Smart Manufacturing Technologies and Data Analytics for Improving Energy Efficiency in Industrial Energy Systems

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ABSTRACT

Smart manufacturing and advanced data analytics can help the manufacturing sector unlock energy efficiency from the equipment level to the entire manufacturing facility and the whole supply chain. These technologies can make manufacturing industries more competitive, with intelligent communication systems, real-time energy savings, and increased energy productivity. Smart manufacturing can give all employees in an organization the actionable information they need, when they need it, so that each person can contribute to the optimal operation of the corporation through informed, data-driven decision making. This paper examines smart technologies and data analytics approaches for improving energy efficiency and reducing energy costs in process-supporting energy systems. It dives into energy-saving improvement opportunities through smart manufacturing technologies and sophisticated data collection and analysis. The energy systems covered in this paper include those with motors and drives, fans, pumps, air compressors, steam, and process heating.

Introduction

In the United States, industrial facilities accounted for about 32% of total national energy consumption in 2014 (EIA 2015). Energy use efficiency, energy costs, and energy availability greatly impact the competitiveness and economic health of US manufacturers. More efficient, smarter energy use lowers production costs, conserves limited energy resources, and increases productivity. Significant opportunities to address energy efficiency exist in common energy systems used across manufacturing sectors, such as motors and drives, fans, pumps, air compressors, steam, and process heating (see Table 1).

The term “smart manufacturing” refers to advanced sensing, instrumentation, monitoring, controls, and process optimization technologies and practices that merge information and communication technologies (including data management and data analytics) with the manufacturing environment for real-time management of energy, productivity, and costs across factories and companies. Smart manufacturing technologies include infrastructure, software, and networked solutions.

It is estimated that investments in smart manufacturing technologies could generate cost savings and new revenues that add $10−$15T to global gross domestic products over the next 20 years. Over that period, the US manufacturing sector can potentially realize savings of $15B in annual electricity costs and a 20% reduction in average company energy demand (Rogers et al. 2013).

Table 1. Process-supporting industrial energy systems

Energy System	**Description**
Steam	Steam systems provide process heating, pressure control, mechanical drive, and component separation and are water sources for many process reactions. They consist of components for steam generation (boiler), distribution, end uses, and recovery.
Process Heating	Process heating systems are used for material heating, melting, heat treating, drying, curing, and so on. They consist of devices to generate and supply heat, transfer heat from source to product, contain heat (e.g., furnaces, heaters, ovens, and kilns), and recover heat.
Compressed Air	Compressed air is considered the "fourth utility" at many facilities. It powers pneumatic tools, packaging and automation equipment, and conveyors. Compressed air systems consist of a supply side, including compressors and air treatment, and a demand side, including distribution and storage systems and end-use equipment.
Pumps	Pumps provide cooling and lubrication services, transfer fluids for processing, and provide the motive force in hydraulic systems. Typical pumping systems contain five basic components: pumps, prime movers, piping, valves, and end-use equipment (e.g., heat exchangers, tanks, and hydraulic equipment).
Fans	Fans are critical for process support uses ranging from shop ventilation to material handling to boiler or furnace applications. A typical fan system consists of a fan, an electric motor, a drive system, ducts or piping, flow control devices, and air-conditioning equipment (e.g., filters, cooling coils, heat exchangers).

Smart Manufacturing Technologies

The 2015 National Science Foundation (NSF) workshop on Research Needs in Advanced Sensors, Controls, Platforms, and Modeling for Smart Manufacturing provides two definitions for smart manufacturing. One definition (NSF 2015) is that *"Smart Manufacturing is about Data →Information →Knowledge → Wisdom" (DIKW)*. It uses advanced sensors to collect data. Data and models provide real-time information. Information is then used to run the manufacturing plants better and generate knowledge (e.g. reduce energy use, improve quality, agility, improve productivity, improve sustainability, etc.). When knowledge is used across enterprise, this is where we have Smart Manufacturing and Wisdom." The simplest definition, according to an ACEEE report (Rogers, E. et.al. 2013), is *"the integration of all facets of manufacturing through the use of information and communication technologies."* In this paper, smart manufacturing technologies include, but are not limited to, sensors, control systems, communications networks, enterprise-level management systems, data analysis, predictive modeling, monitoring, data visualization, intelligent maintenance, etc. [SmartWatt 2016]. The primary goal of smart manufacturing is to integrate all individual energy support systems and units of an organization, regardless of sophistication, to achieve superior control and productivity.

