STRATEGIES TO IMPROVE INDUSTRIAL ENERGY EFFICIENCY

by

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Abstract

Often times a lack of technical expertise, fueled by a lack of positive examples, leads to companies opting not to implement energy reduction projects unless mandated by legislation. As a result, companies are missing out on exceptional opportunities to improve not only their environmental record but also save considerably on fuel costs. This study investigates the broad topic of energy efficiency within the context of the industrial sector by means of a thorough review of existing energy reduction strategies and a demonstration of their successful implementation by obtaining data directly from companies. New information pertaining to industrial energy reduction, provided by several companies, is shown as case studies in this thesis.

The study begins by discussing current industrial energy consumption trends around the globe and within the Canadian manufacturing sector. This is followed by a literature review which outlines 3 prominent energy efficiency improvement strategies currently available to companies: 1) Waste heat recovery, 2) Idle power loss reduction and production rate optimization, and lastly 3) Auxiliary equipment operational performance. Next, a broad overview of the resources and tools available to organizations looking to improve their industrial energy efficiency is provided. Following this, several case studies are presented which demonstrate the potential benefits that are available to Canadian organizations looking to improve their energy efficiency. The information which is presented within the case studies is original data which was collected directly from companies for the sole purpose of this study. Lastly, a discussion of a number of issues and barriers pertaining to the wide-scale implementation of industrial efficiency strategies is presented. It discusses a number of potential roadblocks, including a lack of energy consumption monitoring and data transparency.

While this topic has been well researched in the past in terms of the losses encountered during various general manufacturing process streams, practically no literature exists which attempts to provide real data from companies who have implemented energy efficiency strategies. By obtaining original data directly from companies, this thesis demonstrates the potential for companies to save money and reduce
GHG (greenhouse gas) emissions through the implementation of energy efficiency projects and publishes numbers which are almost impossible to find directly. By publishing success stories, it is hoped that other companies, especially SMEs (small and medium enterprises) will be able to learn from these case studies and be inspired to embark on energy efficiency projects of their own.
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# Table of Contents

Abstract .......................................................................................................................................................... ii
Acknowledgements ........................................................................................................................................ iv
List of Figures ................................................................................................................................................ ix
List of Tables ............................................................................................................................................... xi
List of Nomenclature .................................................................................................................................. xii
Chapter 1 Introduction ................................................................................................................................ 1
Chapter 2 Literature Review ....................................................................................................................... 12
  2.1 Waste Heat Recovery ........................................................................................................................ 14
    2.1.1 WHR technologies ...................................................................................................................... 15
      2.1.1.1 Direct Usage [24] ............................................................................................................... 16
      2.1.1.2 Heat Exchangers [24] ......................................................................................................... 17
      2.1.1.3 Heat Pumps [24,26] .......................................................................................................... 22
      2.1.1.4 Vapour Recompression [24] .............................................................................................. 23
    2.1.2 Combined heat and power (CHP) as an indicator of WHR success ........................................... 24
    2.1.3 Barriers of WHR ....................................................................................................................... 26
      2.1.3.1 Temperature, Waste Stream Composition, and Material Selection .................................. 26
      2.1.3.2 Operating Conditions and Logistics [22] ......................................................................... 27
      2.1.3.3 Low-grade Waste Heat ................................................................................................... 28
      2.1.3.4 WHR from Solid Streams (Manufacturing) ...................................................................... 30
      2.1.3.5 WHR Policies .................................................................................................................. 31
    2.2 Idle Power Losses and Production Rates ......................................................................................... 33
    2.3 Auxiliary Equipment Requirements ............................................................................................ 41
      2.3.1 Pumping systems ..................................................................................................................... 41
        2.3.1.1 Pumping System Principles ............................................................................................. 42
        2.3.1.2 Pump Reliability ............................................................................................................. 44
        2.3.1.3 Pump Efficiency [46] ..................................................................................................... 45
        2.3.1.4 Warning Signs of Inefficient Pumping Systems .............................................................. 45
        2.3.1.5 Corrective Measures for Inefficient Pumping Systems [46] ............................................ 47
        2.3.1.6 Piping Configurations to Improve Pumping Efficiency .................................................. 49
        2.3.1.7 Pump Concerns [46] ....................................................................................................... 51
        2.3.1.8 Rules of Thumb for Improving Piping Configurations [46] ............................................. 53
      2.3.2 Compressed air systems ........................................................................................................... 55
2.3.2.1 Compressed Air System Basics ................................................................. 56
2.3.2.2 Wasteful Compressed Air Practices .......................................................... 57
2.3.2.3 Compressed Air Load Profiles ................................................................. 59
2.3.2.4 Compressed Air System Leaks ................................................................. 59
2.3.2.5 Compressed Air System Pressure Drops ............................................... 62
2.3.2.6 Compressed Air System Controls ......................................................... 63
2.3.2.7 Multi-stage Compression and Multiple Compressors [49] ......................... 65

2.3.3 Motor and drive systems ............................................................................. 66
2.3.3.1 Indications of Poor System Design [50] .................................................. 67
2.3.3.2 Matching Motors to Applications [50] .................................................... 68
2.3.3.3 Common Motor Selection Problems [50] ................................................. 69
2.3.3.4 Efficiency Improvement Strategies ......................................................... 70

Chapter 3 Available Tools and Programs ................................................................. 72
3.1 DOE Energy Efficiency Tools ......................................................................... 74
3.1.1 Pumping system assessment tool (PSAT) .................................................. 74
3.1.2 AIRMaster+ Program ................................................................................ 76
3.1.3 MotorMaster+ ............................................................................................ 77
3.1.4 Process Heating Assessment and Survey Tool (PHAST) ......................... 78

3.2 Modelling Programs ....................................................................................... 79
3.2.1 e!Sankey .................................................................................................... 79

3.3 Matching Inefficiencies and Software Programs .......................................... 81

3.4 Government Programs .................................................................................. 83
3.4.1 CAN/CSA-ISO 50001 Energy Management System ................................... 83
3.4.2 CIPEC [59] ............................................................................................... 83
3.4.3 ecoENERGY ............................................................................................ 84
3.4.4 CanmetENERGY [62] ............................................................................. 84
3.4.5 Canadian Energy Efficiency Act and MEPS ............................................. 85

Chapter 4 Canadian Industrial Case Studies .......................................................... 87
4.1 Pratt and Whitney Canada ............................................................................. 88
4.1.1 Boiler consolidation – Halifax facility ....................................................... 88
4.1.2 Industrial cooling water plant heating project – Montreal facility .......... 89

