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"Strategies to improve industrial energy efficiency"

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Abstract

The broad topic of efficiency is investigated within the context of the general manufacturing sector, which includes anything from computing and electronics to food and textile products, and consumes enormous amounts of energy in order to generate the goods and services we use today. This is unsurprising as it stands to reason that in order to operate the necessary equipment and facilities to produce these products a significant amount of energy and resources must be expended. However, most manufacturing facilities are not operated at a highly efficient rate, in terms of both waste heat and materials. As a result, a number of opportunities exist to develop a more efficient, sustainable general manufacturing sector.

This topic has been well researched in the past in terms of the losses encountered during various general manufacturing process streams, however, less literature exists which attempts to outline an appropriate efficiency loss mitigation strategy for companies to implement. In fact, the Trottier Energy Futures Project, which is, in collaboration with the David Suzuki Foundation, creating an energy roadmap for Canada, has devoted one of its eleven key challenges for creating a more sustainable, low-carbon future for Canada to general manufacturing efficiency improvement. This paper will discuss appropriate efficiency loss mitigation strategies for companies.

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1. Introduction

In today's modern society it is quite evident that the world is at our fingertips, one need only take a look around. A large portion of today's prominent industries have either been created or drastically altered by the use of fossil fuels, which have transformed since the beginning of the industrial revolution. Figure 1 [1] indicates how GHG's have decreased with the introduction of new fuels. However, these gains have been nullified due to increased energy demand.

It is the general belief that use of fossil fuels has allowed today's society to experience current freedoms and liberties. However, our dependence on a finite fuel source will lead to catastrophe if today's consumption practices are not curbed and the process of weaning ourselves from environmentally-degrading energy sources does not begin.

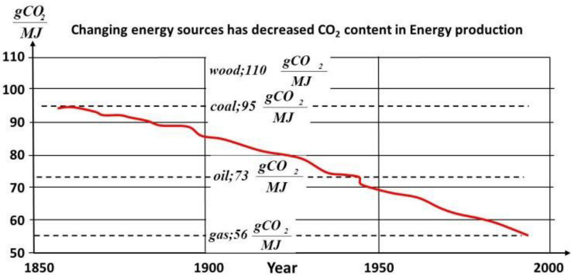

Fig. 1. How fuel source carbon content has changed [1].

Unfortunately, for a vast majority of industries, including general manufacturing, greenhouse gas emissions (and therefore the ecological footprint of their goods) are

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determined to a large extent by the energy needs of the buildings they occupy and by the fuel and electricity consumption of equipment they purchase [2]. While there are often large, cost-effective opportunities for efficiency gains in equipment and its utilization, these energy-saving strategies are not pursued as in-house energy expertise in these firms is limited [2]. Opportunities for Canadian manufacturers to improve their energy efficiency performance do exist; they are simply not being capitalized on.

2. Canadian manufacturing energy consumption trends

It is well understood that Canada, as a large country with a relatively sparse population (especially in northern regions) and cold climate, requires a significant amount of energy to sustain daily life and operate business activities [3]. However, Canada is also very wasteful in terms of its energy consumption practices, which we have known for some time.

According to the latest *"Improving Energy Performance in Canada report"* issued by Natural Resources Canada, secondary energy use increased by 23% between 1990 and 2009 [3]. Statistics from 2009 found that 37.1% of total secondary energy usage (the largest portion) belonged to the industrial sector, of which manufacturing accounted for 67.8% [4]. Likewise, the 2010 ICE (Industrial Consumption of Energy) survey estimated that Canada's manufacturing sector consumed 2136 PJ of energy for that year. To put this into perspective, this amount is roughly equal to the energy consumed for space heating, space cooling, water heating and lighting by all households and all commercial and institutional buildings in Canada in 2009 [4].

In Canada, generally, manufacturing is included under the broad canopy of the "*industrial sector*", which includes all manufacturing, mining (including oil and gas extraction), forestry, and construction activities [3]. Most of the energy consumed by the manufacturing sector is used to power the motors of auxiliary equipment, produce heat to generate steam, and to provide space heating/cooling. Despite attempts to curb energy wastage at the processing level, there still remains much room for improvement within Canada's manufacturing sector. In fact, recent studies have shown that, even with up-to-date plants and industrial processes, industrial energy efficiency can be improved by as much as 20% or more [5].

