opportunities Assessment" (1998 Assessment) led to a greater understanding of:
  - the energy consumption, efficiency opportunities for motors and motor driven systems, and
  - the market uptake of technologies designed to address these opportunities
- Since then, motor-driven system energy efficiency has improved and markets have changed

Motor System Market Assessment

- A new study was performed to more fully understand the additional opportunities for energy efficiency improvement
- New assessment looked at both the industrial and commercial sectors
- Statistically valid information on:
  - What's installed
  - Operating characteristics (e.g., load factor, operating hours)
  - Maintenance, procurement, and design practices
- Can inform:
  - Strategies for reducing electricity costs associated with motor systems
  - Development of new technologies for motor driven systems
  - Design of new utility and/or government programs to promote energy savings
  - Development of new software and literature tools on best practices for motor driven systems
- Study completed in 2023 with data acquisition completed in 2019

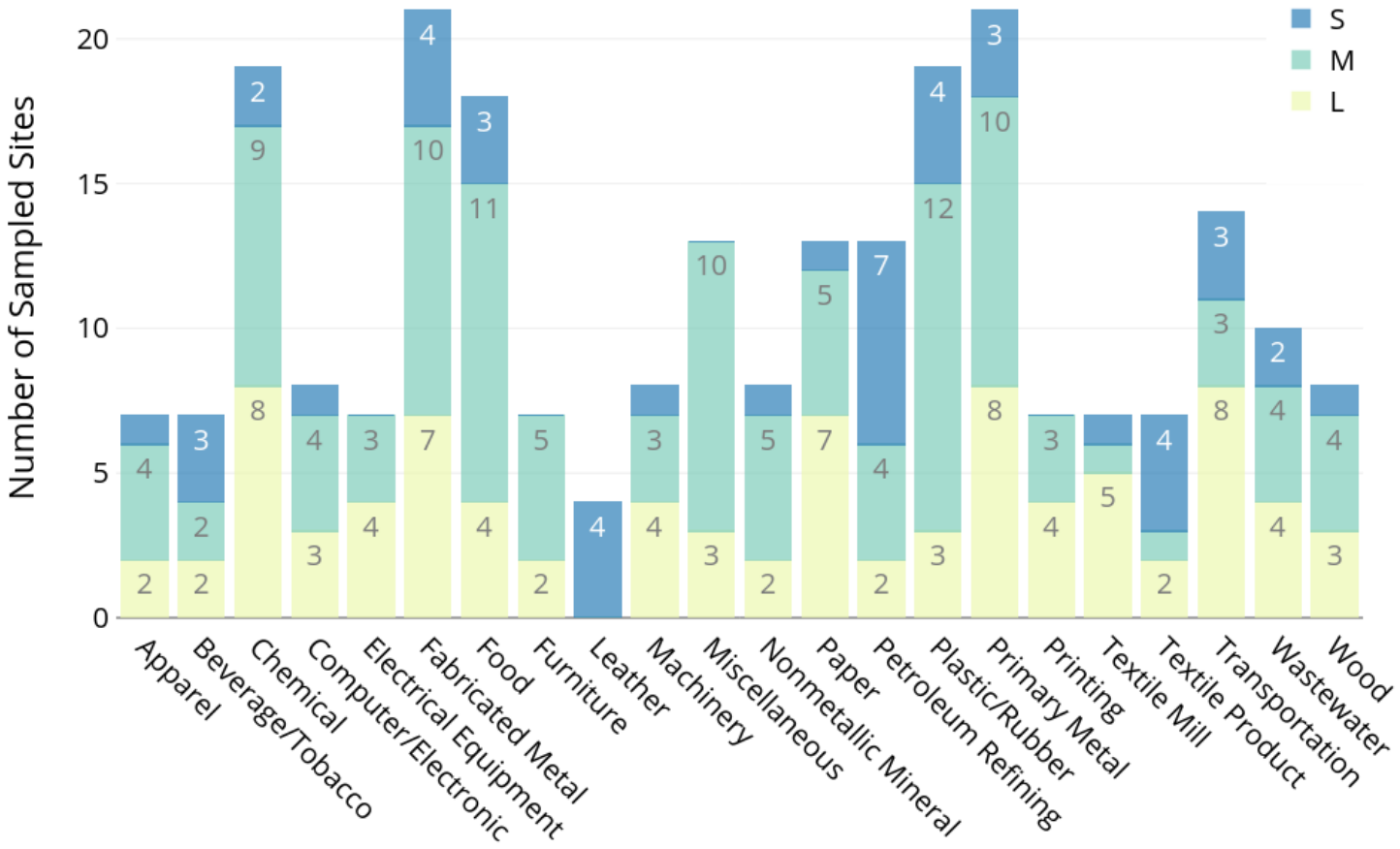
Motor systems considered

- Motor systems driven by a polyphase motor 1 horsepower or greater
- Large (>50 hp) DC motors
- All motor systems considered
  - Pumping
  - Fan
  - Compressed air
  - Refrigeration
  - Materials handling and processing
  - General purpose
- “System” includes: Drive and controller, motor, power transmission, motor driven equipment, distribution system



Sample allocation: industrial

246 assessments to statistically sample ~185,000 manufacturing and wastewater facilities

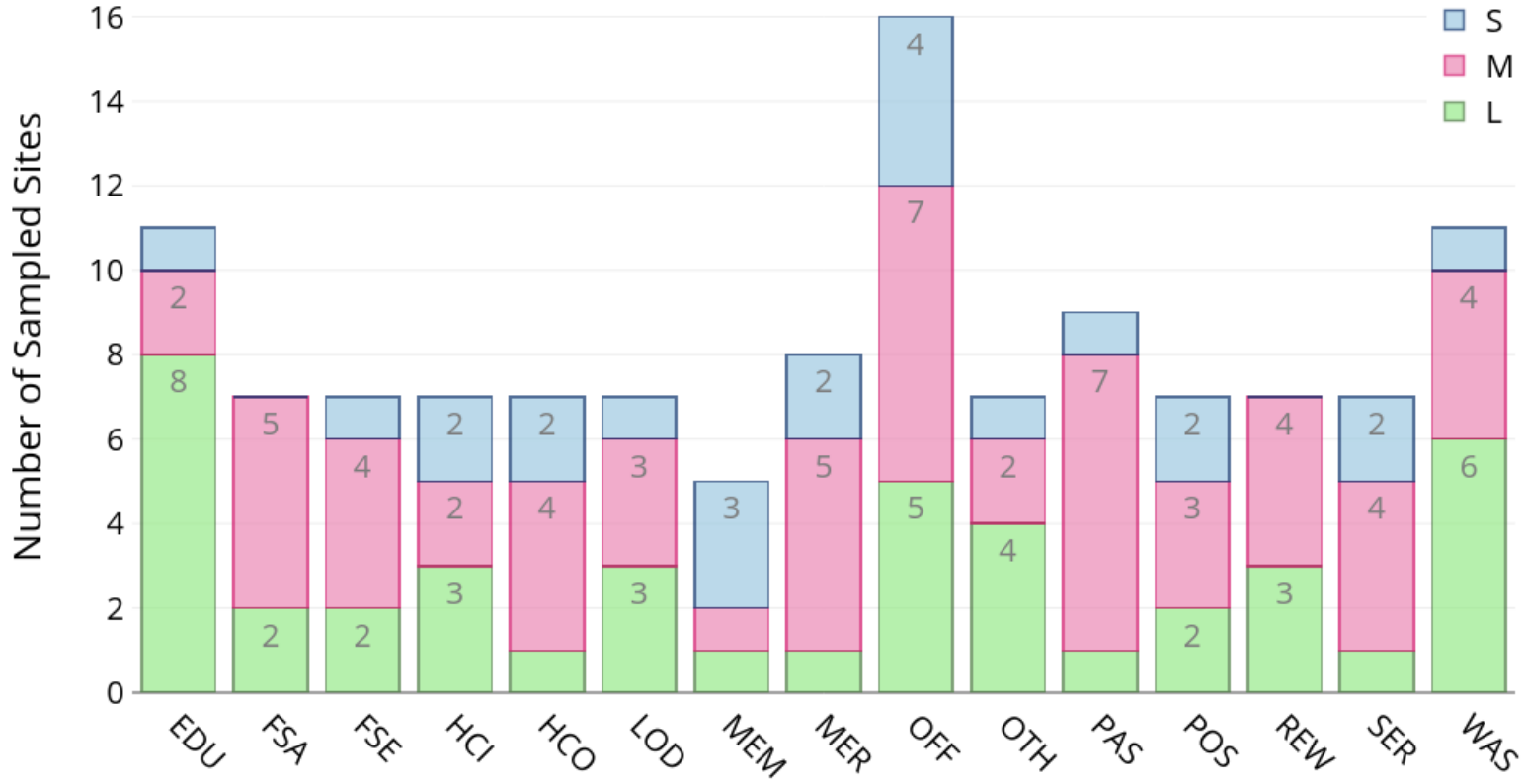


Sector	Total in U.S.
Wastewater	14,780
Food	13,271
Wood	7,727
Printing	15,313
Chemicals	8,289
Plastics & Rubber	8,268
Nonmetallic Minerals	11,997
Fabricated Metals	32,368
Machinery	14,370
Computers & Electronics	6,685
Transportation Equip.	6,270
Furniture	8,258
Misc.	13,495

Beverage, Textile Mills, Textile Product, Apparel, Leather, Paper, Petroleum Refining, Primary Metals, Electrical Equip.: all under 5,000 facilities

Sample allocation: commercial

~123 assessments to statistically sample ~5.5M commercial buildings



EDU- Education	LOD - Lodging (includes Nursing)	POS - Public Order and Safety
FSA - Food Sales	MEM - Mercantile: Retail (other than mall)	REW - Religious Worship
FSE - Food Services	MER - Mercantile: Enclosed and Strip Malls	SER - Service
HCI - Health Care: Inpatient	OFF - Office	WAS - Warehouse and Storage
HCO -Health Care: Outpatient	PAS - Public Assembly	OTH - Other and Vacant

