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Review article

The current state of the industrial energy assessment and its impacts on the manufacturing industry

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ABSTRACT

Energy-intensive manufacturing is the greatest contributor to the U.S. industrial energy consumption today. Globally, manufacturing facilities are being directed to reduce their energy consumption to prepare for a sustainable future. Industrial energy assessment plays a crucial role in helping facilities meet their energy efficiency goals by encouraging the implementation of cost-effective, energy-saving recommendations to the existing equipment and processes. Across the world, programs such as the U.S. Department of Energy (DOE) sponsored Industrial Assessment Centers (IACs) (operational across several states in the U.S. for over four decades), are transforming the future of industrial energy consumption by offering free industrial energy assessments to qualifying facilities. In this review paper, the industrial energy assessment approach and practices are comprehensively reviewed with focus on popular recommendations, procedures, and the current practices of the industrial energy assessment program. Specifically, opportunities for improvement in the most energy-intensive manufacturing processes are examined, concentrating on the energy savings and other non-energy benefits of each of these measures, such as cost savings and emissions reduction. Furthermore, this paper also reviews how these energy-saving opportunities are procedurally evaluated and how factors, such as level and cost of assessments, and assessment metrics, are currently defining industrial energy assessment. In final considerations, existing research on energy management, decarbonization through electrification, and renewable energy in industry is reviewed and discussed, and how these advancements will shape the future of industrial energy assessment is addressed through forward-looking lenses.

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Nomenclature

ASD	Adjustable speed drive
AMO	Advanced Manufacturing Office
AEO	Annual Energy Outlook
AR	Assessment recommendation
BTU	British thermal unit
BEMS	Building energy management system
CIPEC	Canadian Industry Program for Energy Conservation
CO_2	Carbon dioxide
CEE	Consortium for Energy Efficiency
CHP	Combined heat and power
DOE	Department of Energy
ECM	Energy conservation measure
EIA	Energy Information Administration
EIS	Energy information system
EMIS	Energy management information system
EMS	Energy management system
EPA	Environmental Protection Agency
GHG	Greenhouse gases
GPP	Green Power Partnership
HVAC	Heating, ventilation, and air conditioning
IAC	Industrial Assessment Center
IEA	International Energy Agency
IEO	International Energy Outlook
ISO	International Organization for Standardization
IRENA	International Renewable Energy Agency
KPI	Key performance indicator
LED	Light-emitting diode
LCA	Life cycle assessment
MECS	Manufacturing Energy Consumption Survey
MTOE	Millions of tonnes of oil equivalent
NAICS	North American Industrial Classification System
SME	Small-and-medium enterprise
SIC	Standard Industrial Classification
SEP	Superior Energy Performance
SCADA	Supervisory control and data acquisition
OECD	Organization for Economic Co-operation and Development
VFD	Variable frequency drive
WEO	World Energy Outlook

1. Introduction

In current times, the industrial sector contributes to over one-third of the total energy consumption in the United States (U.S. Energy Information Administration, 2021d). This percentage is expected to rise if the current issues in industrial processes are not addressed in a timely manner. The adoption of technologies and practices to promote industrial energy efficiency can alter the trajectory of energy consumption in industry and improve production costs and quality, optimize processes, and reduce air pollution and emissions in the future (IEA, 2015). To adopt these practices, industrial energy assessments are performed to identify improvements and motivate facilities to make energy efficient changes to processes and energy use. On average, industrial energy assessments have the potential to save facilities 8%–10% in energy and cost savings (U.S. Department of Energy, 2021). In the future, industrial energy assessments will continue to play an important part in saving facilities' energy costs and in impacting the current trajectory of industrial energy use for all industry types, both manufacturing and non-manufacturing.

Investing in industrial energy efficiency can sometimes be viewed as a risk for companies to undertake from an economic standpoint. Barriers to implementing industrial efficiency investments may include access to capital, hidden costs, lack of information, and risk of downtime, just to name a few (Sorrel et al., 2011; Shrivastava et al., 2013). Companies may be reluctant to investing in energy efficiency without the technical expertise and advice of a third party outside of their organization. Industrial energy assessments provide that level of technical expertise and direct knowledge to companies, oftentimes free of cost, to encourage the implementation of energy efficient upgrades. For most assessments, the energy and cost savings, capital cost, and payback period of each recommendation is provided directly to the company so they can in turn perform a cost–benefit analysis before investment. It is important that each assessment and resultant list of recommendations is specific to each facility and their unique production levels, equipment types, and generation capacity.

In this paper, the current practices involved in industrial energy assessments conducted throughout the U.S. is reviewed. Starting with an overview of the industrial energy outlook, the trends of both national and global manufacturing energy consumption are first analyzed. Following the outlook of industrial energy consumption, the most energy intensive end uses of manufacturing are examined with special attention to the top three contributors and the most frequently recommended energy savings opportunities in those end uses. Next, the assessment procedure is explained, and the current practice of industrial energy assessment is discussed, focusing attention to the factors that define the assessment such as the rigor of assessment, cost of assessment, and assessment metrics. In final considerations, research on smart energy management, decarbonization through electrification, and renewable energy is thoroughly reviewed to depict the future directions of industrial energy assessment.

2. Industrial energy outlook

2.1. U.S. industrial energy outlook

According to the *2020 Annual Energy Outlook (AEO)*, the U.S. industrial sector's total energy consumption is projected to increase by 36% from 2020 to 2050 (U.S. Energy Information Administration, 2020a). Although energy consumption is projected to increase, the energy intensity, defined by the U.S. Department of Energy as the quantity of energy required per unit output or activity, of the industrial sector is projected to decline. This projection is due to energy efficiency improvements in facilities and a shift towards less energy intensive non-manufacturing facilities in the U.S. (U.S. Energy Information Administration, 2021a). For a more representative comparison, the U.S. Energy Information Administration (EIA) breaks the industrial sector out into two

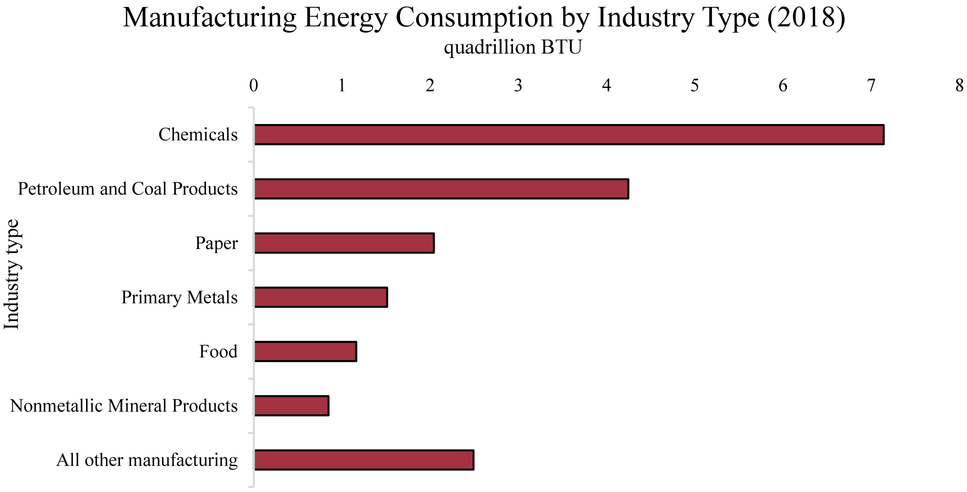

Fig. 1. Manufacturing energy consumption of top industry types, recreated from MECS.

Table 1
Manufacturing energy consumption of all industry types from MECS (U.S. Energy Information Administration, 2021c).