4.2 Magna International Inc. ............................................................................... 91
4.2.1 Hot stamp heat recovery: ........................................................................ 91
4.2.2 Air curtain installation: ............................................................................ 91
Chapter 5 A Discussion of the Need for Better Monitoring and the Creation of an Open Dialogue Surrounding Energy Consumption in Industry ................................................................. 97
5.1 Application of System Dynamics ................................................................. 104
Chapter 6 Conclusions and Recommendations ............................................. 107
List of Figures

| Figure | Description                                                                 | Page |
|--------|-----------------------------------------------------------------------------|------|
| 1      | Global energy consumption and GHG emissions for 1973 and 2011 [1]            | 2    |
| 2      | Share of total global energy use by sector for 2011 [14]                    | 6    |
| 3      | Energy use in Canada by sector [15]                                         | 6    |
| 4      | The three spheres of sustainability [21]                                    | 10   |
| 5      | Metallic radiation recuperator (left); Combination radiation/convection recuperator (right) [22] | 18   |
| 6      | Regenerative furnace design [22]                                            | 19   |
| 7      | Rotary regenerator (heat wheel) design [25]                                 | 20   |
| 8      | Passive gas-to-gas pre-heater (top); Heat pipe heat exchanger (bottom) [22] | 21   |
| 9      | Finned-tube heat exchanger (boiler economizer) design [22]                  | 22   |
| 10     | Heat pump cycle [26]                                                        | 23   |
| 11     | Mechanical vapour recompression [27]                                         | 24   |
| 12     | Conventional energy system efficiency [31]                                  | 25   |
| 13     | Recovery potential of various temperature groups [22]                       | 29   |
| 14     | Energy and material inputs and outputs for manufacturing processes [44]      | 34   |
| 15     | Energy use as function of production rate for various stages of automobile production [44] | 35   |
| 16     | P_o vs. k power requirements as a function of process rate [44]             | 36   |
| 17     | Specific electricity requirements of manufacturing processes as a function of process rate [44] | 37   |
| 18     | Specific energy requirements (SEC) or energy intensity of hydraulic vs. all-electric injection molding machines as a function of process rate [44] | 40   |
| 19     | A typical pumping system and its components [46]                            | 42   |
| 20     | Family of pump curves (top); Performance curves for various impeller sizes (bottom) [46] | 44   |
| 21     | Annual water pumping costs for 1000 ft of pipe of different sizes [47]      | 50   |
| 22     | Proper valve orientation [48]                                               | 51   |
| 23     | Examples of correct vs. incorrect piping system layouts [46]                | 53   |
| 24     | Example of a flow straightener [46]                                         | 54   |
| 25     | Proper support of suction and discharge piping [46]                         | 55   |
| 26     | Components and layout of a standard compressed air system [49]              | 57   |
| 27     | Cost vs. compressed air leak size [49]                                       | 60   |
| 28     | e!Sankey steel reheat furnace representation [57]                            | 81   |
Figure 29: Breakdown of residential and commercial energy usage by purpose (industrial sector unavailable) [7] .................................................................................................................................................................................. 101
Figure 30: Proposed SD diagram for auxiliary systems and monitoring [18] ................................................................. 106
List of Tables

Table 1: Canadian and Scandinavian vs. global energy consumption and emission levels ......................... 4
Table 2: Sample of available energy efficiency reference information ...................................................... 12
Table 3: Potential waste heat sources and end-uses [22] ........................................................................... 15
Table 4: Summary of WHR Technologies [24] ......................................................................................... 16
Table 5: Inefficiency sources, warning signs, and software tools .............................................................. 82
Table 6: MEPS for gas powered boilers [63] ............................................................................................ 86
Table 7: Boiler consolidation project summary ........................................................................................ 89
Table 8: Natural gas consumption and cost summary for PWC's WHR project ....................................... 90
Table 9: Summary of PWC's WHR project ............................................................................................. 90
Table 10: A summary of Magna's key 2013 energy conservation projects ............................................. 94
List of Nomenclature

AC – Alternating current
ASD – Adjustable speed drive
BEP – Best efficiency point
BF – By-product fuels
CHP – Combined heat and power
CIPEC – Canadian Industry Program for Energy Conservation
CSA – Canadian Standards Association
CVD – Chemical vapour deposition
DC – Direct current
EDM – Electrical discharge machining
EGS – Electronic grade silicon
ERIP – Electricity Retrofit Incentive Program
EU – European Union
FRLs – Filters, regulators, and lubricators
GHG – Greenhouse gas(es)
GJ – Gigajoule
Gt – Gigatonne
hp – Horsepower
HVAC – Heating, ventilation, and air-conditioning
ICE survey – Industrial Consumption of Energy survey
IECS – Institute for Environmental Computer Science
IHEA – Industrial Heating Equipment Association
ISO – International Organization for Standardization
IEA – International Energy Association
ITP – Industrial Technologies Program
LCA – Life cycle analysis
kW – Kilowatt
kWhr – Kilowatt hour
MEPS – Minimum energy performance standard
Mt – Megatonne
Mtoe – Mega toe (tonne of oil equivalent)
NEMA – National Electrical Manufacturers Association
NR Canada – Natural Resources Canada
ORC – Organic Rankine Cycle
PHAST – Process Heating Assessment and Survey Tool
P&G – Proctor and Gamble
PJ - Petajoule
PPM – Parts per million
PSAT – Pumping System Assessment Tool
psi – Pounds per square inch
PWC – Pratt and Whitney Canada
SD – System dynamics
SILC – Sustainable Industry Low Carbon
SMEs – Small and medium enterprises
SPIRE – Sustainable Process Industry through Resource and Energy Efficiency
tCO2e – Tonnes of CO2 equivalent
TFC – Total final consumption
UNEP – United Nations Environment Programme
U.S DOE – United States Department of Energy
U.S. EIA – United States Energy Information Administration
VFD – Variable frequency drive
WHR – Waste heat recovery

**List of Variables**

\[ P \] – Total power requirement of a machine (kW)
\[ P_o \] – Required idle power of a machine (kW)
\[ \dot{v} \] – Rate of material processing (cm\(^3\)/s)
\[ k \] – Physical constant associated with the machine (kJ/cm\(^3\))
Chapter 1

Introduction

For decades, scientists – from biologists to climatologists – have warned that the unregulated burning of fossil-based fuels could have devastating effects on the ecosystems of our planet. Despite these dire repercussions, we still rely heavily on fossil fuels for almost all of our daily needs. A large portion of today’s prominent industries have either been created or drastically changed by the use of such fuels. It is the general belief that the 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.

According to the 2013 IEA (International Energy Association) Key World Energy Statistics Report, the total final consumption (TFC), defined as the sum of all the energy consumed by the different end-use sectors, has doubled since 1973 [1]. Accompanying this trend of rampant energy consumption is the continued rise of global greenhouse gas (GHG) emissions, which have also roughly doubled over the last 40 years [1]. These statistics, shown in Mtoe or mega tonnes of oil equivalent (toe), are represented in Figure 1 below. It should be noted that a tonne of oil equivalent (toe) is a unit of energy defined as the amount of energy released by burning one tonne of crude oil [2].
This trend, unfortunately, shows no sign of stopping or even slowing in the near future. According to the UNEP’s (United Nations Environment Programme) 2012 Emissions Gap Report, global GHG emissions were estimated to be 50.1 Gt CO₂e, which is roughly 20% higher than emissions were in 2000 and an estimated 14% higher than the 2020 emission target which has been set in order to limit global warming to 2°C [3]. An upturn in global emissions has also been seen in the last several years, following a slight decline during the economic downturn period between 2008 and 2009 [3]. As the world’s population continues to climb (9 billion by 2050, according to statistics released by the United Nations [4]) and those in the developing world look to achieve the same standard of living as the West, fuel consumption and associated
GHG emissions will only continue to rise unless the way we value energy and the consequences for excessive emissions from companies begins to change. In fact, the U.S. Energy Information Administration (EIA) estimates that fuel consumption in Asia alone will increase by 23% between 2010 and 2015 [5] and April of this year marked the first time in recorded human history that the average concentration of carbon dioxide in the Earth’s atmosphere sustained levels of over 400 ppm (parts per million) for an entire month [6].

Increasing energy consumption has also become prevalent within Canada in recent years. Upon analysing global energy consumption trends, national trends were researched to better understand how Canada fits into the global energy scheme. According to the Natural Resources’ “Improving Energy Performance in Canada Report”, Canada’s total energy consumption or primary energy\(^1\) use for 2009 was estimated to be 11,897 PJ [7]. To put this into perspective, a PJ (petajoule) is equal to \(10^{15}\) J of energy, an almost incomprehensible quantity. Table 1 below is used to compare Canadian and Scandinavian (cold-climate) population, energy consumption, and GHG emission data to that of global trends in an attempt to demonstrate the impact of population density and climate on the overall global energy structure.