Sector	U.S. total
EDU	388,659
FSA	176,739
FSE	379,711
HCI	9,579
HCO	147,155
LOD	157,924
MER	438,261
MEM	164,065
OFF	1,012,373
OTH	420,806
PAS	352,014
POS	83,841
REW	411,799
SER	618,544
WAS	795,668

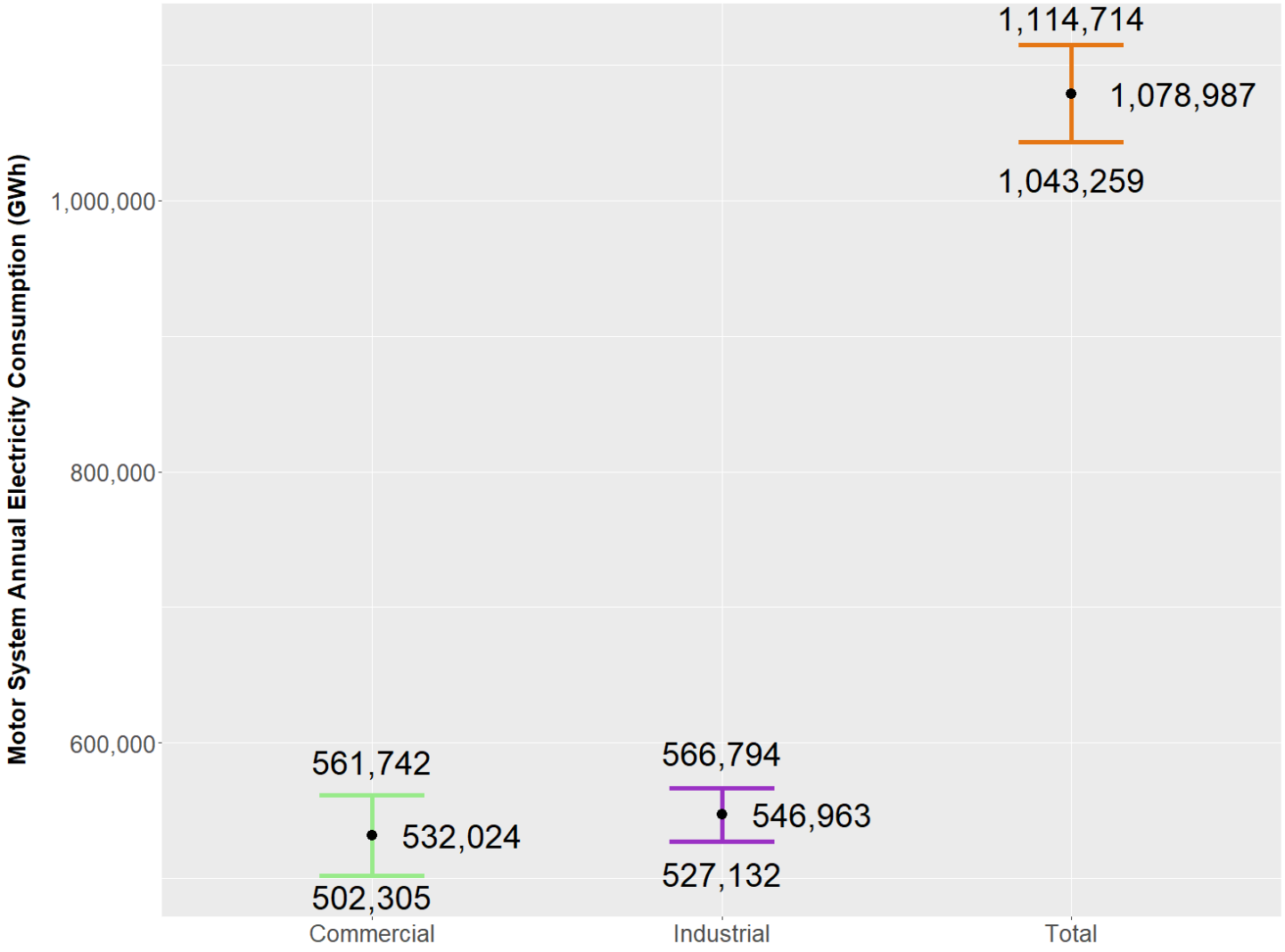
Field assessments

- General Information:
  - Collect information to place within the right context for statistical roll-up
  - Facility address, POCs, sector, annual electricity and energy consumption, # of employees, sq. ft.
- Motor System Inventory
  - Inventory the installed base of motor systems
  - Information collected for each motor: nameplate, operating hours, typical load factor, ASD type, transmission type, driven equipment served, high-level motor repair history

Field assessments

- System Checklists
  - For large (>20 hp and >2000 hrs) compressed air, fan, pump, and refrigeration systems, collect additional information to determine improvement opportunities
  - Type of driven equipment, rated output, load factor information including controls information, additional ancillary equipment, maintenance and procurement considerations/history
- Site Survey
  - Collect information related to facility motor system maintenance and management practices
  - Energy management practices, use of energy efficiency assessments, motor maintenance practices, evaluation of distribution systems, inspection practices

Installed motor system energy consumption



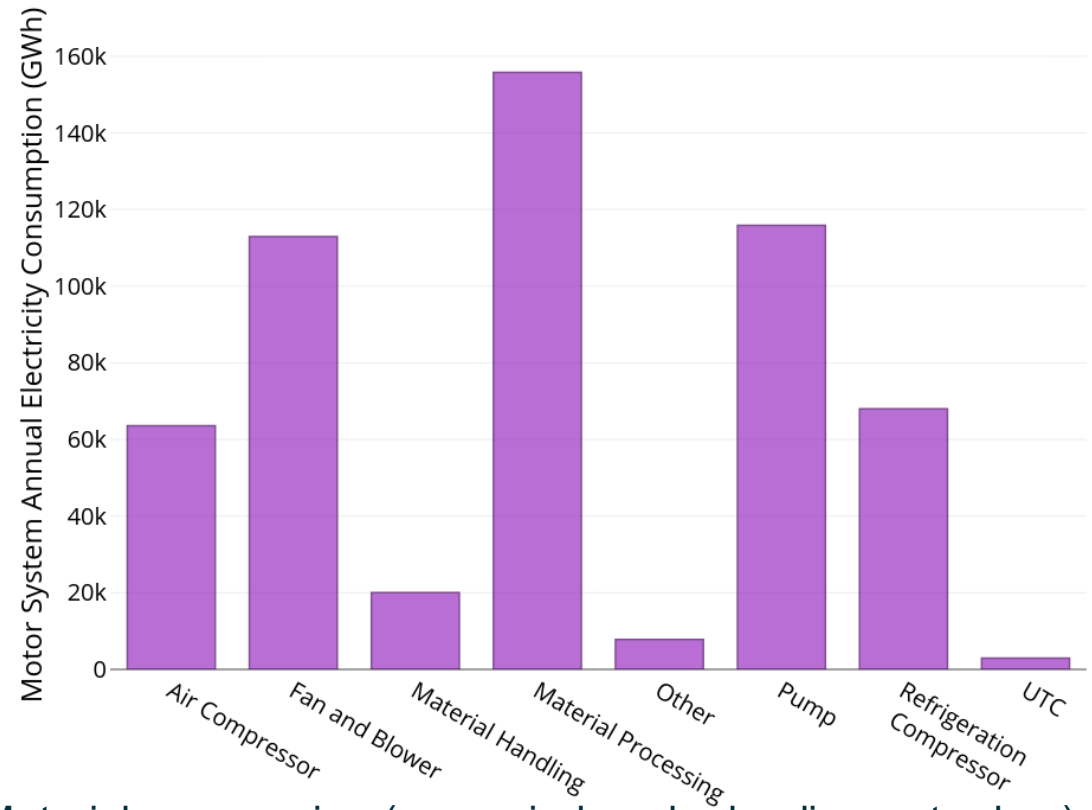
- ***29% of the overall electric grid*** load in the U.S.
- **$116B per year** in electricity costs
- Industrial sector: 69% of its electricity consumption, 13% of its overall energy consumption, 18% of its energy-related emissions, $47B/yr in electricity costs
- Commercial sector: 43% of its electricity consumption, 26% of its overall energy consumption, 28% of its energy-related emissions, $69B/yr in electricity costs
- 9% of all energy-related CO_2 emissions in the U.S.

Energy consumption and costs by driven equipment system

Driven equipment system	Energy (GWh/yr)	Cost ($M/yr)	CO_2 emissions (MMT/yr)
Refrigeration	319,529	38,615	227
Fans	305,027	34,797	216
Pumps	168,775	16,959	120
Materials processing	157,332	13,754	112
Compressed air	76,177	7,167	54
Materials handling	29,280	2,947	21

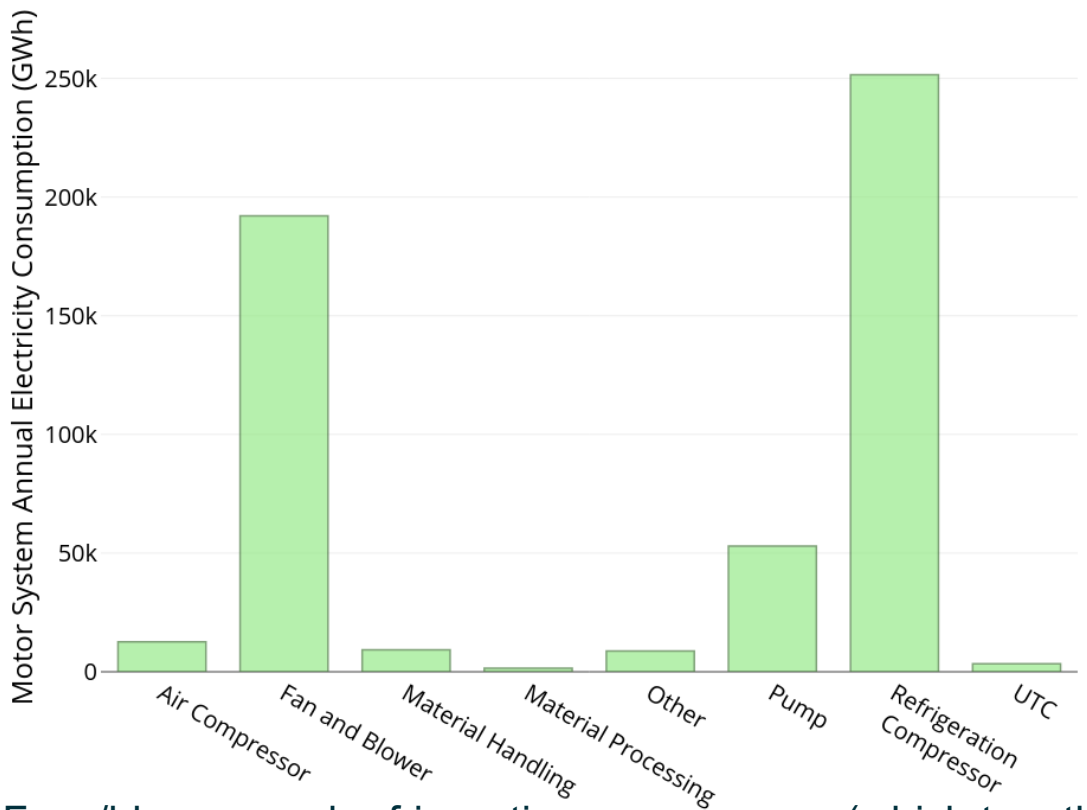
Energy consumption by driven equipment system