3. Influence of production rates & system parameters on energy consumption

While a plant's overall efficiency is closely related to the conversion devices (e.g. engines, motors, light bulbs) and passive systems (e.g. furnaces, steam systems) it utilizes [6], it is also heavily influenced by system factors such as production rates, design and set-up parameters.

3.1 Production rates and energy usage

Manufacturing production rates, which have been studied extensively by Gutowski et al, have been found to be closely related to the efficiency of a manufacturing process [7].

All manufacturing processes involve some utilization of energy to convert material inputs into products and generated waste streams. In a simplifying manner, manufacturing can be thought of as a series of steps which, when taken together, generate a final product. In many cases a number of different processes can be combined into a single machine. However, while modern equipment has greatly reduced the number of separate steps involved, a significant increase in the amount of energy required to operate machinery has occurred as a result. In fact, Gutowski et al have found that additional features tend to dominate machinery energy consumption, with the effect becoming even more pronounced at low production rates [8]. This effect is demonstrated in Figure 2 below, which shows energy consumed as a function of production rate for an automobile production line.

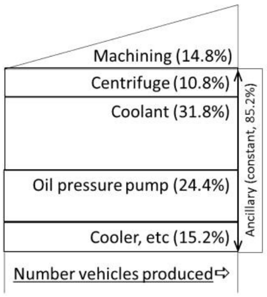

Fig. 2. Energy use as function of production rate for various stages of automobile production [8, 9].

In this example, it can be seen that only 14.8% of the total energy used is required for the actual machining process, while the rest of the energy is used by other equipment features. As well, the other features all require constant energy input (ancillary power) to operate and are not directly correlated to production rates. Branker [10] has developed a useful relationship for calculating ancillary energy (E_A), seen in Equation 1 below, where P_o is a constant or a variable function depending upon the machining process, t_s is the set-up time, t_m is the machining time, t_c is the tool change time and T is the tool life:

$$E_A = P_o\left(t_s + t_m + \frac{t_c t_m}{T}\right) \qquad (1)$$

As part of a comprehensive manufacturing process thermodynamic analysis, Gutowski et al also studied 20 different processes and characterized each of them in accordance to the material and energy resources used as a function of production rates. The results clearly show that the electricity requirements of manufacturing processes have increased greatly over the past several decades [8].

However, an individual process can improve its energy-intensity requirements by operating at a higher production rate, with the opposite being true if a reduction in material throughput occurs. This recent progression within the manufacturing sector toward lower processing rates and higher specific energy requirements is an alarming trend which needs to be closely monitored and assessed [8]. Today's modern processes, although capable of working on smaller scales and dimensional tolerances, should be focusing on improving energy requirements and manufacturing sustainability.

As a result, several strategies have been put forward which can be employed by manufacturers to improve energy efficiency of various manufacturing processes. One such strategy is to closely evaluate support equipment (machine tools and injection molding machines) requirements when purchasing or designing new equipment. The selection of all-electric rather than hydraulic systems, which tend to be much more energy intensive, can greatly reduce energy consumption [8]. Another recommendation is to increase the rate of material throughput for specific manufacturing processes, and to ensure that, where possible, machinery is being used to its full-capacity as to avoid energy loss from idle equipment requirements.

3.2 Machining case study

Of particular concern is machining, one of the most widely used manufacturing processes. The sensitivity of machining energy consumption to variations in system parameters was examined in a study by Munoz and Sheng [11]. The effects of these factors were evaluated for both high-rate transfer line and flexible job shop environments. The objective of the study was to present an integrated analysis of the energy footprint of machining processes and to identify principal methods for minimizing the environmental impact of such practices [11]. Through analysis, the effects of changes in operating, set-up, and design parameters on process energy consumption were estimated and later verified by Branker [10].