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\(^1\) In general, there are two main types of energy use: 1) primary and 2) secondary. Primary energy use represents total energy consumption and includes the energy required to transform energy from one form to another (ex. coal to electricity) and the energy required to deliver energy to consumers [7]. Secondary energy use refers to the energy consumed for residential, commercial/institutional, industrial, transportation, and agricultural purposes [7]. Secondary use is what most of us refer to when we use the term “energy” – it is what turns on lights, powers appliances, and runs offices.
### Table 1: Canadian and Scandinavian vs. global energy consumption and emission levels

|                | POPULATION     | POPULATION DENSITY (ppl/km²) | ENERGY CONSUMPTION (PJ) | GHG EMISSIONS (Mt) |
|----------------|----------------|------------------------------|-------------------------|--------------------|
| **CANADA**     | 35,158,300 [8] | 3.5 [9]                      | 11,863.3 [7]            | 692.4 [7]          |
| **NORWAY**     | 5,084,000 [10]| 12.9 [10]                    | 793.4[11]               | 53.4 [11]          |
| **SWEDEN**     | 9,449,000 [12]| 21.0 [12]                    | 1346.8 [11]             | 61.4 [11]          |
| **WORLD**      | 7,114,000000 [13]|              | 373,378.8 [1]          | 31,342 [1]        |
| Canada’s % Contribution | 0.49% |                          | 3.19%                   | 2.21%              |
| Norway’s % Contribution | 0.07% |                          | 0.21%                   | 0.17%              |
| Sweden’s % Contribution | 0.13% |                          | 0.36%                   | 0.20%              |

It can be seen that Canada, while contributing less than 0.5% of the world’s population, contributes more than 3% of global energy consumption and 2% of GHG emissions. This means that Canada currently exceeds its consumption and emission allowance, by proportion of the global population, by 6.5 and 4.5 times respectively. 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 [7]. However, an abundance of inexpensive energy within the country has created a culture of
overconsumption and resulted in the inefficient use of important fossil-based natural resources in recent years.

This can be seen by comparing our consumption and emission data to that of 2 Scandinavian countries (Norway and Sweden). Both Norway and Sweden have small population densities (a little larger than that of Canada, but still within magnitude) and have to deal with the added energy requirements that come with living in a cold climate. However, despite these hurdles, both Sweden and Norway’s energy consumption and GHG emissions are much more in line with their population than here in Canada. Norway’s energy consumption is roughly 3 times what is allotted for its population, while Sweden’s is 2.8 times this allotment. Likewise, Norway’s emissions are 2.4 times what is allotted for its population and Sweden exceeds its emissions allowance by 1.5 times. While both countries still exceed what would be considered appropriate given their respective populations, they do a much better job at curbing both their consumption and emissions as compared to here in Canada, where our cold climate and sparse population appear to be used as a crutch and as an acceptable reason for our rising emission levels.

Further analysis of global energy consumption trends indicates that no other area consumes more energy across the globe than the industrial sector, within which the largest consumer is manufacturing. Statistics from the U.S. EIA [14], as seen in Figure 2 below, indicate that 51% of global energy was consumed by industry in 2011, far exceeding any other major end-use sector.
Looking further into the breakdown of Canada’s energy consumption, a similar trend emerges. In 2009, 37.1% of total secondary energy usage (the largest portion) belonged to the industrial sector, of which manufacturing accounted for 67.8% [15], as seen in Figure 3 below. From these statistics, it can be seen that the industrial sector is responsible for the largest quantity of Canada’s overall energy needs and is therefore the greatest source of our emissions.

The 2010 ICE (Industrial Consumption of Energy) survey [15] estimates that Canada’s manufacturing sector consumed 2135.9 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 commercial and institutional buildings in Canada in 2009 [15].

This should come as no surprise, as it takes an enormous amount of energy to operate the machinery, tools, and processing systems which create most of the goods used in today’s society [16]. Most of the energy consumed by the industrial sector is used to power the motors of auxiliary equipment, produce heat to generate steam, and provide space heating/cooling. From melting iron in furnaces to pumping coolant to maintain key production equipment, many of today’s industrial processes utilize enormous quantities of energy, often inefficiently.

Recent pressure on industries to be more environmentally conscious and the development of more stringent energy regulations has created a growing emphasis on energy efficiency (within both academia and industry) and the importance it will play in successfully achieving global GHG reduction targets [17]. In recent years, governments across the globe – from Europe and Asia, to North and South America – have identified improved efficiency as a fundamental component of their energy and environmental strategies [18]. Unfortunately, very little has actually been done over the last several decades to curb global energy consumption. Energy efficiency project deployment has been minimal despite extensive research on the topic and a boost of technological developments in the field [17].

This must begin to change if we want to see a downturn in global GHG emission levels by the middle of the century. Energy efficiency improvements offer an excellent opportunity for industry to reduce its environmental footprint while simultaneously saving millions of dollars and becoming more economically competitive with very little overhaul of current facilities or processes. Curbing consumption requirements at the processing level (through equipment and system improvements) could help make Canadian manufacturing more eco-friendly and also cost-effective.
Information on how to determine the most prominent areas of inefficiency and the best ways for companies to meet their energy reduction targets is available from a number of sources including government agencies such as Natural Resources Canada’s Office of Energy Efficiency, energy corporations such as HydroOne in Ontario, and energy management organizations, who work to develop energy solutions for companies. Energy reduction strategies and technologies for companies to begin to improve their overall energy efficiency already exist and have been around for quite some time, however, they are simply not being capitalized on. A number of major energy pitfalls will need to be addressed in order for Canada to significantly improve its manufacturing energy efficiency track record. 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 [19]. These efficiency improvements can come from a number of different areas, including recycling waste energy from equipment and process streams, using auxiliary equipment with more efficient motive systems, and reducing idle power requirements within facilities.

It is clear that there is room for Canadian industry to improve their current energy consumption practices. By simply improving regular maintenance schedules or by increasing the frequency of energy audits, companies can be made more aware of their energy needs and identify areas which can be improved upon. When it comes to manufacturing, in terms of efficiency gains, small changes can mean big savings. 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.

A major barrier to energy efficiency improvement within Canada’s manufacturing sector remains the mind-set and attitude toward sustainable product development in industry. It is important to note that this observation did not arise from a review of academic papers on the
subject, but was identified during meetings held with energy managers for two major Canadian corporations. Human behavior and economic barriers were noted as the number one barrier to new energy conservation project development. Instead of viewing efficiency requirements as a problem, companies must look at them for what they really are – a chance to simultaneously yield economic and environmental benefits.

The reality remains that the main driver for most energy efficiency projects is the economic benefit which often accompanies them, rather than the reduction in environmental impact. The three spheres of sustainability, as determined by Skleros [20] and shown in Figure 4 below, appear to be largely ignored within industry as emphasis remains focused upon economics alone². Unless a source of inefficiency is quite costly or effects operational performance, it is unlikely to be pursued. It is also true that in many small-scale organizations, resources and personnel are simply not available to dedicate to projects unrelated to primary production.