Based on the degree of "smartness" of a manufacturing facility and the sophistication of the technologies to be implemented, smart manufacturing projects are categorized into four levels - levels 0 through 3 (Muller 2016). Air-fuel ratio control in a process heating system is used as an example to illustrate the four technology levels. These control systems must deliver fuel and air to burners in precise proportions for safe, reliable, and energy efficient combustion with the optimum amount of excess air. The least energy-efficient method of air-fuel ratio control, using no smart technologies, is to modulate only the fuel flow rate to achieve the desired temperature and avoid overheating (Figure 1).

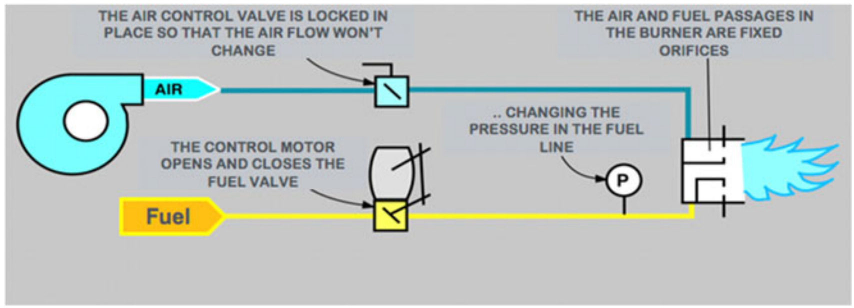

Figure 1. Air-fuel ratio control without any smart technologies (DOE 2015).

The following options illustrate smart technologies from levels 0 to 3 that can be applied to increase the process efficiency.

- Level 0 adds automatic controls to the manufacturing processes or systems. In this control system, which does not communicate with other systems or processes, a mechanical linkage with a single actuator controls the combustion air and fuel supply to the burner (Figure 2).

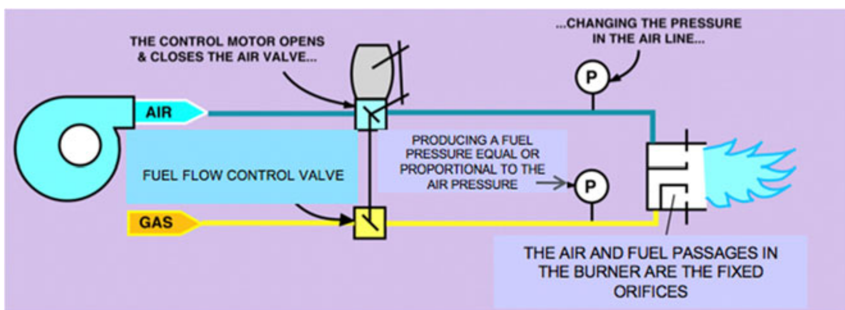

Figure 2. Parallel linkage controlled system - level 0 air-fuel ratio control technology (DOE 2015).

- Level 1 adds a communication system to the existing control system. For example, if a cross-connected air-fuel ratio control system is in use, adding a communication system can deliver air-fuel ratio information to plant operators and send alerts or sound alarms if the system is not working properly or becomes unbalanced (Figure 3).