Munoz and Sheng determined that process energy is independent of operating parameters such as tool speed, feed, and cut depth. However, the results of the case study showed that the selection of cutting-fluid (set-up parameter) heavily influenced energy consumption, as did several design parameters including the geometry of a designed part (dictating the volume of material removed), and work piece material selection (determining the hardness and the shear strength). These parameters can have a significant impact on energy wastage and must be taken into consideration when designing a product for manufacture, as well as when establishing the set-up of a particular production system. The results also showed that set-up planning for energy consumption becomes more significant for a job shop environment than for a transfer line [11].

4. Auxiliary & heating equipment energy consumption

One of the largest industrial energy requirements comes from auxiliary equipment. This includes pumping systems, fans and blowers, compressed air systems [12], and motor/drive systems. The enormous energy consumption by auxiliary equipment is due largely to the use of inefficient equipment and designs

Fortunately, a number of solutions exist for many auxiliary energy issues. These solutions are often simple and cheap to implement if a facility is able to identify their system's main energy needs and sources of inefficiency. The warning signs and solutions outlined in this paper are a summary of the more detailed sourcebooks that have been developed by the U.S. Department of Energy (DOE).

4.1 Pumping systems

Pumps are widely used in industry to provide cooling and lubrication services, to transfer fluids for processing, and to provide motive forces in hydraulic systems [13]. They are essential to the daily operations of many manufacturing facilities so reliability is of high importance. Ensuring that system needs are met during worst-case conditions can cause designers to specify equipment that is oversized for normal operation. Designers try to improve pumping system reliability by oversizing equipment but the result is often less reliability due to additional wear on equipment and low-efficiency operation [13].

Common warning signs of inefficient pumping system operation include excessive noise in pipes and across valves, highly throttled flow control valves, heavy use of by-pass lines, heavy maintenance requirements (frequent replacement of seals & bearings), intermittent pump operation, and high energy costs [13]. These system inefficiencies can be caused by a number of problems including improper pump selection, poor system design, excessive wear-ring clearances, and wasteful flow control practices.

In systems served by oversized pumps, several corrective measures can be taken to lower system operating costs and extend equipment maintenance intervals. The best correct measure to choose will depend on the system in question and on the particular indicator that points to the oversized pump problem [13]. An obvious remedy is to replace the pump/motor assembly with a more appropriately-sized version; however this is costly and may not be feasible in all situations. Alternatives to replacing the entire pump/motor assembly include replacing an existing pump impeller with a smaller impeller, reducing the outside diameter of the existing impeller (impeller trimming), installing an adjustable speed drive (ASD) to control the pump if flow varies over time, and adding a smaller pump to reduce the intermittent operation of the existing pump (pony pump) [13].

In addition to making alterations to pumps, the piping configuration within a system can also be adjusted to make operations more efficient, including determining the proper pipe size, designing a piping system layout that minimizes pressure drops, and selecting low-loss components [13]. As well, systems should be designed to avoid non-uniform flow at the pump inlet. Care must be taken, however, to ensure that the pressure drop across a flow straightener does not cause cavitation [13].

4.2 Compressed air systems

Another vital piece of auxiliary equipment within the manufacturing sector is compressed air. Almost every industrial plant, from a small machine shop to a large-scale facility, has some type of compressed air system [12]. Investing in compressed air system upgrades or improvements can result in energy savings from 20-50% or more of electricity consumption.

Leaks are a significant source of wasted energy in industrial compressed air systems, sometimes wasting up to 20-30% of a compressor's output [12, 14]. As a result, it is important for manufacturers to regularly monitor their compressed air systems and mitigate leak sources where possible. In addition to being a source of wasted energy, leaks can also contribute to other operating losses, such as system pressure drops, increased running time, and added unnecessary compressor capacity.

There are a number of available fixes for compressed air leaks, with many being cheap and easy to implement. Since leaks occur most commonly near joints and connections, fixing leaks may be as easy as ensuring joining areas are sufficiently tightened [14]. As well, selecting high quality fittings, disconnects, and tubing, and installing them properly with appropriate thread sealant will help reduce the occurrence of compressed air leaks.