NAICS code	Industry type	Total quad BTU	NAICS code	Industry type	Total quad BTU
325	Chemicals	7.141	312	Beverage and tobacco products	0.118
324	Petroleum and coal products	4.245	334	Computer and electronic products	0.11
322	Paper	2.041	335	Electrical Equip., Appliances, and components	0.085
331	Primary metals	1.511	313	Textile mills	0.064
311	Food	1.161	339	Miscellaneous	0.061
327	Nonmetallic mineral products	0.846	323	Printing and related support	0.06
321	Wood products	0.388	337	Furniture and related products	0.037
336	Transportation equipment	0.348	314	Textile product mills	0.022
326	Plastics and rubber products	0.257	315	Apparel	0.004
332	Fabricated metal products	0.257	316	Leather and allied products	0.002
333	Machinery	0.148		**TOTAL**	**18.906**

subsectors, manufacturing, and non-manufacturing. Manufacturing is further divided into energy-intensive manufacturing and non-energy intensive manufacturing. In this review paper, only the energy consumption projections and trends of manufacturing industry types are discussed.

The top six energy-intensive industry types include chemicals, petroleum and coal products, paper, primary metals, food, and non-metallic mineral products. In, Fig. 1, the energy consumption of these six subsectors are provided below from the *2018 Manufacturing Energy Consumption Survey (MECS)* (U.S. Energy Information Administration, 2021c). It is important to note that these six industry types make up 87% of the United States' total manufacturing energy consumption (U.S. Energy Information Administration, 2021c). All other manufacturing includes the remaining industry types, accounting for 13% of the total manufacturing energy consumption.

To capture the complete image of industrial energy consumption (as of 2018), the total energy consumption in British thermal units (BTUs), both fuel- and non-fuel-based, of each of the twenty-one North American Industrial Classification System (NAICS) manufacturing codes are included in Table 1. The industry types considered under "All other manufacturing" are relatively low energy consumers yet are still viable candidates for industrial energy assessments and oftentimes have the potential to realize the greatest energy savings percentages from assessment recommendations (ARs) (Espindola et al., 2021).

By 2050, the energy consumption of the top five industry types, excluding the primary metal industry, is expected to grow by varying percentages, as shown in Fig. 2. The projected trends in energy consumption for each industry type are due to an increase in factors such as manufactured goods, global population, and overall industrial demand due to advancements in technology and productivity.

2.2. Global industrial energy outlook

From the 2021 *International Energy Outlook (IEO)*, Fig. 3 shows the predicted growth of each fuel type presently used in the global industrial sector from 2020 to 2050. In 2020, renewables accounted for 9% of the total fuel mix while fossil fuels (liquid fuels, natural gas, and coal) made up 76% of the share and electricity accounted for 15% (U.S. Energy Information Administration, 2021b). In the next 25 years, U.S. EIA projects global industrial energy consumption to increase by almost 50% in 2050 (U.S. Energy Information Administration, 2021b).

The trends of this forecasted growth in industrial energy consumption are comparable between the U.S. and other dominant energy consuming nations, such as China, India, and Organization for Economic Co-operation and Development (OECD) Europe. In terms of energy-intensive manufacturing, China, the world's largest industrial energy consumer, is projected to slightly decrease energy-intensive manufacturing energy consumption, while India is projected to nearly triple their energy-intensive manufacturing energy consumption from 2020–2050, as depicted in Fig. 4.

India's growth in manufacturing energy consumption is largely in part to its urbanization and demand for steel and cement for building construction (Bennett et al., 2021). Although China is expected to proportionately increase their steel and cement manufacturing, their transitioning from manufacturing towards

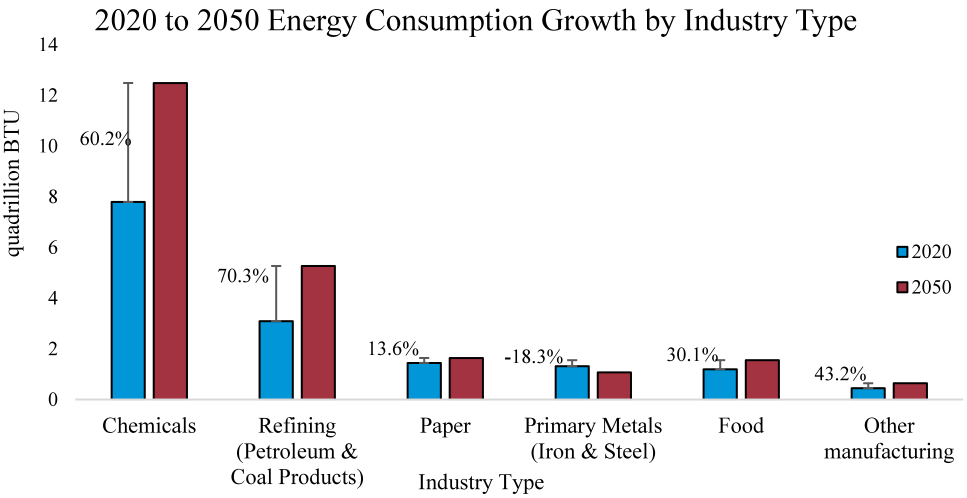

Fig. 2. Energy consumption growth to 2050 by industry type, recreated from EIA (U.S. Energy Information Administration, 2021a).

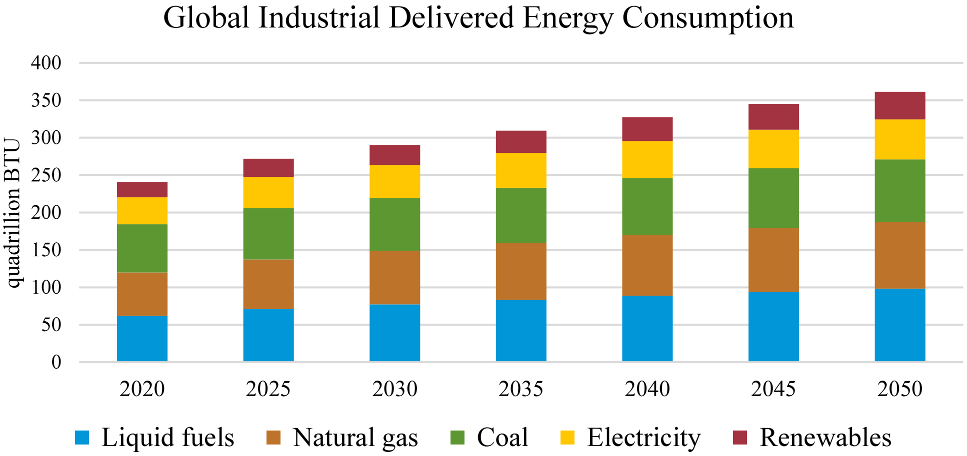

Fig. 3. Global industrial delivered energy consumption, by fuel type (U.S. Energy Information Administration, 2021b).

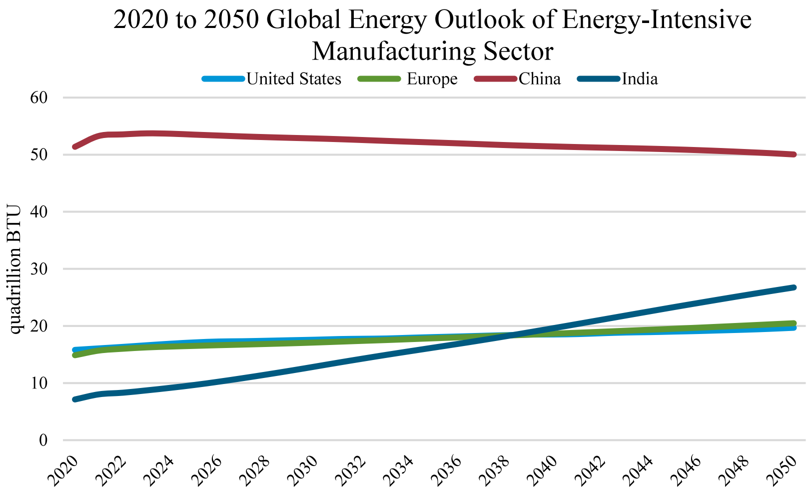

Fig. 4. Global energy consumption growth to 2050 for energy-intensive manufacturing (U.S. Energy Information Administration, 2021b).