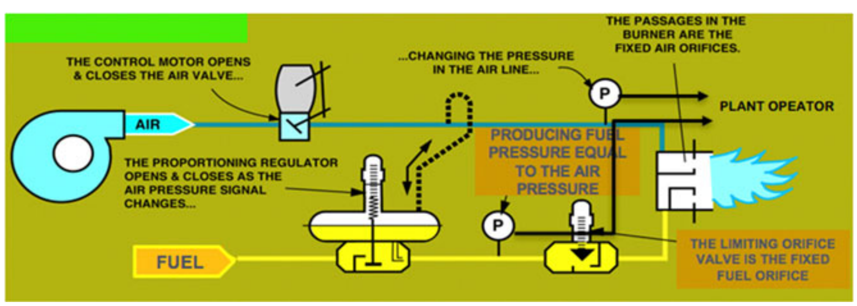

Figure 3. Cross connected firing rate control system - level 1 air-fuel ratio control technology (DOE 2015).

- Level 2 adds both automatic controls and communication systems to manufacturing processes or systems. For example, fully metered, mass flow air-fuel ratio control systems automatically compensate for changes that affect combustion performance, such as air and fuel temperature and pressure and combustion chamber pressure. Ratio regulators modulate air flow control valves to maintain the air-fuel ratio; the ratio information is communicated to the plant operators (Figure 4).

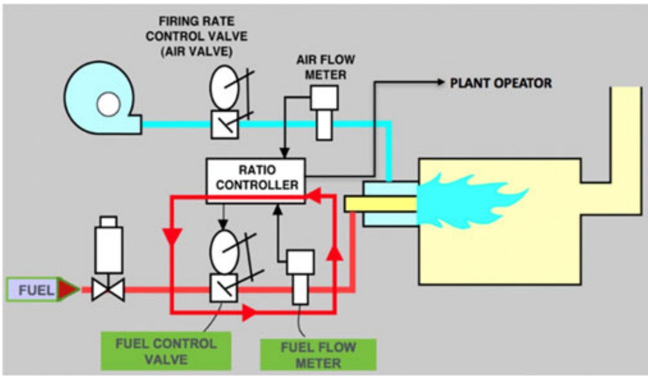

Figure 4. Fully metered, mass flow control system - level 2 air-fuel control technology (DOE 2015).

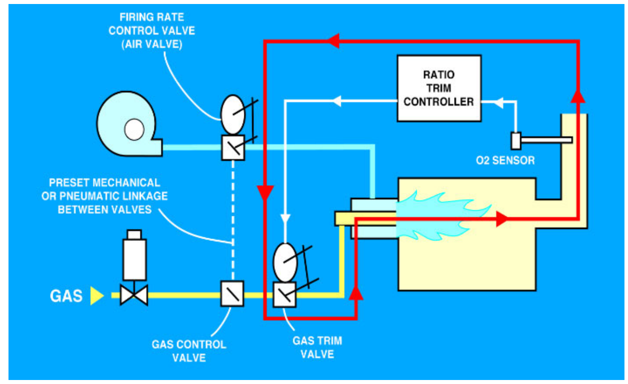

Figure 5. Fully metered mass flow control system with integrated oxygen sensors - level 3 air-fuel control technology (DOE 2015).

- Level 3 uses non-local information in decision making. For example, mass flow control systems also integrate feedback from oxygen sensors in the exhaust stack to enhance safety by ensuring that the equipment is not operating below the stoichiometric ratio. Performance testing is usually required for mass flow control systems to validate that the ratio of air to fuel is correct and stable throughout the operating range. (Figure 5).