² It is important to note that when discussing environmental sustainability, the definition for environment is that used by Szekeres [21] This definition, which was originally adopted by the Mackenzie Valley Pipeline Environmental Impact Review Board, defines the environment as follows: the components of the Earth including (a) land, water and air, including all layers of the atmosphere; (b) all organic and inorganic matter and living organisms; and (c) the interacting natural systems that include components referred to in paragraphs (a) and (b).
As a result, the main focus of the research conducted for this thesis is to demonstrate the successful implementation within industry of energy efficiency improvement strategies. Often times a lack of technical expertise, fueled by a lack of positive examples, leads to companies opting not to implement energy reduction projects unless they are mandatory under legislation. Companies are missing out on exceptional opportunities to improve not only their environmental record, but to also save considerably on fuel costs.

After conducting extensive research to determine the most prominent areas of industrial inefficiency and the solutions available for these areas of concern, numerous companies were contacted directly to get a better understanding of their energy consumption trends and to obtain details regarding old or newly implemented energy efficiency projects and the fuel or emission reduction savings they have seen as a result of these projects. By obtaining original data directly
from companies, this thesis demonstrates the potential for companies to save money and reduce GHG emissions through the implementation of energy efficiency projects and publishes numbers which are almost impossible to find directly.

This thesis offers a fresh perspective on a persistent issue within industry: a lack of consumption data transparency. Energy consumption is often treated as a taboo subject, with many companies not tracking their consumption data or having a thorough understanding of their primary energy needs or prominent areas of inefficiency. Additionally, this thesis promotes the development of energy conservation projects within Canadian industry, as they offer manufacturers an opportunity to reduce future costs, while simultaneously reducing GHG emissions.

New data on raw fuel consumption and cost has been collected directly from Canadian manufacturers and used to develop several case studies in an attempt to demonstrate the potential benefits that can stem from the utilization of existing energy recovery technologies. The information contained within these case studies is new and fills an important gap in current energy efficiency data: that techniques and technologies available for companies to improve their energy efficiency is always cited, but quantitative data outlining the results achieved by utilizing such techniques is rarely made available. By collecting energy data directly from companies and speaking with them about this issue, success stories will be published in hopes that other companies, especially SMEs (small and medium enterprises) will be able to learn from these case studies and be inspired to embark on energy efficiency projects of their own.
Chapter 2

Literature Review

To begin, there are numerous techniques available for companies to implement to improve the energy efficiency of their equipment, processes, and overall production. Companies can work on eliminating wasted energy by altering production schedules to make better use of resources, they can implement various maintenance protocols to catch areas of concern before they become major problems, and they can use alternative energy sources to supply power to plants and facilities in order to offset some of the carbon footprint of their activities. Many of today’s organizations may argue that there is even too much information available on the subject and that deciding where to best target their energy efficiency projects can be, at times, overwhelming.

While it is true that an immense amount of information surrounding energy efficiency and strategies to improve it does exist, it is always the same type of information. Handbooks, sourcebooks, and textbooks (some dating back several decades) have been dedicated to telling companies how to detect an energy sink or an area of inefficiency and even more have been developed to offer them a variety of options that can be deployed to improve the efficiency of their equipment and systems. Table 2 below references a small sample of the resources available to companies looking for information pertaining to industrial energy efficiency.

Table 2: Sample of available energy efficiency reference information

| Reference Title                                      | Author(s)            | Year of Publication | Type of Reference |
|------------------------------------------------------|----------------------|---------------------|-------------------|
| Energy Efficiency in Industry                        | J. Sirchis           | 1990                | Textbook          |
| Energy Management Series for Industry, Commerce, and Institutions | Natural Resources Canada | 1993 | Handbook         |
| Energy Efficiency Manual                             | Donald R. Wulfinhoff | 1999                | Manual            |
| Title                                                                 | Publisher                               | Year | Type     |
|----------------------------------------------------------------------|-----------------------------------------|------|----------|
| Improving Compressed Air System Performance: A Sourcebook for Industry | U.S. DOE                                | 2003 | Sourcebook |
| Improving Steam System Performance: A Sourcebook for Industry         | U.S. DOE                                | 2004 | Sourcebook |
| Improving Pumping System Performance: A Sourcebook for Industry       | U.S. DOE                                | 2006 | Sourcebook |
| Energy-efficient Building Systems: Green Strategies for Operation and Maintenance | Lal Jayamaha                            | 2007 | Textbook |
| Improving Process Heating System Performance: A Sourcebook for Industry | U.S. DOE                                | 2007 | Sourcebook |
| Waste Heat Recovery: Technology and Opportunities                     | U.S. DOE/BCS Inc.                       | 2008 | Guidebook |
| Motor Efficiency, Selection, and Management                           | Consortium for Energy Efficiency Inc.   | 2011 | Guidebook |
| Handbook of Energy Audits                                             | Albert Thumann, Terry Niehus, William J. Younger | 2013 | Handbook |
| Improving Energy Efficiency in Industrial Energy Systems               | Patrik Thollander, Jenny Palm           | 2013 | Textbook |

However, very little of this information exists in the form of examples or real-time data from companies who have pursued such projects. Unfortunately, companies are told how much they can save by implementing a waste heat recovery (WHR) project or by installing an air curtain, but there is limited data to back up such claims – at least not from other companies who have completed similar projects.

It is this information gap that the industrial examples within the case study chapter of this thesis hope to fill, while the literature review portion of the study is dedicated to learning about the prominent sources of inefficiency that occur within industry and the strategies which are available for energy reduction.
It should be noted that for the purpose of this research, 3 prominent areas of inefficiency were focused on during the literature review: 1) Waste heat, 2) Idle power losses and production rates, and 3) Auxiliary energy requirements. A preliminary review was conducted of existing resources and materials pertaining to the field of industrial energy efficiency in order to identify commonly occurring inefficiency trends. After this was complete, the list was narrowed to the 3 areas given above and a thorough review of information pertaining to each area was then conducted – including, but not limited to, efficiency improvement strategies, implementation challenges, maintenance measures, and prominent inefficiency warning signs.

2.1 Waste Heat Recovery

Currently, one of the best ways for companies to reduce their energy consumption, without the need for vast equipment, system, and facility overhauls, is through the implementation of waste heat recovery technologies, which offer the industrial sector an incredible opportunity to save energy and improve efficiency. In fact, the United States Department of Energy (DOE) estimates that somewhere between 20 to 50% of industrial energy input is presently lost as waste heat in the form of hot exhaust gases, cooling water, or from equipment surfaces and heated products [22].

In March, 2008 the U.S. DOE, under its Industrial Technologies Program (ITP), sanctioned a waste heat recovery study which was conducted by BCS Incorporated. The study was a comprehensive investigation into current industrial waste heat recovery practices, opportunities, and barriers [22]. The information utilized within this section draws largely from the conclusions and recommendations of that DOE study. Although the information pertains to American industry, it is representative of all North American manufacturing and is therefore applicable to Canadian facilities.

In order to begin planning for a WHR project, it is important to first know what exactly is being referred to when the term “waste heat” is used within industry and, further, how it can be
harnessed. Specifically, waste heat refers to heat that is generated in industrial processes (via fuel combustion or chemical reaction) and released into the surrounding environment without being put to practical use [22, 23]. While it is apparent that energy lost in waste heat streams cannot be fully recovered, much of it could be recuperated and employed in a number of different ways including generating electricity, pre-heating combustion air and furnace loads, as well as absorption cooling and space heating [22]. By recovering various waste heat streams, the amount of primary fuel consumption required by industries could be significantly reduced, in turn lowering GHG emission levels and improving the environmental footprint of products and services overall.