service industry is the primary reason for the projected decrease in energy-intensive manufacturing energy consumption (U.S. Energy Information Administration, 2020b). The U.S. and Europe are projected to steadily increase energy-intensive manufacturing energy consumption by 25% and 38% respectively, from 2020 to 2050 (U.S. Energy Information Administration, 2021b). Industrial energy assessments will impact the forecasted rise of energy consumption in manufacturing facilities. The growth rate of energy consumption can be curbed by the implementation of industrial energy efficiency improvements and a shift towards on-site

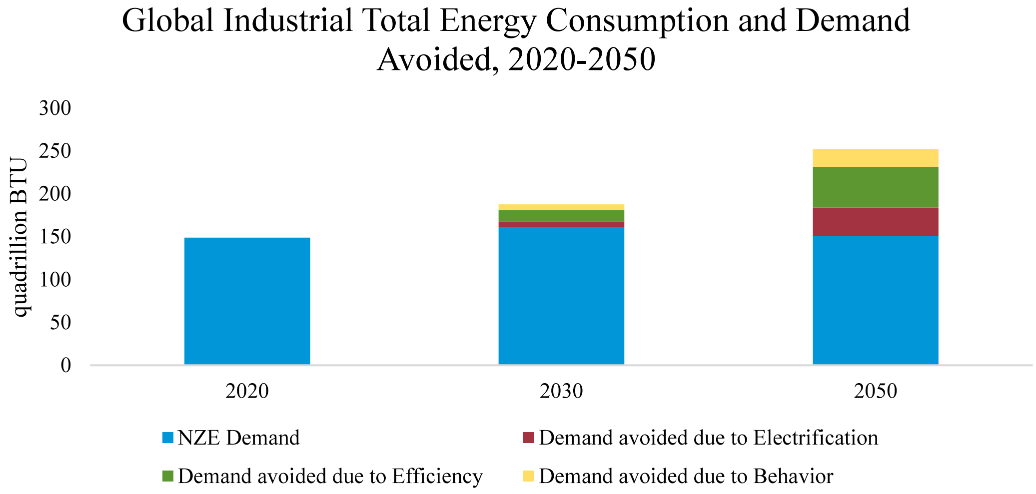

Fig. 5. Global industrial total energy consumption and avoided demand, 2020–2050, recreated from IEA (2021).

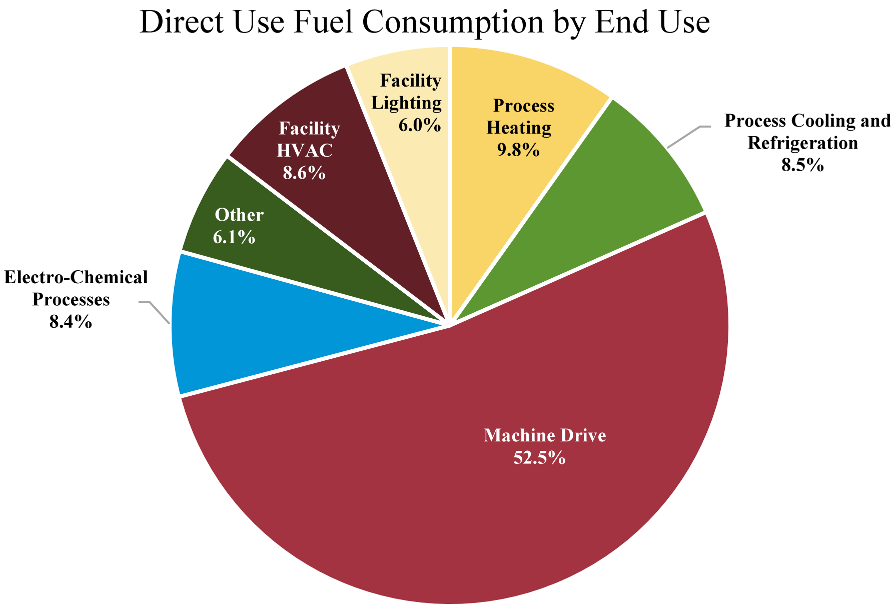

Fig. 6. Electricity consumption by end use, recreated from MECS (U.S. Energy Information Administration, 2021c).

renewable electricity generation (U.S. Energy Information Administration, 2016). In Fig. 5, 2020 global industrial demand is charted alongside predicted global industrial demand in 2030 and 2050. The increase in global industrial demand is avoidable by 2050 through investments in electrification, energy efficiency, and behavioral changes (IEA, 2021).

By conducting industrial energy assessments for manufacturing facilities in the industry types of highest projected increase of energy consumption, recommendations can push facilities towards a future 2050 of lower energy consumption and emissions that is a direct result of the energy efficiency, electrification, behavioral changes, and renewable penetration of industry today.

3. Opportunities for improvement in industrial facilities

Equipment and processes in the highest energy consuming end uses typically make for considerable energy-saving opportunities in industrial facilities. The MECS, released in spring 2021 by the U.S. EIA, aggregates industrial electricity consumption as a fuel in 2018 by various direct process and non-process end uses, shown in Fig. 6. Other end-uses include other process and non-process uses, other facility support, and onsite transportation.

From the current data, the top three industrial end uses are **machine drive** (52.5%), **process heating** (9.8%), and **facility heating, ventilation, and air conditioning** (HVAC) (8.6%). From Abdel-Hadi et al. (2020) motors, electrical demand management, and process heat recovery likewise produced the most energy savings in an energy savings analysis study of all manufacturing sectors. How the equipment and processes in these end uses uniquely use energy at each facility is important for the assessor to understand whilst conducting an industrial energy assessment. Having this knowledge, the assessor can better identify inefficient equipment types in these energy-intensive areas and make recommendations that will produce the most energy savings for the customer. A review of commonly retrofitted

Table 2
Energy savings recommendations and their energy savings range, by end use.

Energy savings recommendation	% of energy savings range	Source
Motors/Machine Drive		
Re-sizing motor to operate efficiently at full load	1%–2% per motor	Lawrence et al. (2008)
VFD to motor drive	22%–44% per motor	Saidur (2010)
Process heating		
Heat recovery mechanisms, such as recuperators and regenerators	10%–30% per furnace	Wünning (2007)
Furnace insulation	up to 5% per furnace	Hill (2016)
Facility HVAC		
Properly sizing HVAC equipment	2%–3% per building	U.S. Department of Energy (2021)
Replacing fuel-burning heating equipment with heat pumps	15%–25% per building	Orlando Utilities Commission (2019)
Advanced HVAC controls	18%–20% per HVAC system	Goetzler et al. (2017)
Smart thermostats/setback timers	1%–2% per building	U.S. Department of Energy (2021)
ASD on HVAC equipment (Chillers, Pumps etc.)	30%–50% per pump	Lung (2021)

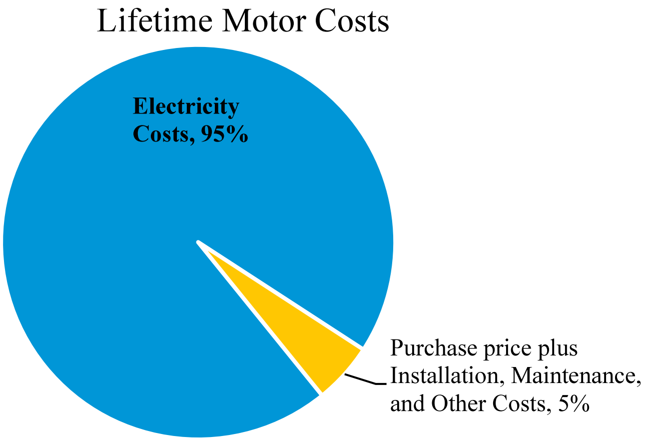

Fig. 7. Lifetime motor costs, recreated from Consortium for Energy Efficiency (2013).

equipment from these top three end uses, as a result of today's industrial energy assessments, are listed in Table 2.

3.1. Machine drive

Machine drive, or motors, is the largest contributor to energy consumption in U.S. manufacturing today. According to Consortium for Energy Efficiency (CEE) (Consortium for Energy Efficiency, 2013), 95% of a motor's lifetime costs are directly from electricity, as pictured in Fig. 7.