Using Smart Manufacturing Technologies to Improve Energy Efficiency

Increased adoption of advanced technologies such as combined heat and power, smart manufacturing, and intelligent efficiency is likely in coming years to help manufacturers reduce facility-level energy intensities (Elliott 2016). Technology vendor Schneider Electric projects massive growth of connected devices globally, with over seven billion devices in use by 2025, over 2.5 million in industrial automation alone (Beudert, Juergensen, and Weiland 2015). The increasing capabilities of energy management systems, advanced metering and submetering solutions, and internet-connected sensors make smart manufacturing technologies an attractive investment for small and large manufacturers. Vendors active in the United States, such as Schneider Electric, General Electric, Honeywell, 3M, Bosch, and Rockwell Automation, provide comprehensive digitalization, monitoring and control platforms to analyze production and energy use data. Such smart tools and solutions could lead to a 20% average reduction in overall energy consumption per industrial facility, and $15B in electricity cost savings, by 2035 (Rogers et al. 2013). They also offer benefits like productivity improvement, better working conditions, safety, and quality control.

Trends in smart manufacturing and the industrial internet of things are already affecting business sectors from retail to industrial. The following are three real-world examples of industrial applications of smart technologies and data analytics.

Example 1: General Mills Managing Energy as an Ingredient

The General Mills project "Managing Energy as an Ingredient" allows 15 plants to manage 1,500 energy submetering points in real time (General Mills 2016). Previously, plants analyzed energy performance based only on monthly utility bills. General Mills developed a solution that assigns each meter an energy usage target based on production and weather data, enabling operators to manage energy use as they manage ingredient waste and equipment failures (Figure 6). General Mills developed the project internally because solutions available on the market could not consider factors that greatly affect energy use, such as the product and the quantity being produced on a manufacturing line. Basing energy use targets on actual production (and using sub-meters to identify the energy required for each product) allows an actionable target—missing a target means that energy is being wasted. Integrating energy meters into production reporting systems and the existing data-driven operation management culture was a significant technical achievement.

The project costed $1M and resulted in annual energy cost savings estimated at $650K, for a simple payback of 1.6 years (General Mills 2016). The system also manages water use and is projected to reduce CO_2 emissions by 5K metric tons annually. The project helped identify process drivers causing higher energy consumption and improve process consistency.

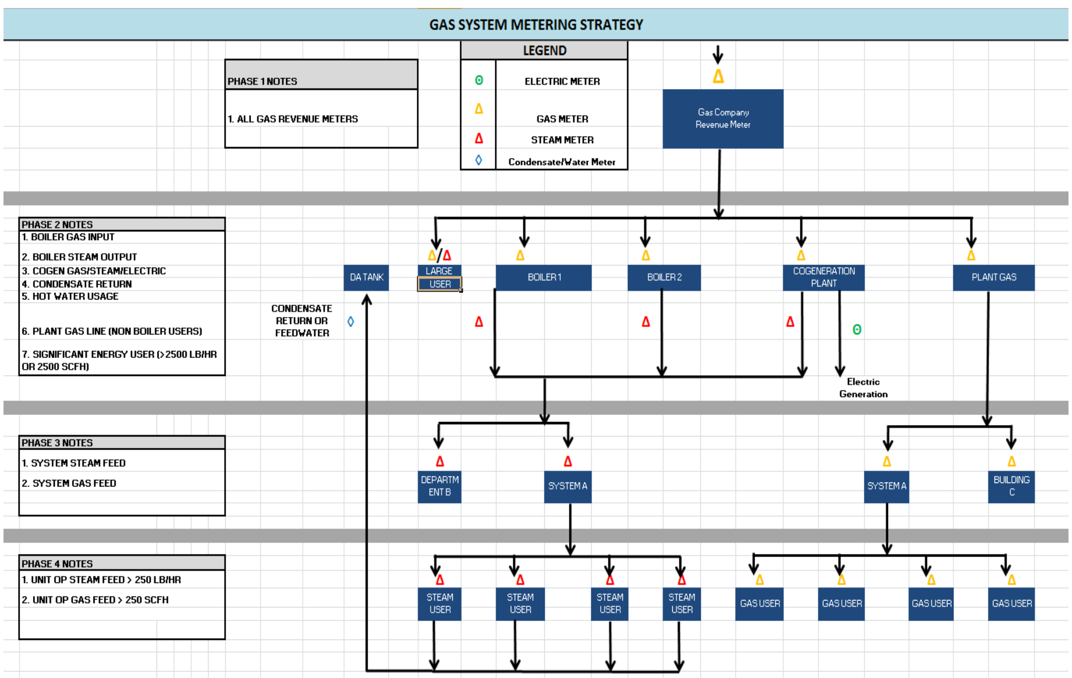

Figure 6. Real-time energy monitoring at General Mills (General Mills 2016).