Industrial



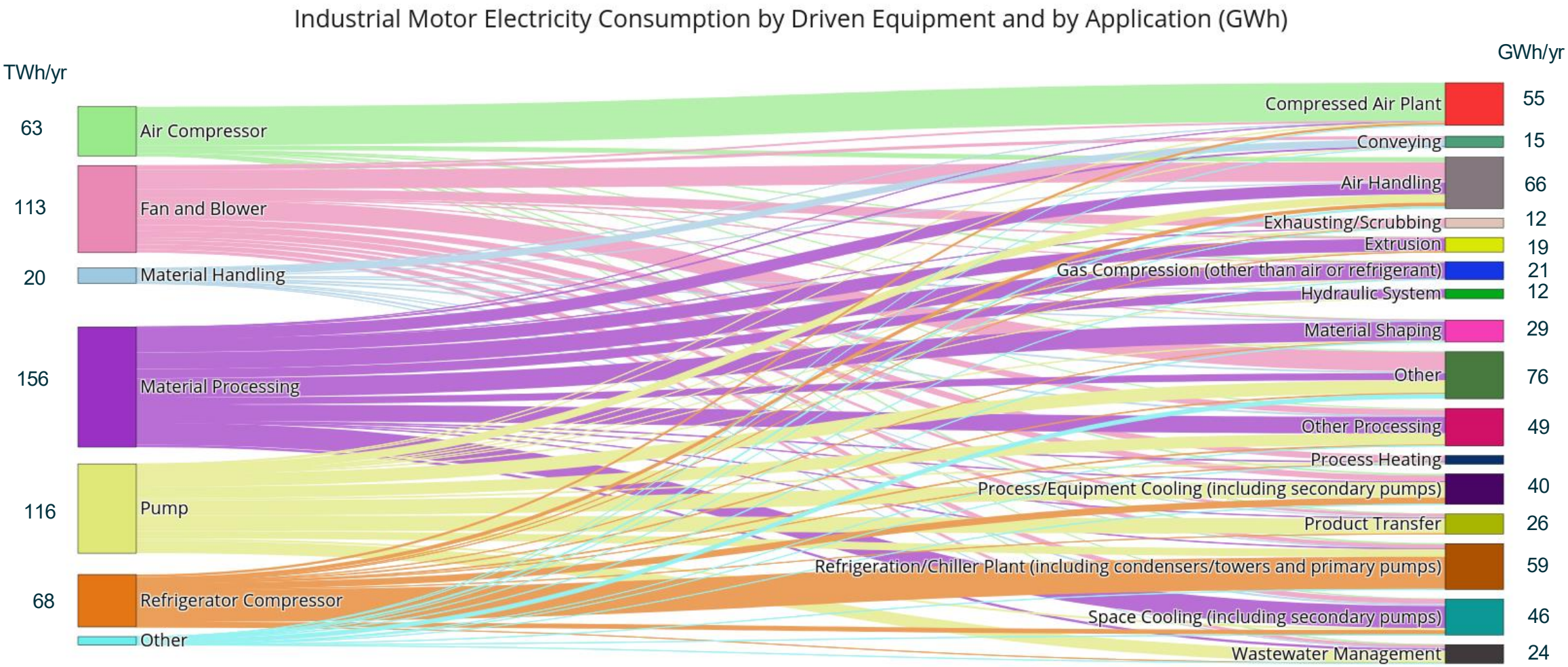
Materials processing (e.g., grinders, hydraulics, extruders) account for more electricity consumption than any other motor driven system in industry, followed by fans/blowers and pumps

Commercial

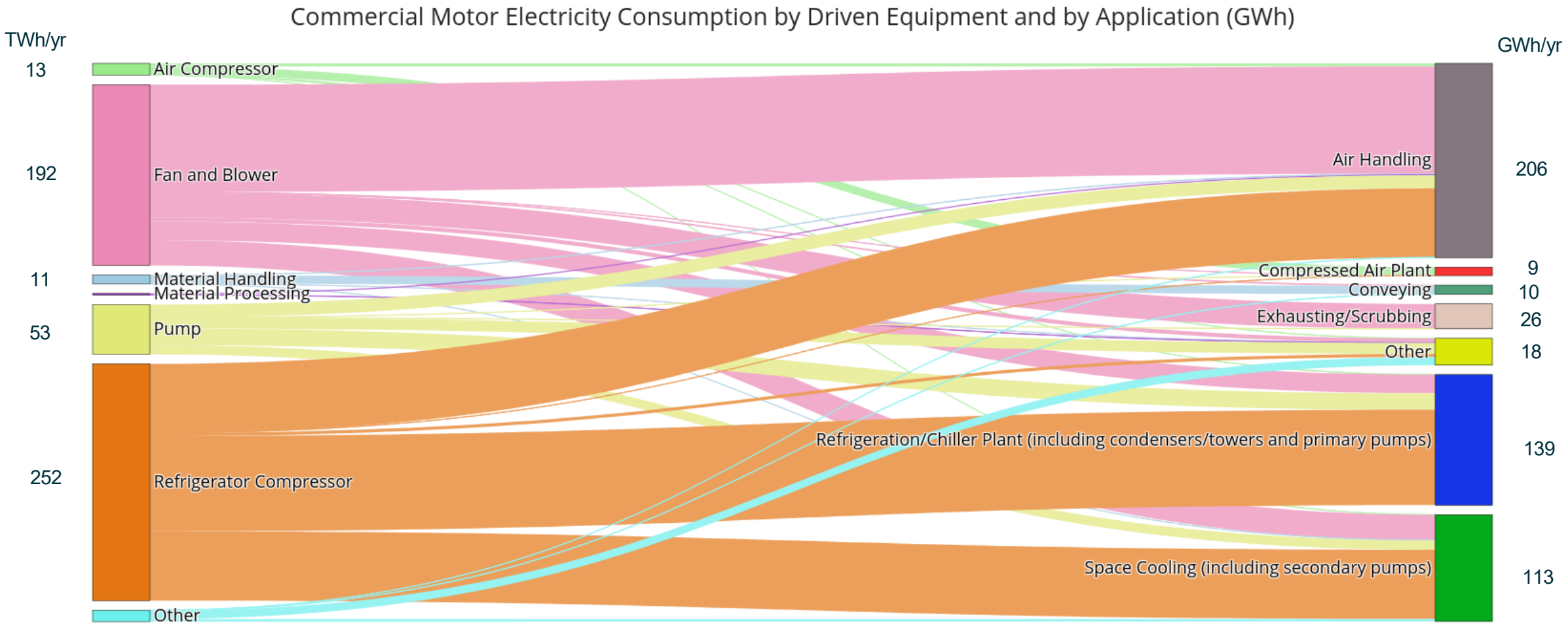


Fans/blowers and refrigeration compressors (which together comprise the core components of an HVAC system) account for more electricity consumption than any other motor driven system in the commercial sector