This statistic indicates that there are cost-saving opportunities in retrofitting existing motors to more energy-efficient motors. In making these upgrades, nearly 60% of industrial facilities utilize energy assessments to identify opportunities for their motor systems and to make energy efficient retrofits (Rao et al., 2021). To emphasize the importance of motors in industrial processes, O'Rielly and Jeswiet (2014) describe motors as the "backbone of the industrial sector" and state that the motor's speed and size are the two best measures to determine if it is both efficient and cost-effective. If a motor is oversized for its daily load, it will use more energy than necessary, hence decreasing process efficiency and increasing facility energy bills (O'Rielly and Jeswiet, 2014). This is a recurring issue identified through industrial energy assessment at various facilities across the U.S., where only 42% of industrial facilities were found to operate their motors at load factors greater than 75% (Rao et al., 2021). Thus, a common recommendation is to resize larger motors with smaller motors that can operate efficiently at 75% load. This adjustment can result in measurable energy savings, improved efficiency and cost savings compared to operating the same motor at 40% load. Another common measure is to install a variable frequency drive (VFD) to a motor. Motors operate most efficiently at full loads with lower speeds and the addition of a VFD to control and reduce the motor's speed, when not operating at full load, optimizes the machine drive and reduces unnecessary energy consumption (UN, E, 2017). Today, only 16% of motor system capacity in industrial facilities have installed VFDs (Rao et al., 2021). Adding a VFD to a motor and running it at 70% speed instead of full speed can save a facility up to 50% in energy related costs (Consortium for Energy Efficiency, 2013) and increase motor efficiency up to 95%–98% (Khalid, 2014). Another common recommendation for motor systems is to use notched or cogged v-belts on belt-driven applications. This recommendation decreases losses between the motor and belt and can improve motor efficiency by 3% (Errigo et al., 2022). Lastly, upgrading existing motors to higher efficiency models is a good investment for facilities. Improving a 100-hp standard efficiency motor by one percent to a premium-efficiency motor can save the average industrial facility 6490 kWh and $500, based on an average industrial electric rate of 7.71 cents from the U.S. EIA, in energy costs each year (McCoy and Douglass, 2014).

3.2. Process heating

Process heating is another energy-intensive component of industrial manufacturing processes. Different technologies are available to improve the overall energy efficiency of process heating operations. In this section, current opportunities for advancements to fuel-based process heating systems are reviewed. In the DOE's *Quadrennial Technology Review* of process heating technologies, the energy efficiency of process heating is defined as producing the desired amount of product using the least amount of energy at the required temperatures (U.S. Department of Energy, 2015). Therefore, energy efficiency is achieved when less energy is used without sacrificing the quality or quantity of production. One frequently implemented energy conservation measure (ECM) in process heating today is the installation of heat recovery equipment to capture waste heat from hot flue gases (U.S. Department of Energy, 2015). In the IAC database, heat recovery is the top category of recommendations for the energy management of thermal systems (U.S. Department of Energy, 2021). Moynihan and Barringer (2017) report that by pre-heating exhaust air for combustion through heat recovery mechanisms, such as recuperators or regenerators, a 20%–30% increase in furnace system efficiency is achievable. Installing a counter-flow heat exchanger to a furnace, as suggested by Kapp et al. (2021), additionally assists in reclaiming and redirecting the heat loss. Another simple, yet effective, opportunity for process heating is insulating furnace walls. If process heating equipment is left uninsulated, not only can the system lose heat, but loss of productivity and process efficiency is possible along with employee safety risk (Buchanan, 2020). If the assessment team determines that process heating equipment is poorly insulated while conducting an assessment, the suggestion to install a high temperature insulating jacket or other form of insulation on the equipment may be a worthwhile investment to the facility. Other recommendations to improve industrial combustion systems, summarized by McLaughlin et al. (2021), include installing combustion controls or dampers, trimming boiler excess air, installing VFD burners, or shutting off boilers during non-production hours. These recommendations produce various fuel savings and are a part of the current practice to optimize combustion efficiency in manufacturing processes. In this section, these upgrades to process heating operations are just a few that are often recommended in today's industrial energy assessments. Regardless, the assessor must ensure that any successful recommendation made for process heating equipment will increase the overall efficiency of the system, maximize the production quota, and minimize heat loss.

3.3. Facility HVAC

Facility HVAC accounts for 49% of non-process energy use and nearly 9% of total energy use across all manufacturing industries today (U.S. Energy Information Administration, 2021c). In its current state, industrial HVAC systems consist of several components, meaning that the opportunities for upgrading equipment in industrial facilities are far from few. The ARs for HVAC equipment must be specific to each customer, as the size of the facility, conditioned space, thermal load, outdoor air requirements, and amount of insulation, windows, and rooms can differ significantly between facility types. HVAC energy efficiency measures are typically divided into two types, **equipment upgrades** and **non-equipment upgrades**. Equipment upgrades involve the complete replacement of inefficient technology, such as ac units, heat pumps, supply fans or pumps, with a more efficient equipment that uses less energy to perform the same task. Non-equipment upgrades consist of keeping the existing equipment, but adding functionality such as controls, temperature setback, or adjustable speed drives (ASD) to lower the energy consumption of the technology. Both types of upgrades are reviewed in this paper to encompass the different levels of recommendations that facilities consider as opportunities in the retrofit of their existing HVAC systems.

One of the simplest energy-saving opportunities for industrial facilities today is to appropriately size HVAC equipment for its intended application (Lawrence et al., 2008). This opportunity is most cost-effective in the initial design phase of the building, but if the HVAC equipment is approaching the end of its useful life, the assessment team can recommend the facility to carefully consider properly sizing the new unit before purchasing. The assessor should advise against oversizing the unit and suggest for facility management to select a smaller unit that performs most efficiently at its full load (McMullan, 2003). Another technology that is penetrating the current industrial HVAC market of today is the replacement of fuel-powered heating equipment, such as furnaces and boilers, with heat pumps. A vast collection of heat pumps is available today for industrial applications that range in capacity and heat delivery mechanism. Regardless of the type of heat pump, heat pumps are more efficient than their fuel-burning counterparts, close to 100% efficient compared to 80% efficient furnaces. Although heat pumps are more expensive on a per unit of energy basis, the cost and energy savings to deliver heat more effectively are worth the capital investment and low payback period of only 2–5 years (McMullan, 2003).

Non-equipment energy efficient upgrades to existing industrial HVAC systems include advanced HVAC controls, setback temperature scheduling, and the addition of ASDs to fans and pumps. Advanced HVAC controls and sensors can save facilities energy 18% on average by utilizing wireless communication to both monitor and control various HVAC applications in the building (Goetzler et al., 2017). The installation of timers or smart thermostats in industrial facilities is a popular recommendation, totaling 96% of the overall recommendations in the space conditioning controls category (U.S. Department of Energy, 2021). Another simple, yet effective, opportunity for facilities to save on energy costs is the set-back of building temperatures during non-production hours or overnight (Lawrence et al., 2008). With the ever increasing per unit costs of electricity, this measure is one that facilities can easily implement to achieve noticeable energy savings without having to invest in expensive equipment. In final consideration, the addition of an ASD to the fans and pumps of chillers, air handlers, or heat pumps can also save anywhere from 30%–50% of equipment energy consumption by controlling the speed and power output of the equipment at different times of the day (Lung, 2021). As previously stated, these upgrades are just a few that facilities can choose to implement upon receiving an industrial energy assessment. In the following section, a common procedure describing how opportunities are assessed and recommendations are made through industrial energy assessments is explained in detail.

4. Industrial energy assessment procedure

To understand the current state of industrial energy assessments, one must become familiar with the complete energy assessment procedure. The assessment procedure in review is a typical procedure followed by the DOE for industrial energy assessments and one is to understand that this method is not the sole way to perform industrial energy assessment. For this procedure, the assessment is divided into three main activities, each with distinct elements that collectively contribute to the assessor's ultimate end goal, to provide real energy-saving and cost-effective recommendations to the facility. These activities are illustrated in Fig. 8.