Example 2: Celanese Energy Dashboards

At Celanese, energy optimization had typically been a management or engineering responsibility (Celanese 2016). Real-time energy control was in the hands of plant operators, but often it was not pursued. Celanese discovered that operators were an underused resource in energy management and could be more effective if given appropriate tools and information to optimize energy use. "Energy Dashboards" were developed to provide operators with access to real-time energy usage, dynamic energy “targets,” and information to enable them to reduce energy by keeping the plant operating within an optimum range.

In 2015–2016, Celanese implemented Energy Dashboards at eight sites globally. In the first plant where dashboards were fully implemented, annual energy savings of over $300K were realized from operators making process adjustments to improve efficiency based on real-time energy information. In addition, new energy reduction projects worth over $1.5M are being implemented at that site as a result of visibility of energy usage, statistical modeling, and operator engagement.

Obtaining accurate data for energy correlation was challenging because of infrequent testing, inaccurate instrumentation, and missing instrumentation. Another challenge was getting buy-in from the operating personnel that the models were accurate and could be acted on routinely and effectively. This challenge was overcome by engaging operations personnel in the project from the beginning and throughout the project development.

Figure 7. Energy dashboards to engage operators in energy optimization (Celanese 2016).

Example 3: Reducing/eliminating overcooling at the final stage of process heating

In a hot strip mill, after leaving finishing stands, hot strips are conveyed through low-pressure, high-volume water spray curtains to be cooled to desired coiling temperatures. Traditionally, spray water pumps run at 100% of their full speed constantly, even if the mill is down or running slowly or if the product coiling temperature has changed. As a result, the pumps provide more water flows than needed most of the time. Furthermore, since coiling temperature is metallurgically critical to the properties of hot-rolled steel (California Steel Industries 2016), uncontrolled or ill-controlled water flow rates in the spray heads may negatively impact the coiling temperature and severely compromise product quality.

Spray water pumps can be equipped with variable frequency drives (VFDs) and inverter-ready motors (or inverter-duty motors for constant torque loads). Instead of running constantly at full speed, pumps can be turned on or off based on the mill operation status; and pump running speeds can be modulated to maintain pressure or water flow rates at spray heads and desired coiling temperatures for different products. The VFDs and advanced control methods eliminated pressure drops when bottom sprays were turned on, significantly improving the coiling temperature controls and product quality.

A case study for a steel manufacturing plant in Indiana shows that since VFDs were installed on four 400 HP motors, the spray water pumps typically run at 60–80% of their full speed, instead of 100%. The annual energy cost savings from this change are estimated at $360K/yr. The project total cost was $820K, with $410K covered by government and utility cost incentives, for a simple payback of 1.2 years for the company (ArcelorMittal USA 2016).

Opportunities Identified by DOE Energy Assessments

The US Department of Energy’s (DOE) systems-based approach to smart manufacturing provides industrial plant managers with information to evaluate opportunities and implement projects that improve energy system efficiency within their production facilities. DOE’s In-Plant Training, online web-based training, and software tools address improving energy efficiency from a systems-based perspective. In October 2005, DOE’s Advanced Manufacturing Office began offering system-based Energy Savings Assessments (ESAs) for large manufacturing plants. Between 2006 and 2011, 1,017 large plant assessments were completed for energy support systems such as steam, process heating, compressed air, pumps, and fans (Wright et al. 2010).