How motor systems are used in industry

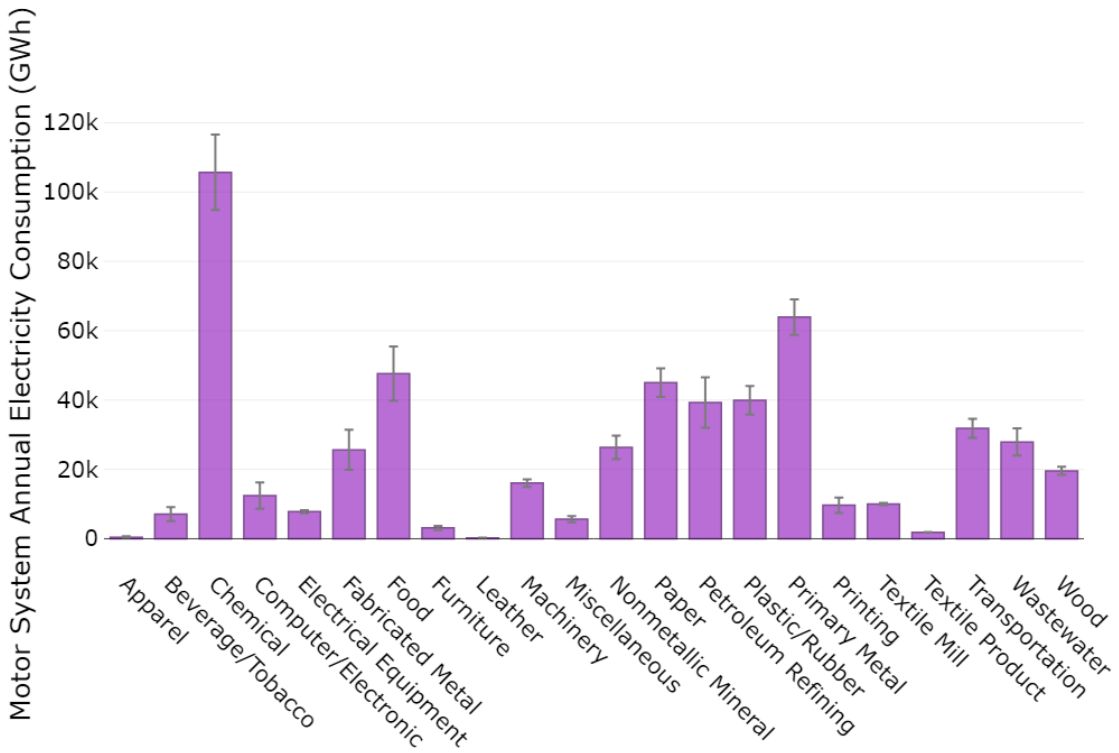


How motor systems are used in commercial



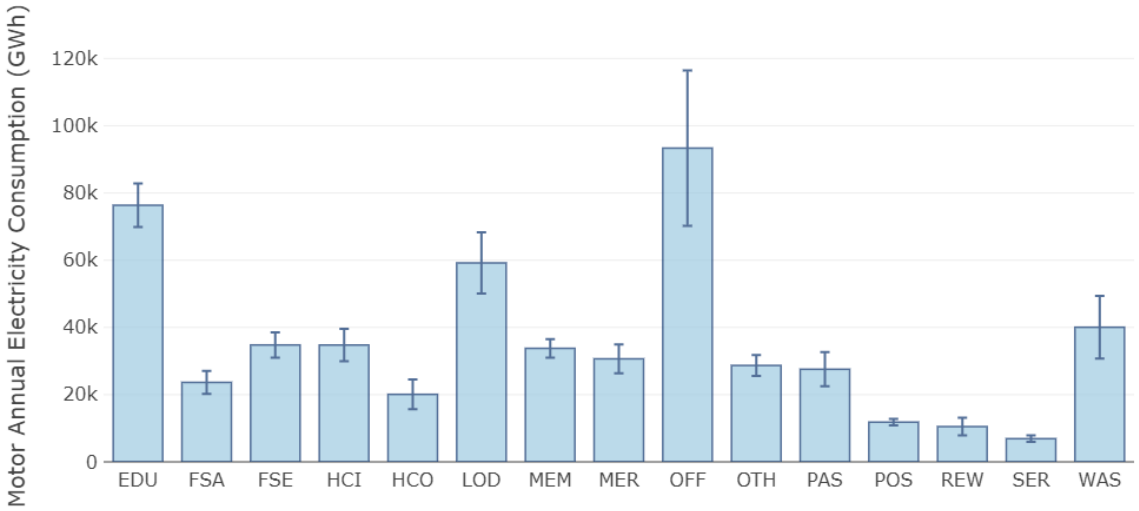
Motor system energy consumption by subsector

Industrial



Top 3 industrial subsectors: Chemical, Primary Metals, and Food

Commercial



Top 3 commercial subsectors: Office, Education, and Lodging

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FSE - Food Services	MER - Mercantile: Enclosed and Strip Malls	SER - Service
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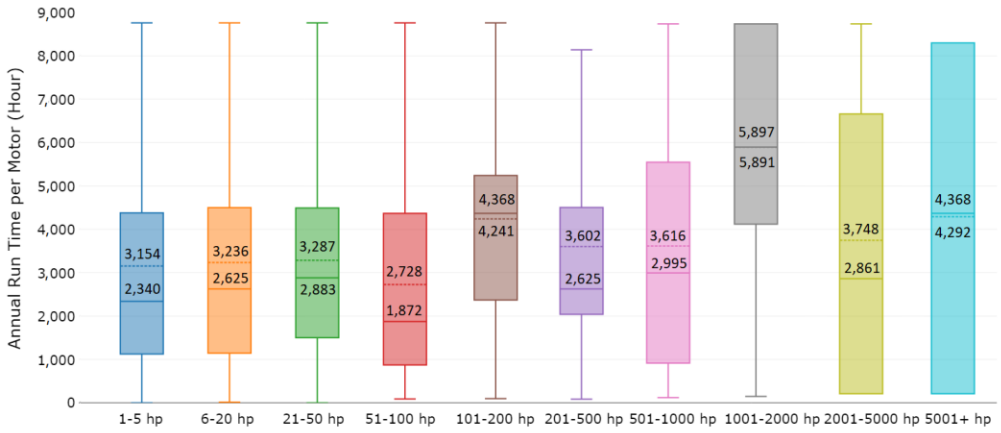
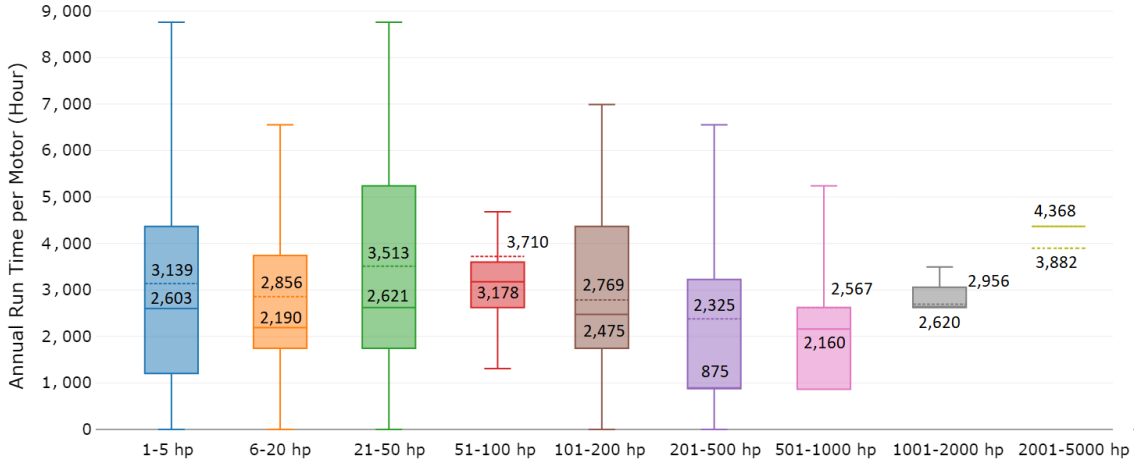
Operating hours

Industrial



~3200 operational hours per year with larger motor systems running longer

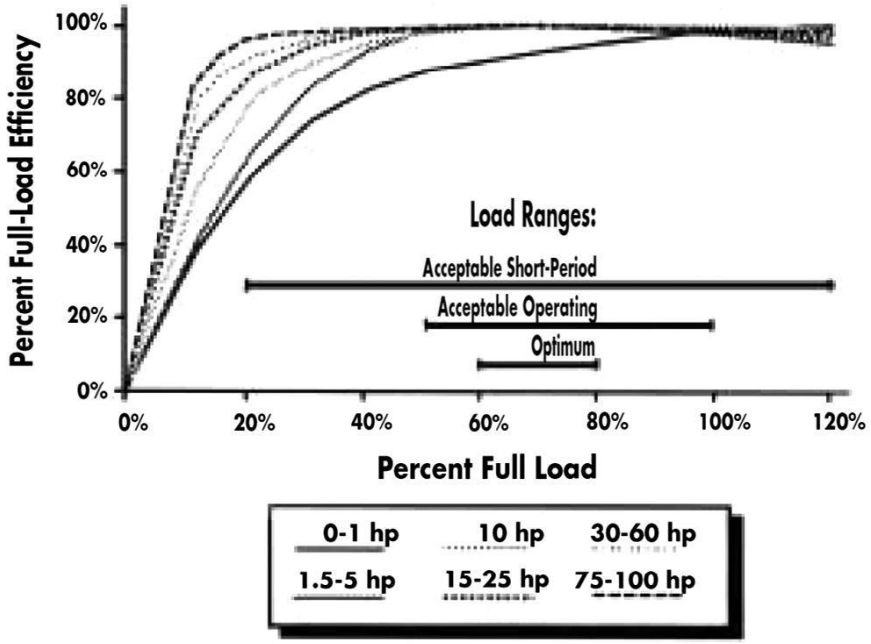
Commercial

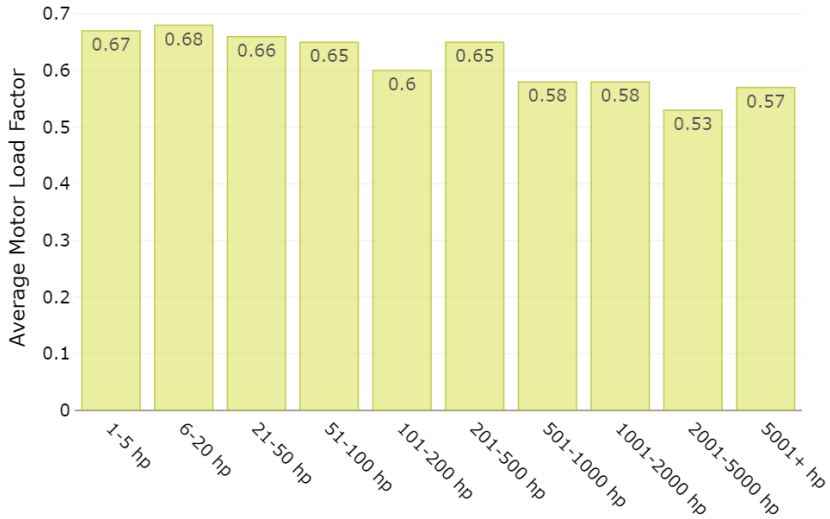


~3000 operational hours per year across all sizes

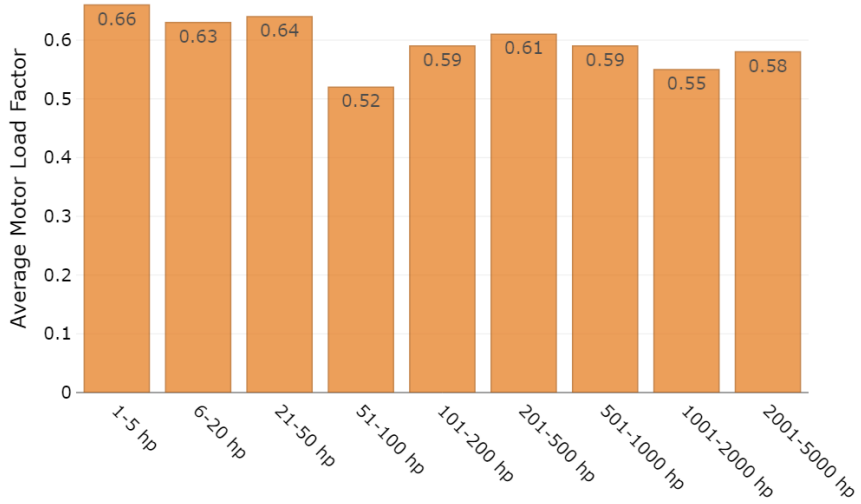
Load factor

Across all motor sizes, large motors tends to be more underloaded than small motors