The first of these activities is the *pre-assessment procedure*, where preliminary tasks prepare the assessor for on-site assessment at the facility. The pre-assessment procedure is divided into two distinct sub-activities, pre-assessment information gathering and pre-assessment analysis. In the pre-assessment information gathering step, facility identifying information is provided by the site contact to the assessment team in a pre-assessment form. This information typically includes the industry type of the facility (e.g., Standard Industrial Classification (SIC) and North American Industrial Classification System (NAICS) codes), description of industrial processes, size of the plant in terms of square footage and production levels, list of major energy consuming equipment, operating hours of the facility and historic utility bills (Stephen et al., 2015). Sometimes, larger facilities may require more operational insight than is provided through a pre-assessment form. At this point in the procedure, the assessor may choose to conduct a pre-assessment interview with the site contact. This interview allows the team to learn valuable intel about the company including, but not limited to, current facility operations, ongoing energy retrofit projects, and facility limitations with future projects (Zhivov et al., 2011). Supplemental documents such as facility layout, monthly production data, and equipment specification sheets may also be collected from the site contact at this time (Hasanbeigi and Price, 2010). At the point when all available preliminary facility information is provided, the pre-assessment analysis can begin. The main task of pre-assessment analysis is energy bill analysis. The assessor graphs past year utility bills, both electricity and natural gas, and attempts to identify trends in energy consumption, establish unit cost of energy, and determine energy-intensive end uses

Fig. 8. Flow chart of industrial energy assessment procedure.

of the facility (Theising, 2016). If monthly production data is available, the unit cost of energy can be calculated as the energy cost per unit of product and the specific energy consumption can be calculated as the energy consumption per unit of product (Lawrence et al., 2019). These energy performance metrics are oftentimes the most valuable metric to facility management in determining process efficiency (Theising, 2016). Completing a pre-assessment energy bill analysis encourages the assessment team to begin brainstorming potential ECMs before any on-site work even begins. At the end of the pre-assessment phase, the assessment team is well informed of the background, operations, and historical energy trends of the facility and is prepared for the on-site assessment at the facility.

During *on-site assessment*, the team first meets with facility personnel to discuss the scope of the assessment to ensure both parties understand the intentions and structure of the day ahead (Barringer III, 2013). The facility personnel may also take this time with the team to review manufacturing processes and production flow and answer any preliminary questions the team may have (Gopalakrishnan et al., 2016). The team then proceeds with a guided tour of the manufacturing floor before data collection activities commence, taking note of key equipment to return to for measurements. It is pertinent at this point in the procedure that the team creates a plan for data collection. As Zhivov et al. (2011) notes, the highest energy consuming, and most used equipment and processes are prioritized for measurement and evaluation. A variety of instruments are used for measurements depending on the equipment type and required parameters for measurement. Generally, each diagnostic instrument falls into one of the following categories as listed in Hasanbeigi and Price (2010): **electrical instrumentation** such as voltmeters, wattmeters, and light meters, **temperature instrumentation** such as thermocouples and infrared thermometers, **flow sensors** such as volumetric flow meters and differential pressure meters, **exhaust gas instrumentation**, and **speed measurement instrumentation**. After all required measurements are taken and recorded, the team collaborates internally to determine which preliminary recommendations to share with the customer. A final briefing takes place with facility personnel at the end of the day to communicate initial findings and prioritize energy-saving opportunities of focus for further analysis. The team is to consider any feedback from facility personnel on proposed improvements in the final activity of the assessment, the *post-assessment procedure*.

Similar to the pre-assessment, the *post-assessment* activity consists of two sub-activities, post-assessment analysis and post-assessment customer follow-up. An energy savings analysis is first conducted for each proposed ECM found from the on-site assessment. With field measurements as inputs, baseline estimates of energy consumption are calculated using simple mathematical models, DOE *BestPractices* software tools, or a combination of the two (Stephen et al., 2015). By knowing the baseline consumption of existing equipment, the team can then narrow down energy efficient equipment options and calculate realistic energy savings for each measure. Final recommendations for each measure cannot be considered without completing a financial analysis to determine implementation costs and payback periods. The financial analysis is often the determinant factor of final facility management implementation decisions. Recommendations with moderate energy savings, lower implementation costs, and shorter payback periods of one to two years are more likely to be implemented. In an analysis of 40 industrial assessments, Abbas et al. (2018) reported average simple payback periods of less than two years for a wide range of ARs, as depicted in Fig. 9. In Fig. 9, EDMUB is electrical demand management and utility bills and WMPE is waste management and productivity enhancement.

After the assessment team finalizes all recommendations, a final report is created and sent to the customer for review. This report includes the annual energy savings, annual cost savings, implementation costs, and payback periods for each AR. After receiving this report, the customer may participate in a post-assessment follow-up with one of the assessors after a period of time after receiving the report to inform the team of the decisions made for each recommendation. In this follow-up, customers share the reasons for or against implementation and the impact of each recommendation in terms of post-retrofit energy and cost savings (Abbas et al., 2018). In the next section, the current practice of industrial energy assessment is discussed, focusing attention on the characteristics and metrics that define today's industrial energy assessments.

5. Current practice of industrial energy assessment

As summarized by Selim et al. (2021), the top three benefits of industrial energy auditing are energy savings, cost savings, and emission reduction. The primary goal of industrial energy assessment programs is thus to assist facilities in upgrading existing inefficient equipment helping to save energy, energy related costs, and additional benefits of energy efficient investments. Industrial energy assessment programs are broadly classified as either a stand-alone or independent energy assessment program. The two types of programs are defined by program design and assessment intentions by Lu and Price (2011). The stand-alone energy assessment program is an independent energy assessment performed by a dedicated team of assessors that focuses solely on recommending energy savings to the facility while the integrated energy assessment program is an industrial energy assessment that focuses not only on saving facilities energy, but also on achieving goals set by energy policies at the program and/or national level (Lu and Price, 2011). An example of this type of energy policy is a voluntary agreement, which is a contractual agreement between a company and an outside authority to form internal energy policies, strategies, and goals around energy usage and carbon dioxide (CO_2) reductions (Lindén and Carlsson-Kanyama, 2002). The United States' main program is a

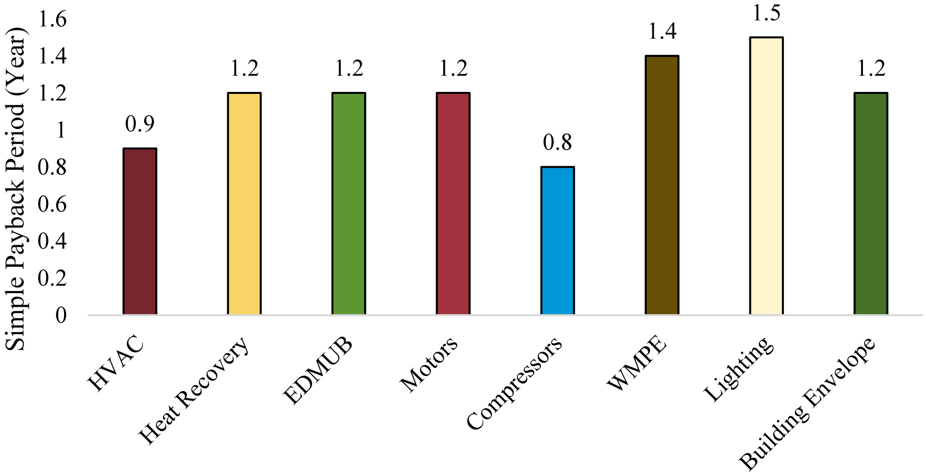

Fig. 9. Average simple payback periods of ARs, recreated from Abbas et al. (2018).

stand-alone energy assessment program. The IAC is the United States' stand-alone energy assessment program that offers energy assessments to qualifying small-and-medium manufacturing facilities, free of charge, with utility bills between $100,000–$3,500,000. The U.S. is not the only country that offers no-cost energy assessments. The U.K. and Japan also have programs that offer free assessments to small-and-medium enterprises (SMEs) in their respective countries (Lu and Price, 2011). Free energy assessments are standard practice of today's industrial energy assessment programs because by making the assessment free, additional costs are alleviated for the facility that can be later reserved for the initial investments of energy-saving equipment.