Non-operating equipment can be an additional source of leaks. As a result, equipment no longer in use should be isolated by installing a valve in the distribution system [14]. Another way to reduce leaks is to lower the air pressure of the system. The lower the pressure, the lower the rate of flow, which results in reduced leakage rates. In some cases, the replacement of aging or faulty equipment, such as couplings, fittings, and drains, may be required.

Once leaks have been repaired, it is important to continue to monitor a compressed air system to ensure system performance is being maintained. In particular, the compressor control system should be re-evaluated periodically to ensure maximum system efficiency is being achieved and to determine potential sources of energy savings [14].

4.3 Motors

Motors are the backbone of the industrial sector; practically every step within a manufacturing process utilizes one or more motors during the course of production. Understanding the requirements of a system and how to size a motor accordingly is an important first step in the motor selection process [15].

Motor efficiencies vary according to several factors but generally range from 85-97% at full load [15]. Two of the primary factors affecting motor efficiency are speed (high-speed motors tend to be more efficient) and motor size (larger motors tend to be more efficient). Unfortunately, motors are often chosen to meet peak loading, meaning they are grossly oversized for day-to-day operations, resulting in poor overall system performance, increased maintenance and decreased reliability [15]. A more effective way of ensuring high reliability is to design a system and specify system components so that the system's operating efficiency is high over the full range of operating conditions.

A number of indicators of poor system design and inefficient motor operation exist including high energy costs, abrupt or frequent system start/stops, high noise levels, hot work environments, and frequent maintenance requirements [15].

Electric motors are relatively inefficient when they are operated at light loads (below 40% of rated load) and are most efficient at about 70-80% load. A good rule of thumb is to size motors to operate at about 75% load [15]. While oversizing motors tends to be the largest issue within industry, undersizing motors can be equally problematic as it causes elevated winding temperatures, which can shorten the operating life of the motor. As a rule of thumb, every 10ºC rise in winding temperature reduces insulation life by half [15].

One of the most common ways to improve the efficiency of a motor system is to simply replace a motor with one of a more appropriate size or type. However, this solution can often be costly as it requires the premature replacement of key equipment. A cheaper alternative can be to install a speed-adjusting device on the motor. The advantages of using motor speed control include lower system energy costs, improved system reliability, reduced maintenance requirements and more effective process control [15].

4.4 Process heating systems

Process heating systems are also an essential aspect in the manufacture of most products and they can be broken into three basic categories: 1) fuel-based, 2) electric-based, and 3) steam-based process heating, with the type of heating source selected depending on the availability, cost, and efficiency of energy sources in a particular area [16].

In order to identify process heating improvement opportunities within the manufacturing sector it is helpful to understand common losses and avoidable costs within heating systems. Unfortunately, many companies focus on productivity related issues and overlook energy savings available from industrial utility systems, such as process heating.

4.4.1 Fuel-based process heating systems

Opportunities to improve fuel-based heating efficiency are related to optimizing the combustion process, extracting and/or recovering energy from the exhaust gases, and reducing the amount of energy lost to the environment [16].

Some common inefficiency warning signs within fuel-based heating systems include the presence of combustion air leaks downstream of a control valve, poor control of the system's fuel/air mixture over its range of operating conditions, higher than necessary operating and exhaust gas temperatures, localized cold spots, furnace shell and casing conditions such as hot spots, cracks, or insulation detachment, as well as piping insulation sagging and distortion [16].

Major loss sources from fuel-based process heating systems include the walls, air infiltration, openings in furnace walls and doors, water or air-cooled parts within the system, extended parts from the furnace, and poor insulation [16]. Insulating materials, such as brick, heat-shields, and fibre mats, as well as the proper sealing of openings, are essential in minimizing heat that can be lost to the surroundings. Fixing leaks around the furnace chamber and properly operating a pressure control system can be a cost-effective way to improve furnace efficiency. As well, water or air-cooled parts should be avoided where possible or insulated to avoid direct exposure to the hot furnace surroundings and the extension of parts from the furnace itself should also be appropriately considered in the design stage in order to mitigate heat loss [16].

Heat transfer improvements can be made by maintaining clean heat transfer surfaces by using soot blowers in boilers, burning off carbon and other deposits from radiant tubes, cleaning heat exchanger surfaces and by establishing proper furnace zone temperatures to increase heat transfer [16].