Industrial



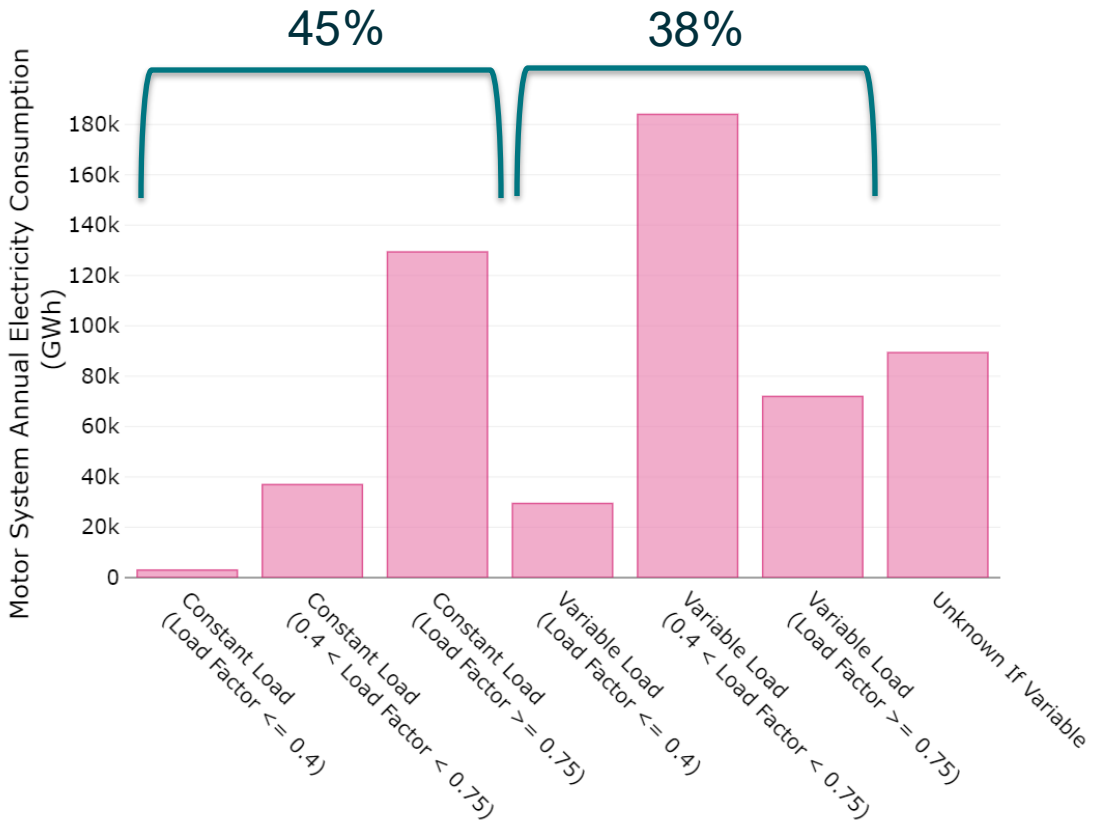
Commercial

Source: Li et al. 2015. A novel method to determine the motor efficiency under variable speed operations and partial load conditions. Applied Energy.

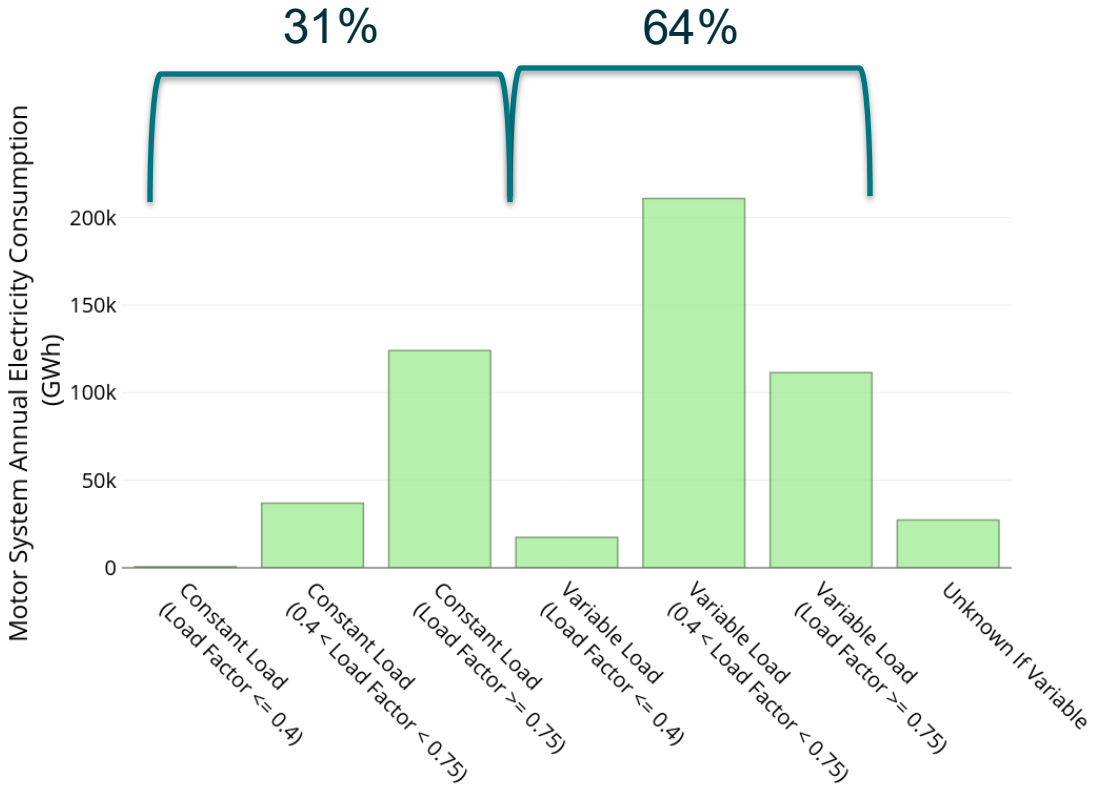
Load variability

Variability of load an indicator of motor system energy consumption

Industrial



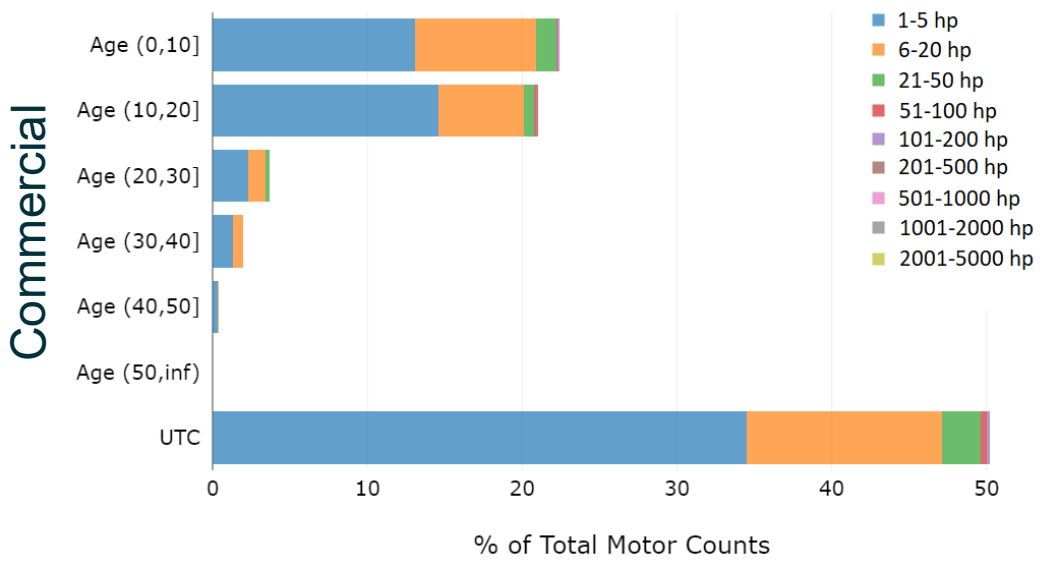
Commercial

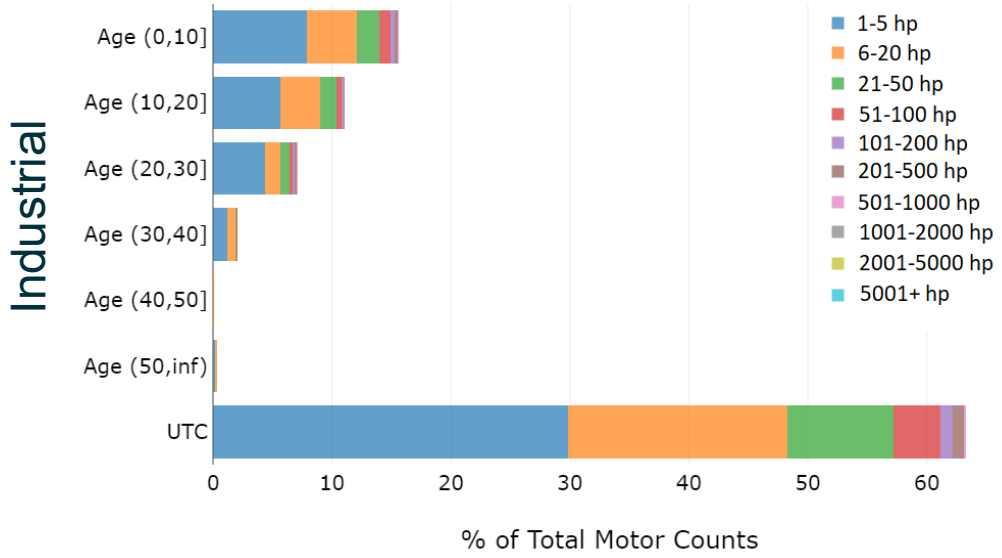


Energy losses in motor systems

- At each component
  - Drive/controller (ex: losses across drive)
  - Motor losses (ex: **inefficient motor**, over rewind, very low load factor)
  - Transmission (ex: slippage, friction)
  - Driven equipment (ex: improper maintenance, improper set points, improper sequencing)
  - Distribution (ex: poor design, **poor condition**)
- Across the whole system
  - **Inefficiently meeting demand**
  - Inappropriate use