Industrial energy assessments are performed either internally by qualified facility staff or externally by trained energy auditors, specialists, or even university students. The degree to which the assessment is performed depends on facility size and level of rigor. Ranga and Abhinav (2014) classify today's industrial energy assessments into two categories: **short audits** and **detailed audits**. Short audits are further divided into **walk-through energy audits**, better designed for SMEs and **preliminary energy audits**, better designed for large facilities (Ranga and Abhinav, 2014). Preliminary energy consumption data and a one-day site visit form the basis of analysis for short audits. Basic equipment measurements are taken to gain intel and make recommendations with shorter payback periods and lower implementation costs. Detailed audits analyze each system of the facility and energy consumption analysis is performed for each end use. A more detailed audit may also follow a specific procedure for resource acquisition and efficiency, such as the framework designed by Choi et al. (2019). This framework focuses on specific resource categories of a facility when making industrial energy assessment recommendations. By focusing on a specific resource category of a facility, such as raw material, water, waste, and/or equipment, unique savings opportunities are generated to achieve industrial efficiency across various resource categories of the facility (Choi et al., 2019). In addition to following a specific framework, standardized software is oftentimes utilized to quantify the energy savings of potential recommendations. The U.S. DOE provides free *BestPractices* software through the Advanced Manufacturing Office (AMO) which incorporates industry best practices in standardizing industrial energy assessment saving methodologies for various industrial systems (Armstrong et al., 2019). This software package is online and free to download and use for both internal facility management and external energy audit teams. The Canadian Industry Program for Energy Conservation (CIPEC) also promotes the use of their *Energy Savings Toolbox* for standardized energy assessment methodologies and energy savings calculations (Hasanbeigi and Price, 2010). This package includes a free online guidebook and equipment specific spreadsheets for assessors to use in the field. Software and manuals are important in standardizing the current practice of industrial energy assessments both nationally and internationally.

Table 3
Top 10 recommendations from historical IAC assessments (U.S. Department of Energy, 2021).

Recommendation description
(1) Utilize higher efficiency lamps and/or ballasts
(2) Eliminate leaks in inert gas and compressed air lines/ valves
(3) Eliminate or reduce compressed air usage
(4) Install compressor air intakes in coolest locations
(5) Use most efficient type of electric motors
(6) Install occupancy sensors
(7) Utilize energy efficient belts and other improved mechanisms
(8) Insulate bare equipment
(9) Use adjustable frequency drive or multiple speed motors on existing system
(10) Recover waste heat from equipment

The most frequently recommended improvements from industrial energy assessments are similar amongst the various industrial energy assessment programs operational in different states in the U.S. For instance, the IAC's top ten recommendations are included in Table 3. These recommendations usually have short payback periods, ranging from six months to four years, making the upgrades attractive from facility's operational and maintenance budgets perspective. Capital and implementation costs are also low for each of these measures (∼$20,000). These recommendations also reflect the energy efficiency trends of today's market. Facilities are already making the decision to install higher efficiency lamps, like light-emitting diodes (LEDs), or to install ASDs to existing motors when it comes time to replace old equipment or buy new equipment. Industrial energy assessment, through programs like the IAC, aids in identifying these cost-effective opportunities to facilities and encourages facilities to implement these recommendations to improve their energy consumption, utility bills, and carbon footprint.

The most valuable metrics of industrial energy assessments are the direct energy, cost, and emission savings at the facility level. There are multiple factors which contribute to a facility's cost savings estimation from industrial energy assessments. These factors include size of the facility, in terms of production, energy bills, or square footage, industry type, and even the equipment types and processes of the facility. Therefore, when quantifying

Table 4
Cost savings of top 10 recommendations, by dollar amount & percentage (U.S. Department of Energy, 2021).

Recommendation description	$ cost savings	% cost savings
$1000–3000		
Install compressor air intakes in coolest locations	$1994	0.26%
Install occupancy sensors	$2537	0.33%
$3000–6000		
Utilize energy efficient belts and other improved mechanisms	$3273	0.42%
Eliminate or reduce compressed air usage	$5095	0.66%
Use most efficient type of electric motors	$5686	0.73%
$6000–9000		
Eliminate leaks in inert gas and compressed air lines/ valves	$6252	0.80%
Insulate bare equipment	$6897	0.89%
Utilize higher efficiency lamps and/or ballasts	$7379	0.95%
>$10,000		
Recover waste heat from equipment	$17,557	2.26%
Use adjustable frequency drive or multiple speed motors on existing system	$20,236	2.60%
Total	**$76,906**	**9.89%**

the benefits of industrial energy assessment, one must understand that savings vary by a number of these factors for each facility. In this section, the cost savings of these top measures listed in Table 3 are considered for an average facility. For the top recommendations in Table 3, the associated cost savings as a dollar amount and percent of total facility energy bills is included in Table 4 from the IAC database.

By implementing these ten recommendations, the average manufacturing facility with annual utility bills of $777,000 can save nearly 10% in energy costs (U.S. Department of Energy, 2021), which is substantial. Again, the cost savings of each measure will vary upon the defining characteristics of each facility. To quantify CO_2 emission savings from industrial energy assessment recommendations implementation, a simple method is to utilize emission factors in terms of lbs. or tons/energy unit. It is important to utilize regional Emission Factors (EF) when quantifying the emission savings of each facility. Taking the product of the total energy savings and the respective EF in units of CO_2 by weight per unit energy directly yields the total emission savings as a function of the direct energy savings (ICF, 2017). This is an important aspect of industrial energy assessment final analysis as companies typically have both energy savings and emission targets to reach and are oftentimes interested in these metrics. In addition to these metrics given at the time of assessment, a life-cycle assessment (LCA) of equipment energy and carbon savings from production to end-of-life may also be of interest to companies (Choi et al., 2018). Conducting a LCA to capture energy efficiency improvements in all stages of an equipment's useful life is a current practice in industrial energy assessment. In the concluding section of this review, the opportunities of smart energy management, decarbonization through electrification, and renewable use and generation are explored.

6. Future directions of industrial energy assessment

The adoption of smart energy management, decarbonization through electrification, and renewable energy practices in industrial facilities will shape the future of industrial energy consumption. In this next section, each of these technologies and their expected contributions to the future of industrial energy assessments are reviewed.

6.1. Smart energy management

Smart energy management in manufacturing involves the strategic integration of smart manufacturing technologies and software with structured energy management programs such as International Organization for Standardization (ISO) 50001. Industrial energy assessments can identify the opportunity for a facility to implement a smart energy management program to monitor, control, and improve energy consumption in real time. The installation of a smart energy management system (EMS) can save facilities costs and energy, at a low investment price, and provide benefits within a short payback period. Therkelsen et al. (2015) discovered that through participation in the U.S. DOE Superior Energy Performance (SEP) program, which requires participating facilities to become certified in ISO 50001 energy management and improve energy performance by at least 5% over three years, quarterly energy cost savings of around 10% were achievable from smart energy management programs. Energy savings up to 10%–20% can also result from energy management programs (National Association of Manufacturers, 2005). More conservative energy savings estimates of 3%–9% were realized by participants in the Smart Energy Analytics Campaign from 2016–2020 (Kramer et al., 2020). For large industrial facilities with annual energy bills of at least two million dollars, a payback period of less than two years is achievable upon initial investments in energy management (Therkelsen et al., 2015). Today, industrial energy assessments are performed to understand how manufacturing processes consume energy. The assessment findings provide the feedback necessary for a facility to determine how worthwhile of an investment an energy management program is to managing equipment energy use and improving overall energy consumption. In the future, an increase in the installation of automated HVAC controls or whole building energy management systems (BEMS) is expected to result from the final recommendations of industrial energy assessments. By installing and continuously monitoring these types of technologies, other potential ECMs can be discovered to improve a facility's energy efficiency. Kramer et al. (2020) found facilities implemented additional measures such as improved HVAC scheduling, economizer operation, and peak demand reduction as a direct result of smart energy management through energy information systems (EIS). Beyond energy and cost savings, there are other additional benefits of EIS. In a survey conducted by Berkeley Lab of participants in the Smart Energy Analytics Campaign, Fig. 10 portrays the percentage of benefits named by facility personnel upon installation of energy management information system (EMIS) technologies.