DOE Industrial Assessment Centers (IACs) work with small- and medium-size manufacturers to identify opportunities to improve energy efficiency, focusing on all major energy systems. The IAC database documents savings recommendations and implementation histories for assessments conducted over 30 years—more than 15,500 assessments and nearly 116,800 savings recommendations (IAC 2017). Many of the database entries recommend implementing smart controls or devices to save energy. Most of those were level 0 or 1 technologies (from simple controls to sensing and control devices). Applying level 2 or 3 technologies (controls with sensing and communication devices) may achieve more energy savings and/or make the savings more sustainable. Tables 1 - 4 provide more detailed energy efficiency opportunity-level data on ESA and IAC recommendations. The data can help industrial facilities estimate typical energy and energy cost savings from smart manufacturing technologies.

Tables 1 and 3 show the number of times smart manufacturing technologies related energy efficiency opportunities were implemented, average annual source energy savings, average percentage of source energy savings over plant total energy consumption, average annual energy cost savings, average percentage of energy cost savings over plant total energy cost, and simple payback. Tables 2 and 4 show data for different industry sectors. The IAC assessments data includes cross-cutting energy assessments conducted between 2000 and 2016. The ESA data includes system-specific large plant assessments conducted between 2006 and 2011. It is important to note that the IAC assessments and ESAs cover only energy support systems (steam, compressed air, process heating, pumps, and fans). The opportunities identified during the DOE energy assessments do not (or almost on an insignificant level) cover the process related improvements. The impact of SM technologies on industrial processes would be even more significant. As per the Clean Energy Smart Manufacturing Innovative Institute (CESMII), energy savings were estimated conservatively at 12.5% for each of first 5 years with steadily increasing market penetration of CESMII's SM technologies to 5% by year 5. In years 5 through 10, energy savings of 20% were assumed with market penetration steadily increasing from 5% to 15%. These assumptions are based on direct results from current Smart Manufacturing Leadership Coalition, and information provided by industry partners. During the first 10 years of operation, over 2,100 TBtu of energy can be saved by CESMII's actions, which will create energy savings of $195 billion (CESMII 2017).

Higher-level smart manufacturing technologies (level 2 or 3) could increase energy savings and/or make savings more sustainable. For example, United Technologies reported seeing a 25% increase in energy efficiency and a 47 % reduction in water use since adopting smart manufacturing technologies (UTC 2016). Higher levels of smart manufacturing technology implementation can enable plant operators to monitor the status of energy systems more closely so they can correct or optimize the operation of energy systems in a timely manner. In many cases, at higher levels, operations would be optimized automatically and operator intervention might be guided by predictive maintenance.

Table 1. Energy efficiency opportunities implemented during ESAs that could be upgraded to higher levels of smart technologies

Energy Efficiency Opportunity	**Energy System**	**No. of times Implemented (2006-11)**	**Avg. % Savings of Total Plant Source Energy**	**Avg. % Savings of Total Plant Energy Cost**	**Avg. Payback (Year)**
Reduce air leaks	Comp. Air	46	0.4%	0.3%	0.6
Improve end use efficiency	Comp. Air	23	0.4%	0.4%	0.8
Reduce system air pressure	Comp. Air	22	0.4%	0.3%	0.5
Install/improve multiple compressor controls	Comp. Air	17	0.7%	0.7%	0.7
Reduce run time	Comp. Air	11	0.4%	0.3%	1.5
Improve trim compressor part-load efficiency	Comp. Air	7	0.9%	0.9%	0.3
Shut off unneeded fans	Fans	5	0.2%	0.2%	0.1
Use variable-speed drive	Fans	3	0.2%	0.2%	1.6
Reduce oxygen content of flue (exhaust) gases	Process Heating	67	0.9%	1.2%	0.5
Reduce/eliminate openings and air leakage in the furnace	Process Heating	27	1.0%	1.2%	1.2
Proper insulation and maintenance of furnace structure or parts	Process Heating	21	0.7%	0.8%	2.3
Furnace scheduling, loading, shut down —avoiding delays, waits, cooling between operations etc.	Process Heating	16	2.1%	2.2%	0.2