Upgrading the motor – current situation





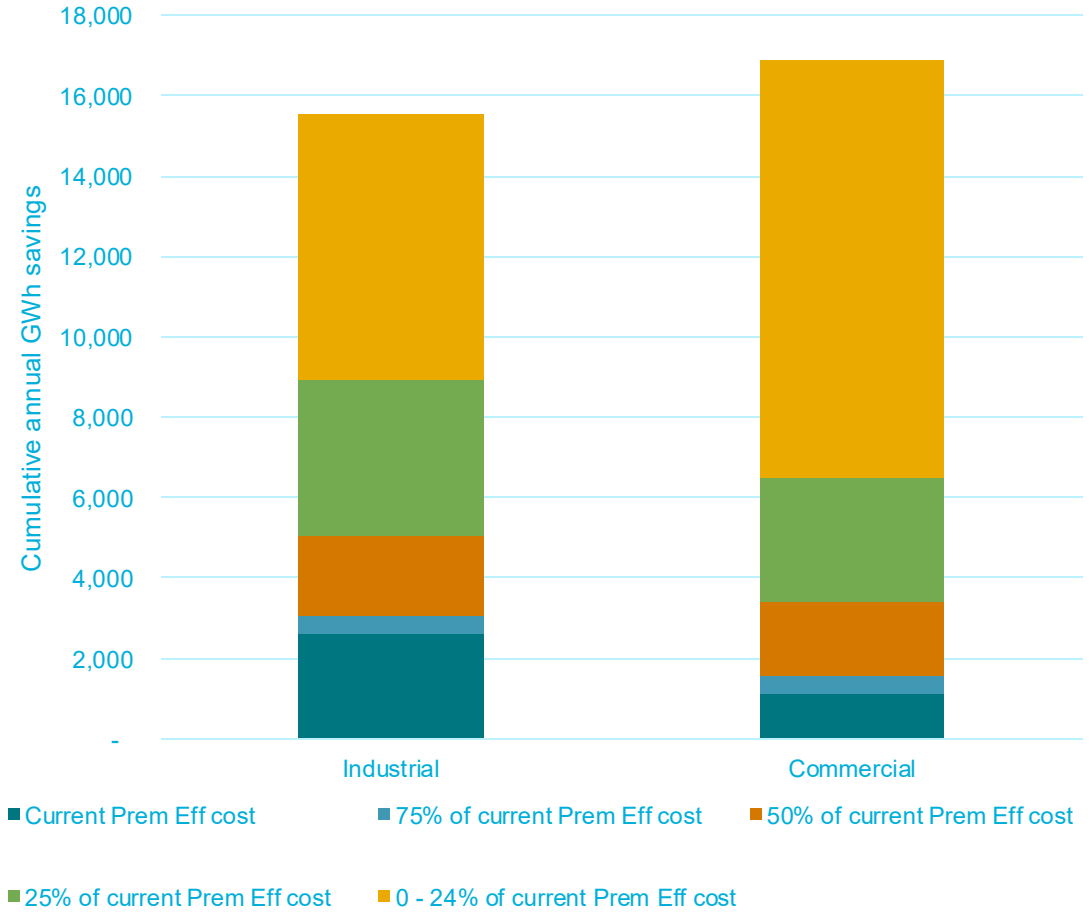
Sector	Motor size (hp)	Average efficiency of installed base	Premium Efficiency/IE 3 performance level
COM	[1.0, 6.0)	82%	85.5% – 89.5%
	[6.0, 21.0)	89%	89.5% - 93%
	[21.0, 51.0)	91%	93% - 94.5%
	[51.0, 101.0)	92%	94.5% - 95.4%
	[101.0, 201.0)	93%	95.4% - 95.8%
	[201.0, 501.0)	94%	95.8% - 96.2%
	[501.0, 1001.0)	94%	-
	[1001.0, 2001.0)	95%	-
	[2001.0, 5001.0)	95%	-
IND	[1.0, 6.0)	83%	85.5% – 89.5%
	[6.0, 21.0)	89%	89.5% - 93%
	[21.0, 51.0)	92%	93% - 94.5%
	[51.0, 101.0)	93%	94.5% - 95.4%
	[101.0, 201.0)	93%	95.4% - 95.8%
	[201.0, 501.0)	93%	95.8% - 96.2%
	[501.0, 1001.0)	93%	-
	[1001.0, 2001.0)	92%	-
	[2001.0, 5001.0)	86%	-
	[5001.0, inf)	91%	-

Savings from upgrading to Premium Efficiency/IE3

	Electricity savings (GWh/yr)	% of motor system consumption	Cost savings ($M/yr)	CO_2 savings (MMT/yr)
Industrial	15,571	3%	1,308	11
Commercial	16,877	3%	2,278	12
Total	32,448	3%	3,586	23

Cost effective early retirement of motors

US Dept. of Energy regulation went into effect in 2016 requiring most new 1-500 hp motors purchased meet Premium Efficiency standards.

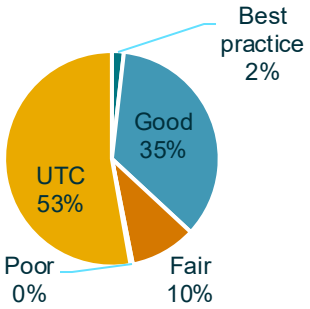


	Industrial (GWh/yr)	Commercial (GWh/yr)
At current Prem. Eff. cost	2,620	1,130
75% of current Prem. Eff. cost	418	426
50% of current Prem. Eff. cost	1,997	1,835
25% of current Prem. Eff. cost	3,905	3,089
0-24% of current Prem. Eff. cost	6,632	10,396
Total	15,571	16,877

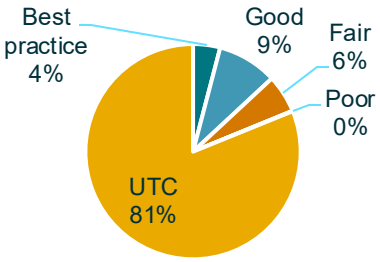
Improving condition of distribution systems

Grade	Characteristic
Best practice	No leaks; superior maintenance practices; compressed air is dry
Good	Minimal leaks; sufficient maintenance practices; compressed air mostly dry
Fair	Some leaks; improvements needed to maintenance practices; moisture in compressed air
Poor	Rampant leaks; no evidence of maintenance practices; compressed air not dried

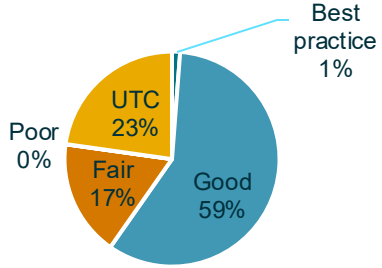
Industrial Pump Systems



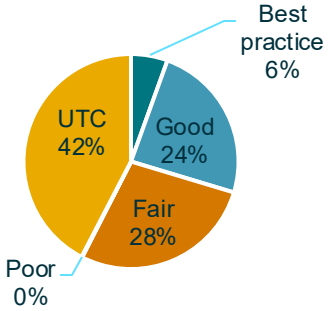
Commercial Pump Systems



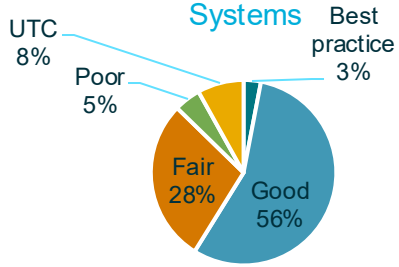
Industrial Air Ducts



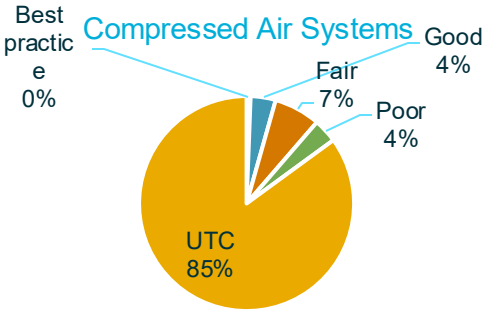
Commercial Air Ducts



Industrial Compressed Air Systems



Compressed Air Systems



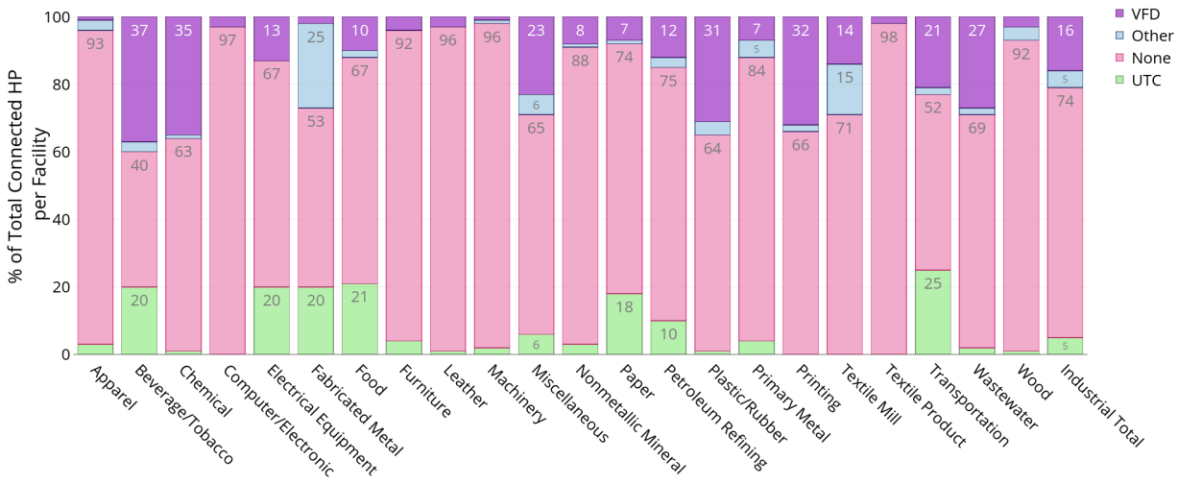
Improving condition of distribution systems