To realize the most of these benefits, the successful design and execution of an energy management program is essential. This starts with understanding the energy flows and consumption of all equipment and processes and planning to continuously improve baseline energy usage through direct monitoring (Medojevic et al., 2018). Training facility staff to easily interpret energy

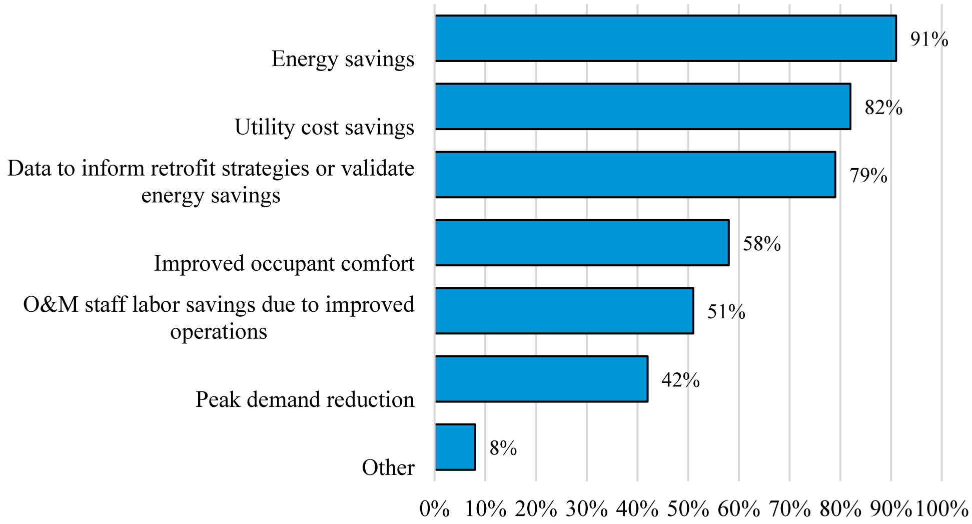

Fig. 10. Benefits of implementing EMIS, recreated from Kramer et al. (2020).

management software and further recommend relative energy savings opportunities based upon key performance indicators (KPIs) is imperative to the continual improvement of facility energy consumption (Vikhorev et al., 2013). Through the utilization of supervisory control and data acquisition (SCADA) software, visual energy data through intuitive charts and graphics can assist facility staff in making informed energy-saving decisions backed by real time data (Vikhorev et al., 2013). To increase productivity and optimize EMS, Medojevic et al. (2018) review the benefits of integrating aspects and solutions of Industry 4.0 with smart energy management. This includes the integration of connected devices with data collection for energy consumption management and the implementation of innovative concepts of Industry 4.0 including Big Data and intelligent manufacturing (Medojevic et al., 2018). Javied et al. (2018) also explore the possibilities of integrated EMS and Industry 4.0 and emphasize the importance of continual energy consumption monitoring through the communication of a network of sensors in a cloud-based system. Ensuring these elements of a smart energy management program are fully executed will help to maximize the energy and cost savings potential of smart energy management in a facility.

6.2. Decarbonization through electrification

In 2020, electricity accounted for 15% of the total available energy sources used by industry worldwide (U.S. Energy Information Administration, 2021b). Compared to fossil fuels, which accounted for 76%, the use of electricity as an energy source in global industry is significantly lower (U.S. Energy Information Administration, 2021b). There is potential for the electrification of industry as there are a number of benefits that can result from switching equipment and processes, typically powered by fossil fuels, to being powered directly or indirectly by electricity. Some of the direct energy benefits of electrification include better grid support and flexibility while other non-energy benefits include economic development, energy security, process improvements, and reduced greenhouse gases (GHG) (Deason J. Wei et al., 2018). In manufacturing, different technologies are available for fuel-switching. Several cutting-edge technologies, with varying levels of technical potential for electrification, are found from the review of a number of sources (Deason J. Wei et al., 2018; Hasanbeigi et al., 2021; Lechtenbohmer et al., 2016; Rightor et al., 2020; Rissman et al., 2020; Ruhnau et al., 2019; Steinberg et al., 2017).

The opportunities for electrification include heating equipment upgrades, such as electric boilers, electric arc furnaces, and industrial process heat pumps. Trading traditional melting methods for induction melting or plasma melting and traditional heating methods for induction heating and electro-magnetic heating also present fair opportunities. Lesser potential for electrolysis and indirect electrification are worth noting as well. The direct electrification of equipment including electric water heaters and electric pumping systems are feasible when considering equipment upgrades.

The majority of these technologies are improvements to process heating, one of the top three energy intensive end uses of industry. Process heating not only accounts for a large share of industrial energy consumption, but Rightor et al. (2020) found process heating to contribute 32% of the industrial U.S. GHG emissions. In fact, emissions from energy use in industry accounts for 24.2% of total global greenhouse gas emissions, as illustrated in Fig. 11.

Converting industrial technologies, conventionally powered by fossil fuels, to their electric counterparts can catalyze the future of industry decarbonization. Currently in industry, many energy-intensive processes are powered by fossil fuels. Processes powered by electricity do not yield the same carbon intensive GHG emissions as processes powered by the combustion of fossil fuels (Steinberg et al., 2017). So, naturally, GHG emissions will be lower upon switching to powering equipment and processes by electricity. But true decarbonization of industry is not possible unless clean sources of electricity are utilized in lieu of grid generated electricity, which have higher associated CO_2 emissions factors. In the future, industrial energy assessments will emphasize and recommend the electrification of potential technologies to manufacturing facilities. Instead of recommending a simple efficiency improvement to existing boilers and furnaces, a complete retrofit of equipment and processes to their electrified counterparts is expected to become the new standard. It is important to note that the complete electrification of processes can come with some limitations such as considerable upfront costs, higher purchase price for electricity, and complexity of equipment (Rissman et al., 2020). Although the capital cost of a complete retrofit of electrified equipment is oftentimes high, the enhanced efficiency, energy savings, and emissions reductions are worth the investment. By electrifying industry through recommendations from industrial energy assessments, the decarbonization of industry is possible.

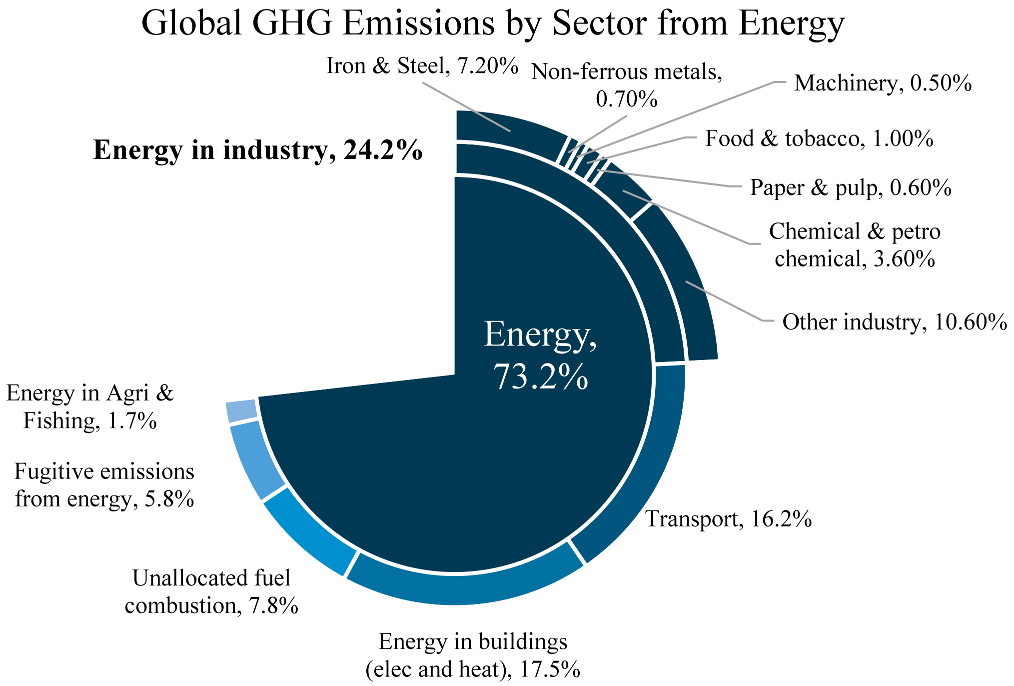

Fig. 11. Global GHG emissions by sector from energy (Climate Watch, 2020).