Energy Efficiency Opportunity	Energy System	No. of times Implemented (2006-11)	Avg. % Savings of Total Plant Source Energy	Avg. % Savings of Total Plant Energy Cost	Avg. Payback (Year)
Load or charge preheating using heat from flue or exhaust gas or other source of waste heat	Process Heating	6	1.3%	1.6%	1.2
Control (reduce) makeup air for ovens to meet the process safety requirements	Process Heating	6	0.9%	1.0%	0.3
Clean heat transfer surfaces—radiant tubes, heat exchangers, heating elements	Process Heating	5	0.3%	0.3%	0.5
Eliminate excess unburned hydrocarbons (CO, H_2, CH_4, soot in the exhaust gases)	Process Heating	4	0.2%	0.3%	0.4
Reduce excessive valve friction loss by removing unnecessary flow paths, excessive no. of fittings, poor suction geometry, etc.	Pumps	13	0.3%	0.3%	1.2
Improve insulation	Steam	60	0.4%	0.4%	1.4
Change condensate recovery rates	Steam	31	0.5%	0.7%	0.9
Change boiler blowdown rate	Steam	28	0.3%	0.4%	1.3
Reduce or recover vented steam	Steam	22	0.4%	0.4%	0.4
Multiple boiler optimization	Steam	13	0.6%	0.9%	0.3

Table 2. Opportunities for smart manufacturing energy efficiency technologies identified during ESAs for major industries

Industry	No. of times Implemented (2006-11)	Avg. % Savings of Total Plant Source Energy	Avg. % Savings of Total Plant Energy Cost	Avg. Payback (Year)
Mining (except oil and gas)	35	0.6%	0.7%	1.9
Food	231	0.5%	0.6%	1.2
Beverage and tobacco product	6	0.9%	0.6%	1.5
Textile mills	11	1.2%	1.5%	6.2
Textile product mills	9	0.7%	1.3%	0.8
Wood products	17	0.8%	0.9%	0.9
Paper	249	0.4%	0.5%	1.6
Printing and related support activities	16	0.4%	0.4%	1.1
Petroleum and coal products	84	0.7%	0.8%	1.3
Chemical	234	0.8%	0.9%	1.2
Plastics and rubber products	68	0.6%	0.6%	1.4
Nonmetallic mineral product	212	1.2%	1.2%	1.4

Industry	No. of times Implemented (2006-11)	Avg. % Savings of Total Plant Source Energy	Avg. % Savings of Total Plant Energy Cost	Avg. Payback (Year)
Primary metal	293	1.0%	1.2%	1.3
Fabricated metal product	61	0.8%	1.1%	0.9
Machinery manufacturing	28	1.3%	1.3%	1.8
Computer and electronic products	24	0.4%	0.4%	0.5
Electrical equipment, appliance, and component	18	0.6%	0.8%	0.7
Transportation equipment	236	0.7%	0.7%	1.0
Miscellaneous	14	0.7%	0.8%	2.7

Table 3. Smart manufacturing energy efficiency technologies implemented during IAC assessments that could be upgraded to higher levels of smartness