**Table 3: Potential waste heat sources and end-uses [22]**

| Waste Heat Source                                      | End-use (general)                                                                 |
|--------------------------------------------------------|-----------------------------------------------------------------------------------|
| Combustion exhausts from:                              |                                                                                   |
| Glass melting furnaces                                 | Combustion air pre-heating                                                        |
| Cement kilns                                           | Boiler feedwater pre-heating                                                       |
| Boilers                                                | Load pre-heating                                                                  |
| Fume incinerators                                      | Power generation                                                                  |
| Aluminum reverberatory furnaces                        | Steam generation                                                                  |
|                                                          | Space heating                                                                     |
| Process off-gases from:                                | Absorption cooling                                                                |
| Steel electric arc furnaces                            | Domestic water heating                                                            |
| Aluminum reverberatory furnaces                        | Transformation of liquid and gaseous process streams via condensation or evaporation|
| Cooling water from:                                   |                                                                                   |
| Furnaces                                               |                                                                                   |
| Air compressors                                         |                                                                                   |
| Internal combustion engines                             |                                                                                   |
| Conductive, convective, and radiative losses from      |                                                                                   |
| equipment                                              |                                                                                   |
| Conductive, convective, and radiative losses from      |                                                                                   |
| heated products                                        |                                                                                   |

### 2.1.1 WHR technologies

A number of technologies for recovering energy from gas, liquid, and even solid waste streams are already in existence and have been around for quite some time [22]. Certain technologies are more common than others, depending on the accessibility of the waste stream, as
well as the feasibility of installing a particular recovery system. In general, there are 4 main types of technologies which are utilized during waste heat recovery: 1) Direct usage, 2) Heat exchangers, 3) Heat pumps, and 4) Vapour recompression [24]. The first 2 technologies involve utilizing waste heat “as is.” This means that the quality of the waste heat is already adequate for use. The other 2 technologies involve waste heat upgrading or boosting the energy level of a particular waste stream so that it can become more useful. Heat exchangers and heat pumps have the widest range of applicability, regardless of industry type, while vapour recompression tends to be limited to larger plants and complex process systems [24].

Table 4: Summary of WHR Technologies [24]

| Recovery Type          | Waste Heat State      | Waste Heat Temperature                  |
|------------------------|-----------------------|----------------------------------------|
| Direct usage           | Use as is             | High                                   |
| Heat exchanger         | Use as is             | High-medium-low                        |
| Heat pump              | Requires energy boosting | Low-medium                             |
| Vapour recompression   | Requires energy boosting | Low (vapour state only)                 |

2.1.1.1 Direct Usage [24]

As the name direct usage implies, certain waste streams may be harnessed directly for use after discharge. Several examples of direct WHR strategies include syphoning hot boiler gases for drying purposes, compensating hot water usage in a system with expelled heat exchanger cooling water, or extracting hot air from a mechanical room to heat a storage or shop area.

One of the main issues surrounding the idea of direct usage is the potential for contaminants within the waste stream to infiltrate clean air and water systems. As a result, practically all direct usage projects should integrate the use of an adequate filtration system to prevent cross-contamination. With the exception of filtration requirements, minimal alterations
and capital are required to permit the use of many waste heat discharge streams directly, making it one of the most simple and cost-effective WHR strategies to implement.

2.1.1.2 Heat Exchangers [24]

When waste heat cannot be used directly, heat exchangers are often used to transfer heat from one stream to another. Heat exchangers are specialized pieces of mechanical equipment that are designed to allow highly efficient heat transfer between 2 fluid streams (a liquid or a gas) without having them mix [24]. The fact that the two streams can remain separate during the heat extraction process means that contamination is prevented, which is of high importance in many industries, including food processing and medical equipment manufacturing.

Available in a number of different designs and configurations, heat exchangers are used widely throughout industry and the technology is well-established. The various designs of each are suited to meet a wide-range of needs, as well as numerous material, temperature, and operating conditions [24].

2.1.1.2.1 Recuperators [22]

Recuperators recover exhaust gas waste heat in medium to high-temperature applications such as soaking or annealing ovens, melting furnaces, afterburners, gas incinerators, radiant tube burners, and re-heat furnaces [22]. Recuperators can be based on radiation, convection, conduction, or a combination of the 3. A simple radiation recuperator consists of 2 concentric lengths of ductwork, as shown in Figure 5 below [22]. Hot waste gases pass through the inner duct and heat transfer is primarily radiated to the wall and to the cold incoming air in the outer shell. The pre-heated shell air then travels to the furnace burners.

The convective, or tube-type recuperator, on the other hand, passes the hot gases through relatively small diameter tubes contained in a larger shell [22]. The incoming combustion air enters the shell and is baffled around the tubes, picking up heat from the waste gas. Another alternative is a combination radiation and convection recuperator, which is also shown below.
The system includes a radiation section followed by a convection section in order to maximize heat transfer effectiveness [22].

2.1.1.2.2 Furnace regenerator [22]

Regenerative furnaces consist of 2 brick “checkerwork” chambers through which hot and cold air flow alternately [22]. As combustion exhaust passes through one chamber, the bricks absorb heat from the gas and increase in temperature. The flow of air is then adjusted so that the incoming combustion air passes through the hot checkerwork, which transfers heat to the combustion air entering the furnace. 2 chambers are used so that while one is absorbing heat from the exhaust gases, the other is transferring heat to the combustion air, as seen in Figure 6 below [22]. The direction of airflow is altered roughly every 20 minutes. Regenerators are most frequently used with glass furnaces and coke ovens and are especially suited to high-temperature applications with dirty exhausts [22]. One major disadvantage is the large size and capital costs, which are significantly greater than for recuperators [22].
2.1.1.2.3 Rotary regenerator (heat wheel) [22]

Rotary regenerators, sometimes referred to as air pre-heaters or heat wheels, operate in a manner similar to fixed regenerators in that heat transfer is facilitated by storing heat in a porous media and by alternating the flow of hot and cold gases through the regenerator [22]. Using a rotating porous disc, composed of a high heat capacity material, placed across 2 parallel ducts, one containing the hot waste gas, the other containing cold gas, the disc rotates between the 2 ducts and transfers heat from the hot gas duct to the cold gas duct, as seen in Figure 7 below [22].

Heat wheels are generally restricted to low and medium-temperature applications due to the thermal stress created by high temperatures. Likewise, large temperature differences between the 2 ducts can lead to differential expansion and large deformations, compromising the integrity of duct wheel air seals [22]. Another challenge with heat wheels is preventing cross contamination between the 2 gas streams, as contaminants can be transported in the wheel’s porous material. One advantage of the heat wheel is that it can be designed to recover moisture as well as heat from clean gas streams [22]. This makes heat wheels particularly useful in air conditioning applications, where incoming hot humid air transfers heat and moisture to cold outgoing air.
2.1.1.2.4 Passive air pre-heaters [22]

Passive air pre-heaters are gas-to-gas heat recovery devices for low to medium-temperature applications where cross-contamination between gas streams must be avoided [22]. Passive pre-heaters can be of 2 types – plate-type and heat pipe. The plate-type exchanger consists of multiple parallel plates that create separate channels for hot and cold gas streams [22], as seen in Figure 8 below. Hot and cold flows alternate between the plates and allow significant areas for heat transfer. These systems are less susceptible to contamination compared to heat wheels, but they are often bulkier, more costly, and more susceptible to fouling problems [22].