6.3. *Renewables*

Increasing the presence of renewable generation and power in industry will mitigate the rise in global temperature and help to reach net-zero targets by 2050. In fact, the International Renewable Energy Agency (IRENA) (IRENA, 2019) projects a 20% global increase in the direct use of renewables in industry necessary for keeping the rise of global temperature below 2 degrees Celsius. In global industry's fuel mix today, only 9% is renewable electricity (U.S. Energy Information Administration, 2021b). Therefore, the generation and use of renewables must significantly increase to reach these targets by 2050. Industrial energy assessments can help facilities make contributions to the widespread adoption of renewables. Those available opportunities for renewable energy use and generation are explored in this section, focusing on the opportunities in the most energy-intensive sectors of manufacturing.

Similar to electrification, process heating applications present the most potential in terms of powering manufacturing technologies with renewable sources. In fact, 85% of the potential for renewable energy technologies in manufacturing exist in process heating (Kempener and Saygin, 2014). For high heat temperature processes, which account for two-thirds of the total process heating applications, biomass is the best alternative to fossil fuel (Kempener and Saygin, 2014). By converting traditional fossil fuel processes to biomass, manufacturing facilities can produce less emissions and will benefit from using a cleaner source of electricity. Although oftentimes less feasible and cost-effective than fueling with biomass, solar thermal systems also have great potential for powering low-heat processes in manufacturing (Kempener and Saygin, 2014). The current global renewable use in industrial heating processes in 2019 and potential in 2030 is included in Fig. 12 in units of millions of tonnes of oil equivalent (MTOE) from the *World Energy Outlook* (WEO) (IEA, 2020). Bioenergy, in the form of biogas for elevated temperature processes and biomass for low-temperature processes, is the most used fuel type in industrial heating. Its use is expected to grow by 24% in 2030 and 48% by 2040 (IEA, 2020). By conducting industrial energy assessments, manufacturing facilities can better understand the potential benefits of utilizing one of these renewable forms of energy for process heating in the near future.

Using renewable forms of energy to power equipment and processes is one way for industrial facilities to add to its share of renewables. But also, the procurement of renewable energy onsite is a secondary way to increase the presence of renewables in industry. Procuring onsite renewable energy includes both onsite generation and onsite contracted renewables (IEA, 2017). Onsite renewables are typically generated by the following technologies: wind, solar, geothermal, biomass, hydropower, and fuel cells that use renewable hydrogen (U.S. Enviromental Protection Agency, 2017). Combined heat and power (CHP) systems are also oftentimes found onsite at manufacturing facilities but can only be considered a renewable source of energy if the fuel type is renewable, such as renewable natural gas or biomass. In the U.S., the Environmental Protection Agency's (EPA) Green Power Partnership (GPP) encourages facilities to contract a percentage of annual energy use to source from green power (U.S. Enviromental Protection Agency, 2017). This type of program, in combination with industrial energy assessment programs, can collaborate in the future to increase the generation and use of renewables in industry.

7. Conclusion

Industrial energy assessment programs will transform the future of industrial energy consumption and efficiency through the identification and recommendation of energy efficient improvements to existing equipment and processes. In summary, this literature review analyzed the current outlook and future trends of U.S. and global energy consumption to better understand the projections of industrial energy use in energy-intensive manufacturing. Next, the fuel consumption percentages by end use for a typical manufacturing facility were examined. Following, a comprehensive list of common ARs and their relative energy savings for the top three end uses (motors, process heating, and facility HVAC) were explored for the average manufacturing facility. A typical energy assessment procedure utilized by the U.S. DOE, detailing each main activity (pre-assessment, on-site assessment,

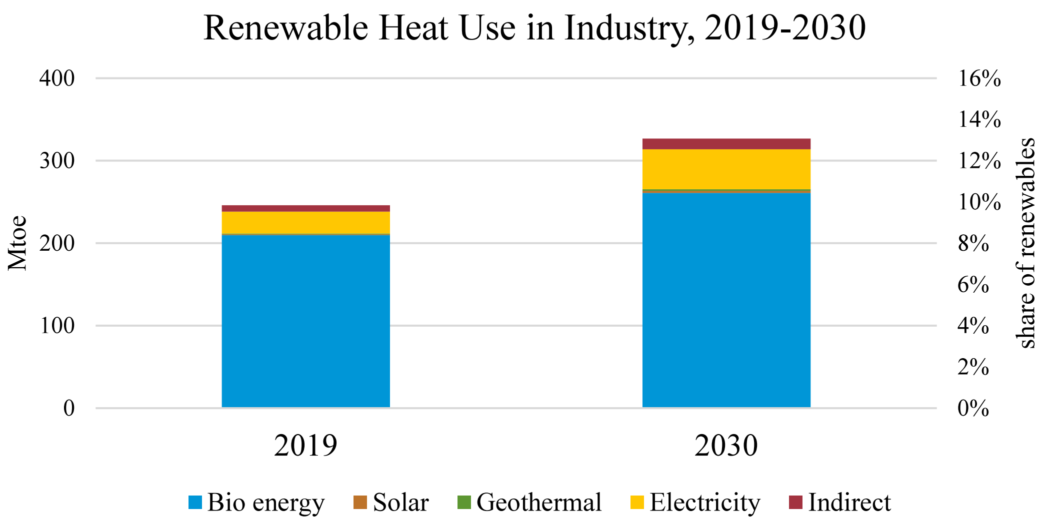

Fig. 12. Renewable heat use in industry, 2019–2030, recreated from IEA (2020).

and post-assessment) of the procedure was also reviewed. In addition, the current practice of today's industrial energy assessment with attention to assessment characteristics including assessment type, rigor, and metrics was assessed. Specifically, the IAC's top 10 recommendations and their respective cost savings by dollar amount and percentage were considered. In final considerations, elements of smart energy management, decarbonization through electrification, and renewable generation were researched to apprehend the future contributions of these practices to the current practice of industrial energy assessment.

In summary, this literature review:

- Analyzed the current electricity usage and future usage predictions of the U.S. and other major energy consuming nations using the U.S. EIA *Annual Energy Outlook* and *World Energy Outlook*
- Discussed industrial energy use in energy-intensive manufacturing across various sectors
- Explored a comprehensive list of common assessment recommendations and their relative energy savings for:
    - Motors/machine drive:
        - Resize larger motors with smaller motors
        - Operate motors efficiently at 75% load
        - Install a variable frequency drive (VFD) to a motor
        - Use notched or cogged v-belts on belt-driven applications
        - Upgrade existing motors to higher efficiency models
    - Process heating:
        - Install heat recovery equipment (heat exchangers) to capture waste heat from hot flue gases
        - Insulate furnace walls
        - Install combustion controls or dampers
        - Trim boiler excess air
        - Add VFDs to burners
        - Shut off boilers during non-production hours
    - Facility HVAC:
        - Appropriately size HVAC equipment for intended application
        - Replace fuel-powered heating equipment, such as furnaces and boilers, with heat pumps
        - Install advanced HVAC controls
        - Setback temperature scheduling
        - Add ASDs to fans and pumps
- Reviewed the current practice of industrial energy assessment and compared the different assessment types, metrics, and procedures
- Researched the future contributions of smart energy management, decarbonization through electrification, and renewable generation to the current practice of industrial energy assessment

CRediT authorship contribution statement

McKenna Patterson: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft, Visualization. **Prashant Singh:** Conceptualization, Writing – review & editing, Supervision. **Heejin Cho:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Heejin Cho reports financial support was provided by US Department of Energy. Heejin Cho reports a relationship with Elsevier that includes: board membership and advisory fees.

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