Energy Efficiency Opportunity	Energy System	No. of times Implemented (2000-16)	Avg. Savings % of Total Plant Source Energy	Avg. Savings % of Total Plant Energy Cost	Avg. Payback (Year)
Improve combustion control capability	Process Heating	36	2.6%	2.4%	2.2
Install automatic stack damper	Process Heating	10	0.9%	0.8%	1.2
Enhance sensitivity of temperature control and cutoff	Process Heating	12	2.6%	3.6%	0.7
Use demand controller or load shedder	Other	33	0.0%	2.8%	1.2
Use power factor controllers	Motor	90	0.3%	3.5%	1.6
Install motor voltage controller on lightly loaded motors	Motor	10	1.5%	1.5%	2.2
Use multiple speed motors or adjustable-frequency drives (AFDs) for variable pump, blower and compressor loads	Pump	391	2.1%	2.0%	1.9
Use AFD to replace motor-generator set	Motor	30	5.2%	4.3%	1.4
Use AFD to replace throttling system	Motor	118	5.9%	2.4%	2.0
Use AFD to replace mechanical drive	Motor	117	3.8%	3.1%	1.9
Upgrade controls on compressors	Comp. Air	230	2.3%	1.9%	0.9
Use controls to operate equipment only when needed	Other	175	2.6%	2.3%	0.9
Install set-back timers	Other	72	2.3%	2.7%	0.5

Energy Efficiency Opportunity	Energy System	No. of times Implemented (2000-16)	Avg. Savings % of Total Plant Source Energy	Avg. Savings % of Total Plant Energy Cost	Avg. Payback (Year)
Install timers on light switches in little used areas	Lighting	73	1.0%	1.0%	0.8
Use photocell controls	Lighting	267	1.0%	0.9%	0.7
Install occupancy sensors	Lighting	1183	0.7%	0.6%	1.2
Use computer programs to optimize heating, ventilation, and air conditioner (HVAC) performance	HVAC	29	4.5%	4.2%	0.5
Install outside air damper/economizer on HVAC unit	HVAC	72	4.1%	3.4%	1.5
Install timers and/or thermostats	HVAC	275	2.3%	2.0%	0.6
Centralize control of exhaust fans to ensure their shutdown, or establish program to ensure manual shutdown	Fan	10	1.1%	1.1%	0.4
Use sensors controlling roof and wall openings	Building Envelope	3	1.4%	1.2%	0.0
Sub-meter / quantify water use	Pump	34	0.0%	3.4%	0.5
Use flow control valves on equipment to optimize water use	Pump	19	0.0%	1.8%	0.9
Install sensors to detect defects	Other	7	0.1%	9.5%	0.3

Table 4. Industry level impacts of Level 0 to 1 Smart Manufacturing energy efficiency projects implemented during the IAC assessments

Industry	No. of times Implemented (2000-16)	Avg. Savings % of Total Plant Source Energy	Avg. Savings % of Total Plant Energy Cost	Avg. Payback (Year)
Food	443	0.9%	1.8%	1.2
Wood product	173	2.1%	2.4%	1.4
Paper	197	1.3%	2.1%	1.2
Chemicals	202	1.4%	2.1%	1.1
Plastics and rubber product	427	1.4%	2.2%	1.3
Primary metal	231	1.1%	1.4%	1.3
Fabricated metal product	379	1.9%	2.5%	1.2
Computer and electronic product	323	1.7%	1.9%	0.9
Elec. equip. appliances, components	153	1.8%	2.1%	1.4
Transportation equipment	194	1.6%	1.6%	1.3

Conclusions

Smart Manufacturing (SM) technologies and data analytics approaches can improve energy efficiency and reduce energy costs in process-supporting energy system. Many manufacturers are already taking advantage of the increasing capabilities of technologies such as energy management systems, advanced metering and sub-metering solutions, and internet-connected sensors. There are some sporadic efforts to quantify potential energy and economic impacts from the SM technologies. There is a need for a sophisticated energy impacts analysis to quantify energy and economic impacts on national, industry sector, facility, energy system and equipment levels. The researchers/analysts could start their energy impacts analysis work by analyzing the DOE energy assessments (IAC as well as Energy Savings Assessments) databases. The preliminary data analysis shows that most of the energy efficiency technologies implemented from the DOE IAC and ESA assessments are level 0 or 1 (simple controls or control devices with sensors). Implementing higher-levels of smart technologies (level 2 or 3) is likely to increase energy savings and could make energy savings sustainable.

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