	Annual Savings from Upgrading from Current Condition to a Best Practice Level	Industrial	Commercial
Compressed Air Systems (8% loss)	Electricity consumption savings (GWh)	10,751	1,877
	CO_2 emission reduction (MMT)	7.6	1.3
	Electricity cost savings (million $)	907	253
Pump Systems (5% loss)	Electricity consumption savings (GWh)	4,431	1,504
	CO_2 emission reduction (MMT)	3.1	1.1
	Electricity cost savings (million $)	374	203
Fan Systems (5% loss)	Electricity consumption savings (GWh)	8,959	12,935
	CO_2 emission reduction (MMT)	6.4	9.2
	Electricity cost savings (million $)	756	1,746
Total	Electricity consumption savings (GWh)	24,141	16,316
	% of motor system electricity consumption	4%	3%
	CO_2 emission reduction (MMT)	17.1	11.6
	Electricity cost savings (million $)	2,037	2,202

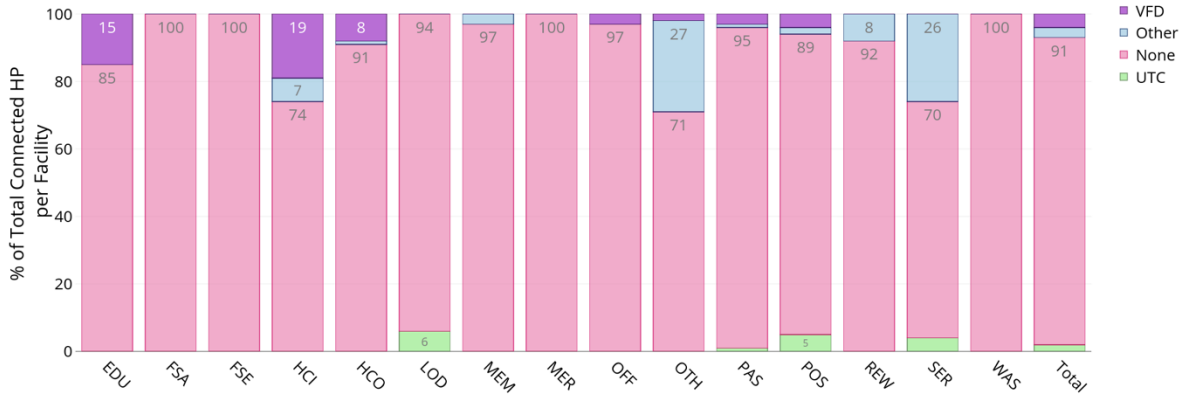
Current load matching techniques

Low VFD uptake with particularly low uptake in the commercial sector

Industrial ~ 16% VFD uptake



Commercial ~ 4% VFD uptake



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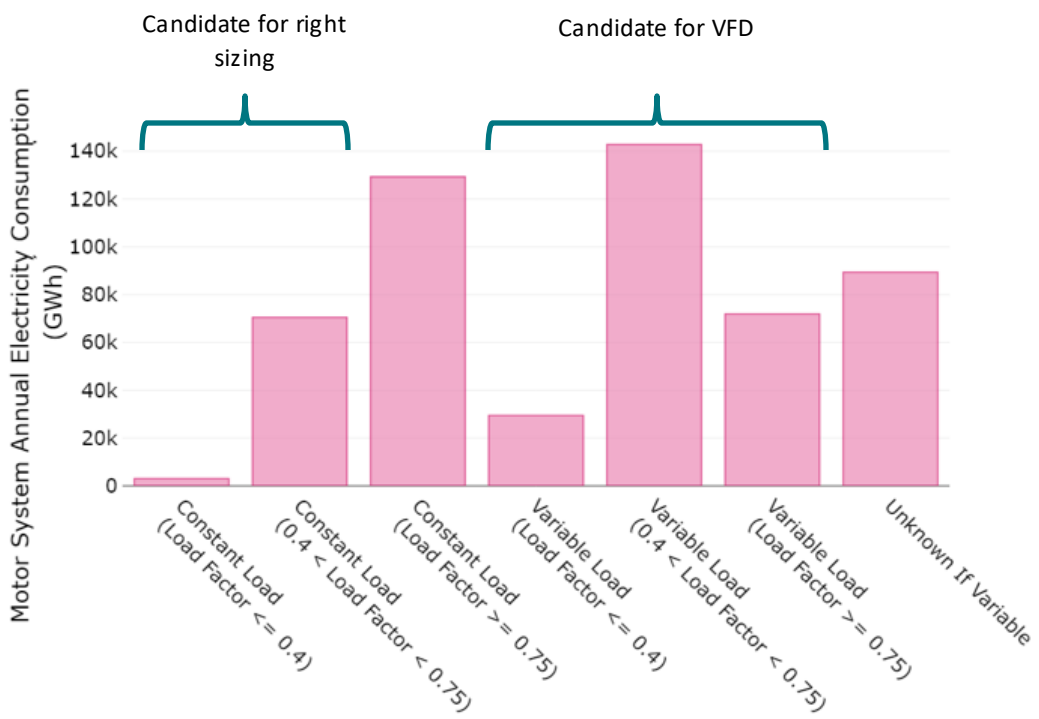
Load matching

Industrial

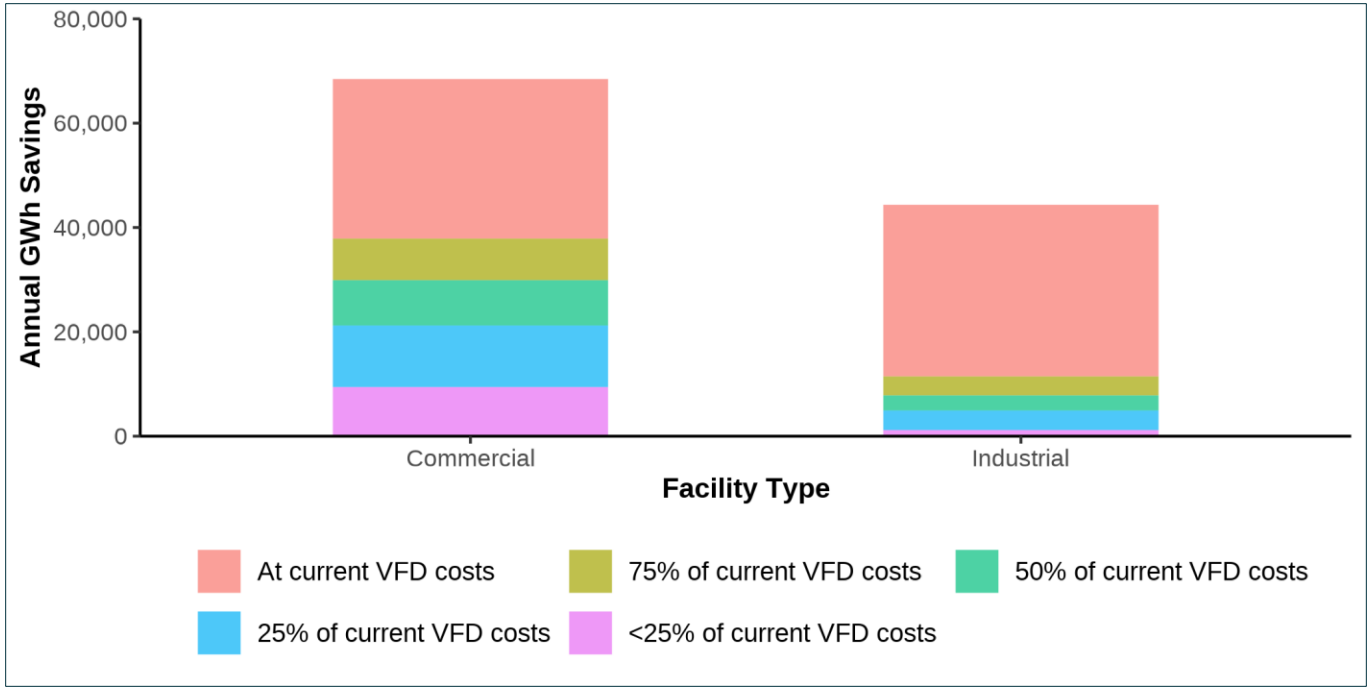


Commercial

Savings from installation of a VFD

	Energy savings (GWh/yr)	% of motor system electricity consumption	Cost savings ($M/yr)	CO_2 savings (MMT/yr)
Industrial	44,355	8%	3,743	31.4
Commercial	68,461	13%	9,241	48.5
Total	112,861	10%	12,984	80