The heat pipe heat exchanger consists of several pipes with sealed ends. Each pipe contains a capillary wick structure that facilitates movement of the working fluid between the hot and cold ends of the pipe [22]. As shown in Figure 8 below, hot gases pass over one end of the heat pipe, causing the working fluid inside the pipe to evaporate. Pressure gradients along the pipe cause the hot vapor to move to the other end of the pipe, where the vapor condenses and transfers heat to the cold gas [22]. The condensate then cycles back to the hot side of the pipe via capillary action.
2.1.1.2.5 Finned-tube heat exchangers [22]

Finned-tube heat exchangers are also used to recover heat from low to medium-temperature exhaust gases for heating liquids. Some common uses for finned-tube heat exchangers include boiler feedwater pre-heating, hot process liquids, hot water for space heating or domestic hot water [22]. The finned-tube consists of a round tube with attached fins that maximize surface area and heat transfer rates [22]. Liquid runs through the tubes and receives heat from hot gases flowing across the tubes. Figure 9 illustrates a finned-tube exchanger where boiler exhaust gases are used for feedwater pre-heating, a setup commonly referred to as a boiler “economizer”.

Figure 8: Passive gas-to-gas pre-heater (top); Heat pipe heat exchanger (bottom) [22]
2.1.1.3 Heat Pumps [24,26]

Heat pumps, or waste heat upgrading devices, are frequently used within industry as a means to increase the effectiveness of waste heat streams which would typically be classified as low-grade or at a temperature below what is necessary to perform useful work [24]. They transfer heat by circulating a refrigerant through continuous cycles of evaporation and condensation. Heat pumps use an external energy source (i.e. electricity) to improve waste heat quality, essentially working as a refrigeration cycle in reverse [26].

The main operation of a heat pump cycle, as demonstrated in Figure 10 below, relies on the exchange of a refrigerant between 2 heat exchanger coils [26]. In the first coil the liquid refrigerant is evaporated at low pressure by the low temperature incoming waste heat stream. The refrigerant vapour is then compressed and its temperature is increased due to absorption of mechanical energy from the compression process. This high temperature refrigerant vapour is then passed through the second heat exchanger coil, where the absorbed heat is released to the fluid to be heated as the refrigerant condenses back to a liquid. It is through this process that waste stream temperatures are increased enough so that they can be put to use for applications such as space and domestic hot water heating.
2.1.1.4 Vapour Recompression [24]

Like heat pumps, vapour recompression is used during instances where waste heat is unusable at its current temperature and needs to be transformed into a usable state. Unlike heat pumps however, vapour recompression is utilized only for very specific cases, where the waste heat stream is in the form of low temperature vapours [24].

The process involves compressing waste stream vapours to facilitate the absorption of energy from the surroundings, thereby increasing the vapour temperature, as seen in Figure 11 [24]. The newly compressed vapour is then returned to the process stream for use in supplying heat for evaporation purposes – the most common application for vapour recompression cycles. It is more efficient than conventional heat pumping, but far less flexible in its application [24].
2.1.2 Combined heat and power (CHP) as an indicator of WHR success

While the use of WHR strategies at individual plants or facilities is still largely unexplored within industry, its success has already been demonstrated on a mass-scale and the concept has been in use for quite some time [28]. Combined heat and power (CHP) projects, sometimes referred to as cogeneration, clearly demonstrate the potential for WHR to improve efficiency. Several large-scale plants are in operation around the world, including a straw-fired CHP station in Masnedo, Denmark which has been in operation since 1996 [29] and the Metz Biomass CHP station which burns local waste wood and forest residues in order to generate 9.5 MW of renewable electricity and 35 MW of thermal energy that feeds a 100 km long district heating network in Metz, France [30].

During typical electricity generation, waste heat created during the process is simply released into the atmosphere, making it highly inefficient. Rather than recovering this source of energy for use in residential and industrial heating applications, typical generation keeps electrical and thermal energy as 2 separate streams. As a result, their inefficiencies become magnified throughout the grid system, as can be seen in Figure 12 below.
Cogeneration, on the other hand, differs from conventional electricity generation in that it involves the simultaneous production of electrical and thermal energy [32]. Cogeneration captures the wasted heat from electricity generation and uses it to provide residential, commercial, and industrial space heating and cooling, water heating, and industrial process heating [32].

While most conventional ‘electricity-only’ generation systems have efficiencies between 40-45%, cogeneration systems have overall system efficiencies between 70-85% [33] – a
significant improvement. Figure 12 above clearly demonstrates that by using waste heat from the electricity generation phase of the process to produce thermal energy, substantial gains in energy efficiency can be achieved, which also results in a decrease in fuel consumption and emission generation. CHP projects demonstrate the economic and environmental gains that are possible through WHR technologies. Currently, about 7% of Canada’s electricity is generated using cogeneration technologies [32], with the potential for a much greater capacity to be developed in the next several decades as restrictions on district heating are lifted and existing heating and electricity infrastructure begin to deteriorate.

2.1.3 Barriers of WHR

While numerous technologies are commercially available for waste heat recovery and a number of industrial facilities have upgraded or are improving their energy efficiency by installing these technologies, waste heat recovery remains relatively unexplored. This is largely due to the fact that heat recovery is not feasible or possible in certain instances, and a number of barriers still exist to its wide-spread implementation. Barriers are defined as both technical and non-technical issues which prevent the successful implementation of WHR and require additional research and development in order to ensure wide-scale adoption of waste energy recycling.

Despite the significant environmental and energy benefits of waste heat recovery, its implementation still depends primarily on economics and perceived technical risks. In fact, the DOE suggests that most industrial manufacturing facilities are unlikely to invest in WHR projects that have a payback period of more than 3 years [22].

2.1.3.1 Temperature, Waste Stream Composition, and Material Selection

Temperature range has important ramifications for the selection of materials in heat exchanger designs and WHR systems [22]. This is largely due to the fact that corrosion and oxidation reactions, like most chemical reactions, are accelerated dramatically at elevated temperatures. Fouling, or the build-up of substances on heat exchanger surfaces, is a common
problem in heat exchange and can substantially reduce heat exchanger effectiveness or cause system failure. The build-up of substances can significantly impede performance and reduce heat transfer rates to the point where the system can no longer be used efficiently.

Methods for addressing fouling do exist and include filtering waste heat streams to remove harmful substances and contaminants, constructing heat exchangers using advanced materials, increasing heat exchanger surface area to compensate for fouled portions, and designing heat exchangers for easy maintenance, access, and cleaning [22].

It is important to note that the use of advanced alloys or composite materials can increase system costs considerably and, in some cases, even make recovery unfeasible. In the case of titanium, which is highly corrosion resistant, the cost of using it can be prohibitive. The global price for titanium as listed in July, 2014 was $6.15 USD/kg [34], while stainless steel and carbon steel were listed at $3.16 USD/kg [35] and $0.711 USD/kg [35] respectively. Obviously, based on these prices, the cost of using advanced alloys is often too great to allow for their usage in the design of typical heat exchangers and alternatives must be utilized instead. Alternatives to using advanced materials (and thereby reducing costs considerably) include bleeding air into exhaust gases to dilute and lower temperatures or using ceramics, whose material composition provides better heat resistance than metallics. In the case of air bleeding, the quantity of heat contained in the exhaust stream remains constant, but the quality is reduced due to the decrease in temperature [22].

2.1.3.2 Operating Conditions and Logistics [22]

There are a number of conditions which should be assessed before a WHR project is given approval, including the effect of production scheduling on waste stream availability.

Operating schedules within a plant or facility can cause problems for WHR systems. For instance, if a waste heat source is only available for a portion of time every day, the system’s heat exchanger may be exposed to fluctuating temperatures, which can, in turn, lead to thermal cyclic
fatigue. Ensuring a heat exchanger is made from a material of considerable strength and durability so that it can withstand such thermal loading is a key consideration.