4.4.2 Steam-based process heating systems

Boilers account for a significant amount of the energy used in industrial process heating. In fact, the fuel used to generate steam accounts for 84% of the total energy used in the pulp and paper industry, 47% of the energy used in the chemical manufacturing industry, and 51% of the energy used in the petroleum refining industry [17].

Steam-based process heating can be very complex and as a result a number of sources of inefficiency can arise within a system. The most common sources of loss within a steam system include the presence of excess air, clogging of boiler surfaces, steam leaks, steam ventilation, inadequate piping, valve, fitting, and vessel insulation, unused lines within the system, and the loss of heat through exhaust flue streams [17].

Fortunately, mitigation strategies and techniques exist to deal with such losses including increasing the thickness of insulation within the system to reduce heat loss from piping and equipment surfaces, monitoring boiler surfaces and cleaning them regularly to promote effective heat transfer from combustion gases to the steam, regularly monitoring for steam leaks and repairing them where to possible to mitigate steam loss, and isolating steam from unused lines in order to minimize avoidable losses [17].

One or all of the above mentioned techniques, in addition to regular system maintenance, monitoring, and upgrading can ensure a highly efficient process heating system is achieved.

5 Waste heat recovery systems

Waste heat recovery offers the manufacturing sector an incredible opportunity to save energy and improve efficiency. It is estimated that somewhere between 20-50% of industrial energy input is lost as waste heat in the form of hot exhaust gases, cooling water, or heat lost from equipment surfaces and heated products [18].

Numerous technologies are commercially available for waste heat recovery and a number of industrial facilities have upgraded or are improving their energy productivity by installing these technologies. Despite this, waste heat recovery remains relatively unexplored. This is largely due to the fact that heat recovery isn't feasible or possible in certain instances and a number of barriers exist to the implementation of these technologies [18].

In March of 2008 the DOE in the U.S., under its Industrial Technologies Program (ITP), had a waste heat recovery study conducted by BCS Incorporated. The study was a comprehensive investigation into current industrial waste heat recovery practices, opportunities, and barriers. The information utilized within this section draws largely from the conclusions and recommendations of that study.

In general three essential components are required for waste heat recovery to be successful: 1) accessible source of waste heat, 2) recovery technology, and 3) use for the recovered energy [18]. Despite the significant environmental and energy benefits of waste heat recovery, its implementation depends primarily on the economics and perceived technical risks, with most industrial manufacturing facilities are unlikely to invest in waste heat recovery projects that have a payback period of more than 3 years [18].

Evaluating the feasibility of waste heat recovery requires characterizing the waste heat source and the stream to which the heat will be transferred. Important waste stream parameters include heat quantity or a measure of how much energy is contained in a waste heat stream, heat quality, waste stream temperature, and composition.

Temperature range has important ramifications for the selection of materials in heat exchanger designs, as corrosion and oxidation reactions, like all chemical reactions, are accelerated dramatically by temperature increases [18]. If the waste heat source contains corrosive substances, the heat recovery surfaces can quickly become damaged and certain materials, like carbon steel above 425ºC and stainless steel above 650ºC, can begin to oxidize. As well, heat transfer rates in heat exchangers are highly dependent on composition and phase of waste heat streams and the deposition of fouling substances. Methods for addressing fouling include filtering contaminated streams, constructing the exchanger with advanced materials, increasing heat exchanger surface areas, and designing the heat exchanger for easy access and cleaning [18].

Several additional factors can determine whether heat recovery is feasible in a given application. For example, small-scale operations are less likely to install heat recovery systems, since sufficient capital may not be available, and because payback periods may be longer. Another concern is the ease of access to the waste heat source. In some cases, the physical constraints created by equipment arrangements prevent easy access to the heat source, or prevent the installation of any additional equipment for recovering the heat [18]. Additionally, constraints are presented by the transportability of heat streams. Hot liquid streams in process industries are frequently recovered, since they are easily transportable. Piping systems are easy to tap into and the energy can be easily transported via piping to the recovery equipment. In contrast, hot solid streams (e.g. ingots, castings) can contain significant amounts of energy but it is not easily accessible or transportable to recovery equipment [18]. As a result, waste energy recovery is not widely practiced with hot solid materials.