Cost effective VFD savings potential

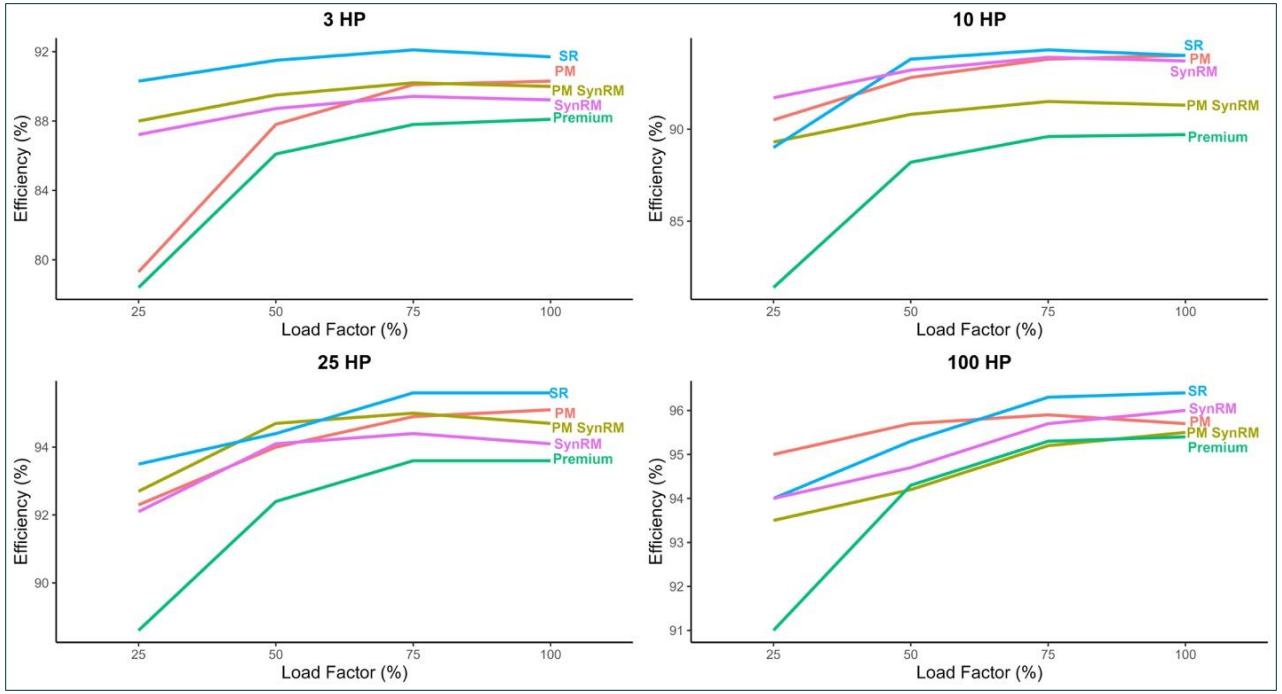


	Industrial (GWh/yr savings)	Commercial (GWh/yr savings)
At current VFD cost	32,895	30,595
75% of current VFD cost	36,541	38,562
50% of current VFD cost	39,431	47,236
25% of current VFD cost	43,175	59,046
<25% of current VFD cost*	44,355	68,461

Advanced technologies performance benefits

Performance benefits beyond conventional technologies

- 5 advanced technologies considered:
  - Permanent Magnet (PM; 1-500 hp)
  - Switched Reluctance (SR; 1-200 hp)
  - Synchronous Reluctance (SynRM; 1-500 hp)
  - Permanent Magnet Synchronous Reluctance (PMSynRM; 1-200 hp)
  - Copper Rotor (CR; 1-20 hp)
- Higher efficiency than Premium Efficiency across all loads (see right)
- PM, SynRM, and PMSynRM require VFD
- SR inherently variable speed capable



Savings from advanced technologies

Variable load systems currently w/out a VFD

	Industrial				
	Prem. Eff. w/VFD	PM	SR	SynRM	PM SynRM
Energy Savings (GWh/yr)	34,030	34,351	24,712	34,351	23,613
CO_2 Emissions (MMT/yr)		24.36	17.52	24.35	16.74
Cost Savings ($M/yr)		2,898	2,076	2,898	1,983
	Commercial				
Energy savings (GWh/yr)	66,392	67,567	67,693	67,281	64,090
CO_2 emissions (MMT/yr)		47.90	47.99	47.70	45.44
Cost savings ($M/yr)		8,806	8,886	8,770	8,428

Baselines: 53,545 GWh (industrial) and 154,668 GWh (commercial)

All systems

	Electricity Savings (GWh/yr)	Cost Savings ($M/yr)	CO_2 Savings (MMT/yr)
Permanent Magnet			
Industrial	45,014	3,788	31.91
Commercial	82,180	10,862	58.27
Switched Reluctance			
Industrial	36,059	3,042	25.57
Commercial	85,927	11,484	60.92
Synchronous Reluctance			
Industrial	44,105	3,711	31.27
Commercial	80,051	10,568	56.76
Permanent Magnet Synchronous Reluctance			
Industrial	31,688	2,668	22.47
Commercial	76,985	10,249	54.58
Copper Rotor			
Industrial	2,430	205	1.72
Commercial	7,004	1,015	4.97

Additional consideration with advanced technologies

Additional benefits

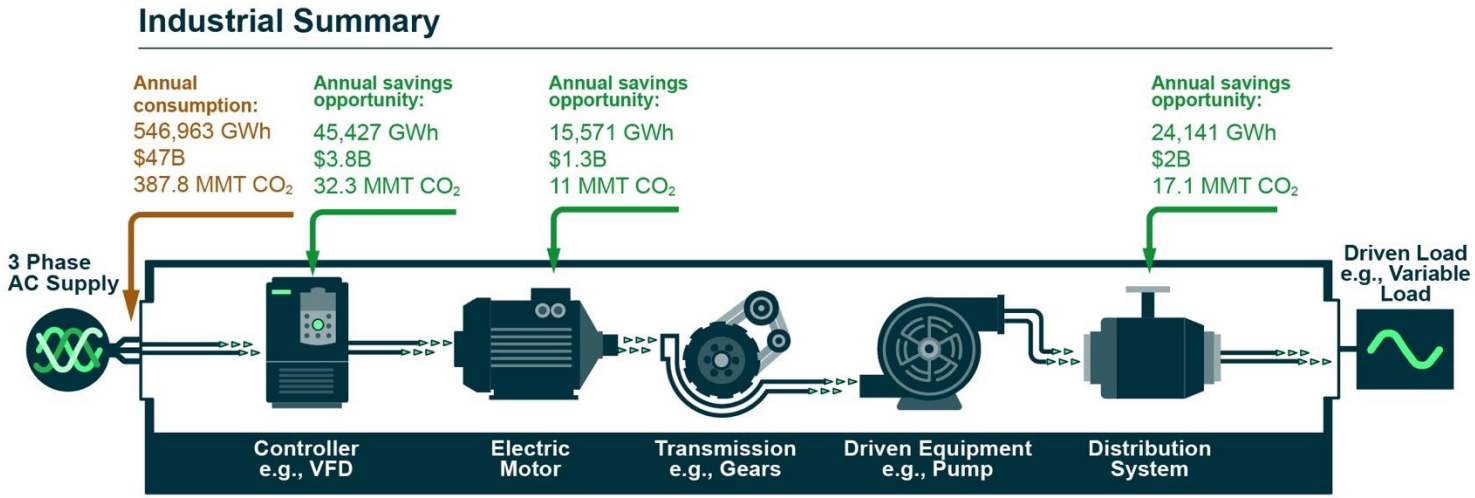
- Greater power density (watt/m^3)
- Lighter weight
- Inherently line start
- Supports grid reliability

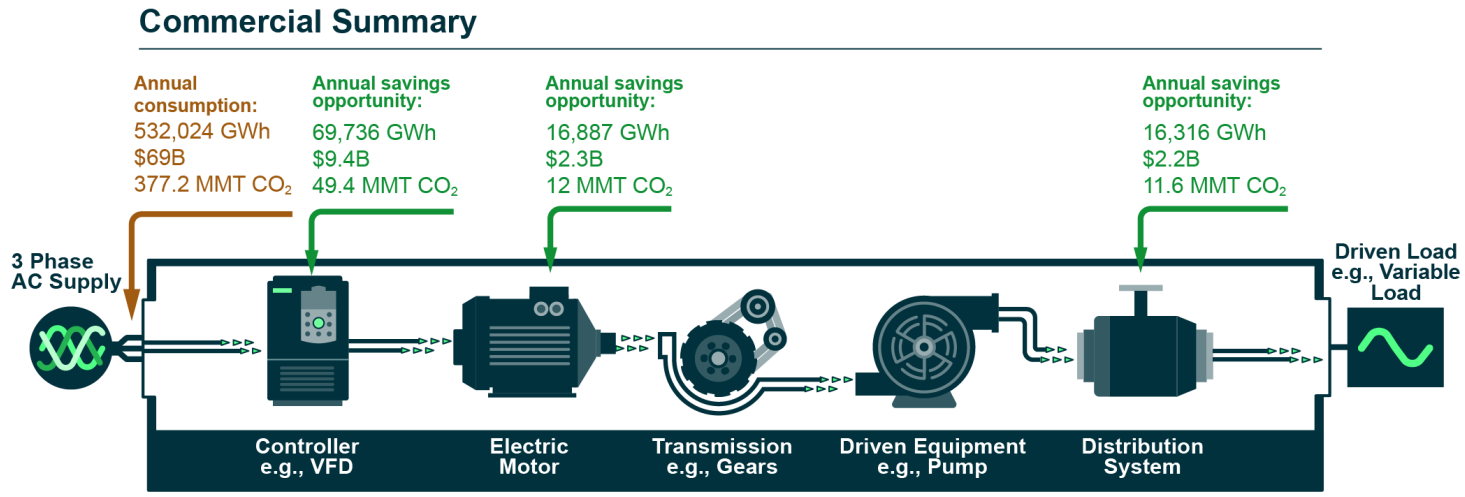
Challenges

- Require rare earth materials
- Costs
- Size range availability
- Fitting within existing frame sizes
- SR motors are loud

Summary

- Operation of industrial and commercial motor systems are responsible for 29% for all U.S. grid electricity consumption
- Motor system energy consumption has the technical potential to reduce:
  - Motor system energy consumption and CO_2 emissions by 17%
  - Motor system energy costs by 18%
- Visit motors.lbl.gov to access reports and results





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Thank You!

Questions?

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