Additionally, it is important that the schedule for a heat source match the schedule for the heat load within the system. If supply and demand for a waste heat stream does not match up, an additional (i.e. fuel-burning) system may be required to provide heat during peak loading. This issue can usually be avoided by appropriately analysing and tweaking process schedules to ensure waste heat supply and demand are in sync or, as an alternative, ample thermal storage for the recovery system must be available. While scheduling a facility to ensure an energy recovery system is operating efficiently may be time-consuming, it is important for WHR reliability and feasibility. As well, it is much less costly than installing mass thermal storage for a system.

2.1.3.3 Low-grade Waste Heat

WHR opportunities are often categorized by dividing temperature into 3 distinct ranges: 1) low quality (232ºC or less), 2) medium quality (650-232ºC), and 3) high quality waste heat (649ºC or higher) [22]. Unfortunately, one of the greatest barriers to the implementation of mass WHR remains the unfeasibility of recovery from low-temperature waste streams, which actually possesses the greatest potential based on recoverable volume, as depicted in Figure 13 below [22].
Currently, 3 major challenges hinder the wide-spread industrial usage of low-temperature waste heat. The first challenge is the frequent corrosion of heat exchanger surfaces as water vapour contained in exhaust gases cool, allowing some of it to condense and deposit corrosive residues on heat exchange equipment [22]. As a result, heat exchangers must be designed to withstand exposure to corrosive deposits. This often requires the use of advanced materials or frequently replacing heat exchanger components, which can lead to large incurred expenses and makes many WHR systems unfeasible.

The second major issue plaguing low-temperature heat exchange is the requirement of large heat exchange surfaces in order to facilitate adequate heat transfer [22]. Heat transfer rates are a function of the thermal conductivity of the heat exchange material, the temperature difference between the 2 fluid streams, and the surface area of the heat exchanger [22]. Since low-temperature waste heat involves a smaller temperature gradient between 2 fluid streams,
larger surface areas are required to compensate in order to achieve similar heat transfer rates. This often limits the practicality of low-grade heat exchangers.

Lastly, finding a use for low-temperature recovered heat is often more difficult than for the medium and high-temperature ranges [22]. Recovering heat in the low-temperature range will only make sense if a plant has a use for it. Potential end uses include domestic hot water, space heating, and low-temperature process heating [22]. Other options include using a heat pump to upgrade heat to improve its usefulness, as discussed in Section 2.1.1.3 above.

Fortunately, a number of applications where low-grade waste heat has been cost effectively recovered for use in industrial facilities have been developed in recent years. The success of low-grade WHR is due in large part to Organic Rankine Cycle (ORC) technology, which is based on the thermodynamic process of the same name. A number of studies have been published in recent years which have outlined the benefits and potential of the ORC for heat recovery using heat sources at temperatures in the 200-400°C range [36].

During the ORC, heat is transferred to an organic fluid (with a boiling point lower than water) at a constant pressure [37]. The fluid is vapourized and then expanded in a vapour turbine that drives a generator, producing electricity. The spent vapour is then condensed back to a liquid and recycled [37]. The development of ORC technologies has significantly increased the recoverability of waste streams in the low-temperature range, meaning that one of the largest untapped sources of waste heat can now be harnessed more successfully.

2.1.3.4 WHR from Solid Streams (Manufacturing)

Significant sources of solid waste heat exist within industry, especially from metal casting. This includes hot coke, by-product fuels (BF) slag, as well as cast and hot rolled metal products from furnaces. Current heat losses from solid streams are quite high, totaling around 527.5 PJ/yr [22]. However, recovering heat from solid streams is difficult, with one of the biggest issues surrounding solid stream recovery being transportability and accessibility [22]. It is often
quite difficult to access heated products during manufacture and ensuring quality and that heat
recovery technologies do not impact production is extremely important. Even once the issue of
access to a heated product is resolved, the issue of transportability remains. If heat is captured in a
fluid stream, it is easy to transport the fluid to an area where heat is needed and extract it at a
point source. Heat itself is difficult to transport, so when it is captured in a solid product, the lack
of mobility of the waste stream significantly reduces the recoverability and usability of that heat
[22]. As a result, waste energy recovery is currently not widely practiced with hot solid materials
and is considered a barrier to wide-scale implementation.

This does not mean there are not potential ways of utilizing this form of waste heat. One
example is the use of a coilbox to maintain the temperature of heated steel products as they pass
from a roughing mill to a finishing mill, thereby improving efficiency and resulting in more
uniform metallurgical properties of products [38]. Currently, one of the most common options for
reducing heat losses from cast products is hot charging, in which slabs are brought to a re-heating
furnace while still hot [22]. Hot charging is done at a few plants in the U.S.; however, it is usually
applied to only a fraction of production due to logistical reasons, such as mismatched capacities
and large distances between casters and rolling mills. Despite this, hot charging has the ability to
save a considerable amount of energy per tonne of generated product [22]. In order to achieve
these savings, more research and funding must be devoted to solving the issue of solid stream
heat transportability.

2.1.3.5 WHR Policies

Within industry, the economics of WHR, rather than the potential environmental benefits
of these projects, often dominate the approval process, with most manufacturing facilities being
unlikely to invest in a WHR project with a payback period of greater than 3 years. This is rather
unfortunate as WHR offers considerable potential for saving energy. In fact, SPIRE (Sustainable
Process Industry through Resource and Energy Efficiency) in the EU (European Union) has
identified recovery of energy from industrial processes as “the single greatest opportunity for reducing energy use [39].” In addition to emission reduction, potential job opportunities, including manufacturing the necessary equipment, and designing, installing, and maintaining recovery systems, are other clear social benefit stemming from WHR projects [40].

In recent years, due to advancements in recovery technologies, rising energy costs, and (particularly in Europe) the development of heat recovery policies, industrial facilities and companies have developed a much greater interest in energy recovery applications [36]. The large scale European “20-20-20” Climate and Energy Package, which calls for a reduction in GHG emissions by 20% below 1990 levels, increasing the share of Europe’s energy from renewable sources to 20%, and improving their energy efficiency by 20% by 2020 [41], has been a driver for WHR and CHP development, as both sets of projects can help the EU reach these targets.

With such a large emphasis on energy efficiency, many European countries have worked to remove existing WHR barriers and implement new heat recovery policies designed to encourage industries to harness this potential energy source. One such example is the SILC (Sustainable Industry Low Carbon) initiative, which aims to help sectors achieve specific GHG emission intensity reductions in order to maintain their competitiveness [36]. The SILC scheme is intended as a practical, industry-based initiative at the EU-level which identifies, develops and deploys both technological and non-technological innovation measures [42]. As part of the initiative, the EU will co-finance up to 75% of the costs of industry-led projects which meet the goals and requirements of the program [42]. WHR projects have benefited considerably from this program, since it removes many of the perceived economic risks for companies.

Fully embracing WHR opportunities will require re-designing current government policies surrounding energy efficiency requirements [40]. Currently, Canada has many voluntary energy efficiency programs, including CanmetENERGY, CIPEC (Canadian Industry Program for Energy Conservation), and ISO-14001 (International Organization for Standardization
Environmental Management Systems). While these programs are an excellent investment for organizations looking to improve their environmental footprint, they do little to enforce energy efficiency standards.

The Canadian government has created numerous retrofit and energy efficiency improvement programs in recent years through Natural Resource Canada’s Office of Energy Efficiency; it is time they begin a number of initiatives to promote the recovery of waste energy streams within industry, much like what has been implemented in Europe. It could benefit Canadian industry tremendously by reducing primary fuel consumption and overall energy costs, increasing productivity and job creation, and preventing millions of tons of CO₂ from entering the atmosphere – a win-win for economists and environmentalists alike.