6 Tools and resources for Canadian manufacturers

Energy efficiency presents enormous opportunities for Canada, saving Canadians money, stimulating economic growth and job creation, increasing productivity, improving our competitiveness and increasing exports [3]. Not only does increased efficiency offer the potential for significant economic savings, it also provides a significant reduction in environmental impact. In fact, improving energy efficiency levels within the general manufacturing sector is one of the most cost-effective ways that Canada can meet its emission reduction target of 17% below 2005 levels by 2020 [3].

6.1 Tools

As previously mentioned enormous energy savings can result by improving the efficiency of industrial systems, however many companies shy away from these opportunities due to lack of expertise or inadequate resources. Fortunately, a number of programs and resources exist which can aid in the implementation of efficiency improvement strategies.

Some examples of useful software programs for manufacturers looking to improve their facilities' energy efficiency include the Pumping System Assessment Tool (PSAT), the MotorMaster+ database, the AirMaster+ program, and the Process Heating Assessment and Survey Tool (PHAST), available through the U.S. DOE. These programs are designed to help industrial users assess the efficiency of their auxiliary and process heating systems. They use the most up-to-date performance data available to calculate potential savings in energy and the costs associated with system modifications. It can be extremely beneficial for manufacturing facilities, both large and small, to use these programs, as it saves both time and resources and allows companies to focus efficiency programs on the most effective areas.

6.2 Canadian industrial example

A Canadian jet fan manufacturer is an example of a company that has been proactive in increasing manufacturing efficiency and environmental performance, including the reduction of waste products and toxins from all its manufacturing facilities.

The company has undertaken a number of energy efficiency initiatives at two separate manufacturing facilities. In one facility this includes the consolidation of an existing boiler system. In Canada, gas and oil boilers under 300 000 Btu/hr (88kW) are regulated under the Canadian Energy Efficiency Act [19], hence compliance with the Act was necessary. In the U.S. boilers over 300 000 Btu/hr (88kW) are subject to standards under the National Energy Policy Act, which states that large gas-fired boilers must have a steady-state thermal efficiency of at least 80%, and large oil-fired boilers must have a steady-state thermal efficiency of at least 83%.

The project involved the replacement of the plant's original oil-fired boilers with natural gas fired boilers. Prior to the project, the plant burned heating and waste oil in its four boilers – two for hot water and two for steam. The steam was used for process heating and hot water for perimeter heating. It was originally assumed that the steam and hot water boilers were 70% efficient and that they were running at more than 75% capacity year round, hence any increase in efficiency would result in savings. Engineering analysis of the existing boiler system, as per the Act, showed the boilers were only operating under 40% capacity and were highly fouled and inefficient (less than 50%).

By consolidating the boiler system and converting to natural gas, which emits $56 \frac{gCO_2}{MJ}$ [1] there was a reduction of 680-780 Mt of CO_{2e}. As well, the project, which cost roughly $450k to install, is estimated to save roughly $180-350k annually, with a payback period of only 1.5-2 years. This project clearly demonstrates the enormous opportunities available to manufacturers to reduce both their cost and emissions.

7 Conclusions

It is clear from the existing literature that it is quite possible for Canada's industrial sector to become more energy efficient, with very little overhaul of its current facilities or processes. While making progress in the area of energy efficiency is often deemed to be too difficult, time-consuming, and expensive, in many instances the exact opposite is true. Often the savings available to manufacturers from energy efficiency projects far outweigh any incurred project implementation costs, as can be seen from the case study cited in section 6.

One of the major barriers to energy efficiency improvement within Canadian manufacturing remains the mind-set and attitude toward sustainable product development in industry. Instead of viewing efficiency requirements as a problem, companies must look at them for what they really are – a chance for companies to simultaneously yield economic and environmental benefits. Major gains in Canadian industrial energy consumption are quite possible, we need only open our minds to the idea that these gains are worth the effort. After all, "*one of the greatest sources of untapped energy is the energy we waste*."[3] It's time we started using or at least reducing it!

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