2.2 Idle Power Losses and Production Rates

Another area which can result in major energy consumption improvements is that of manufacturing production rates and idle power losses, which has been studied extensively by Gutowski et al, and has been found to be closely related to the efficiency of a manufacturing process. [43].

Manufacturing processes include a wide variety of operations – subtractive processes such as machining and grinding, net-shape processes such as injection molding, and additive processes such as chemical vapour deposition (CVD) and sputtering [44]. All manufacturing processes involve utilization of energy to convert material inputs into products and generated waste streams [44], as demonstrated in Figure 14 below.
In a simplifying manner, manufacturing can be thought of as a series of steps which, when taken together, generate a final product. When it comes to high levels of production, many of these steps are often automated and require a number of different pieces of equipment to complete a process. Each one of these processes can generate waste heat or exhaust streams and requires a specific amount of energy to operate. As a result, each stage of a manufacturing process can have its own potential consequences for the environment and sustainability, especially if a process is being carried out on a large-scale [45].

In some cases, a number of processes can be combined into a single machine. An example of this can be seen in a modern milling machine, which includes a wide range of functions including work handling, lubrication, chip removal, tool changing, and tool break detection in addition to the basic function of the machine tool [44]. Unfortunately, while modern equipment has greatly reduced the number of separate steps involved, it has also significantly increased machinery energy requirements. 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 [44]. This can be seen in Figure 15 below, which shows the energy used as a function of production rate for an automobile production line.

**Figure 14: Energy and material inputs and outputs for manufacturing processes [44]**
In this example, provided by Gutowski, it can be seen that only 14.8% of the total energy used was required for the actual machining process, while the rest of the energy was used by other equipment features [44]. It is also important to note that 14.8% is the maximum machining energy requirement and that the portion of energy used for machining was significantly reduced at low production rates [44]. As well, the other features all required constant energy input to operate and were not directly correlated to production rates. This is due to the fact that, in general, a significant amount of energy is required to start-up and maintain manufacturing equipment in a “ready” position [44]. Once it has achieved the amount of energy required to reach this “ready” state, there is then an additional energy requirement which is proportional to the quantity of material processed or, in other words, a portion of the energy consumed is dependent on the production rate [44]. This relationship is represented by the following equation:
$P = P_o + k\dot{v}$ \hspace{1cm} (1)

In this equation, $P$ represents the total power requirement of the machine in kW (kilowatts), $P_o$ is the required idle power in kW, $\dot{v}$ is the rate of material processing in cm$^3$/s, and $k$ is a physical constant with units of kJ/cm$^3$ \cite{44}. In general, $P_o$ comes from the equipment features required to support a process, while $k$ comes from the physics behind the process. For example, for a cutting tool, $P_o$ comes from the energy of the coolant pump, hydraulic pump, computer console, and other idling equipment, while $k$ is the energy required to cut a product and is related to both the work piece hardness and the specifics of the cutting mechanics \cite{44}. Similarly, for a thermal process, $P_o$ comes from the energy required to maintain a furnace at an appropriate temperature, while $k$ is related to the incremental heat required to raise the temperature of a unit of product \cite{44}.

![Figure 16: $P_o$ vs. $k$ power requirements as a function of process rate \cite{44}](image)

As a result of these observations, Gutowski et al concluded that the energy requirement of a specific manufacturing process is very strongly correlated to material throughput. This is quite different from what is typically used by LCA (life cycle analysis) software, which often selects or estimates a constant value for a process’ specific energy requirements \cite{44}. As was demonstrated in the examples above, in general, this is not true and the value can vary substantially.
As part of a comprehensive manufacturing process thermodynamic analysis, Gutowski et al also studied 20 different processes and characterized each in accordance to the material and energy resources used as a function of production rates [44]. The study covered a wide range of processes including conventional processes (machining, casting, injection molding), advanced processes (electrical discharge machining (EDM), abrasive waterjet machining), and micro/nano-manufacturing processes (vapour-phase processes). The results of the study are shown in Figure 17 below.

![Figure 17: Specific electricity requirements of manufacturing processes as a function of process rate [44]](image)

The results show that the electricity requirements of manufacturing processes have increased greatly over the past several decades, with energy intensity (or the amount of energy it takes to produce a certain quantity or number of products) for modern processes increasing by 8
orders of magnitude [44]. It is important to make the connection as to where this energy intensity increase is stemming from. It can be seen from the plot above, and is also noted in literature, that the electrical power requirements of most manufacturing processes varies by only 1 or 2 orders of magnitude, typically being constrained in the range of 5-50 kW [44]. There are a number of reasons for this, relating to electrical and design standards, process portability, and efficiency.

The range of material throughput, on the other hand, can vary by as much as 10 orders of magnitude [44]. This is largely linked to the fact that new technologies, in conjunction with lower energy prices, have shifted manufacturing trends toward higher precision, working to finer dimensions and smaller sizes [44]. Therefore, many modern manufacturing processes, which often operate in the vapour phase, have much smaller throughputs, resulting in large electrical energy requirements [44]. This trend can be observed in the figure above.

With further analyzing, it can be seen that older, more conventional processes – machining, metal melting for castings – are found at the bottom of the plot, while the very top of the diagram is dominated by modern processes, which require a high electrical energy input [45]. One such example is that of thermal oxidation, which is used to produce extremely thin layers of oxidized silicon for semiconductor devices [45]. This process is carried out at elevated temperatures and is extremely time-consuming. Another modern process example is that of EDM drilling, which is used to produce fine curved cooling channels in turbine blades [45]. It also utilizes precise dimensions and is a rather slow process. Fortunately, these techniques do not process large quantities of material and therefore represent only a fraction of manufacturing electricity usage [45].

The middle portion of the plot contains a number of advanced processes which are often used by the semiconductor industry, including sputtering, dry etching, and variations of the CVD process [45]. While the energy intensities of these techniques are not the highest on the plot, a number of them actually process vast quantities of material. For example, CVD is an important
step in the production of EGS (electronic grade silicon) and has an energy intensity of around 1 GJ/kg [45]. Given that worldwide EGS production now exceeds 20,000 tonnes, it can be seen that a large amount of energy, on the order of 20 PJ of electricity, is required to use this process in the semiconductor industry alone [45]. As a result, it should not be thought that these modern, energy-intensive processes are only being operated on a small quantity of material throughput and therefore only contribute a small percentage of the overall energy requirements of the manufacturing sector [45]. In many cases the exact opposite is true.

An individual process can improve its energy intensity requirements by operating at a higher process rate. The opposite will be true if a reduction in material throughput for a particular process occurs. An example of this would be seen if a milling machine were to be used for finishing machining rather than rough, surface machining or if a CVD process was used to operate on a single wafer rather than a large batch [44].

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 [45]. Today’s modern processes, although capable of working on smaller scales with higher dimensional tolerances, should also be focusing on improving energy requirements and manufacturing sustainability. The data clearly shows that the most important characteristic of a manufacturing process, in terms of energy intensity, is its production rate. This is due largely to the fact that equipment support feature energy requirements continue to grow and often dominate the overall energy consumption of a machine rather than the actual physical mechanism of the process itself [44].

As a result, a number of strategies have been put forward by Gutowski et al which can be employed by manufacturers to improve the energy efficiency of various manufacturing processes. One such strategy is the re-design of support equipment (machine tools and injection molding machines) to operate using all-electric rather than hydraulic systems, which tend to be much more
energy intensive [44]. The reduction in energy requirements by switching such an energy source can be seen in Figure 18 below.

![Figure 18: Specific energy requirements (SEC) or energy intensity of hydraulic vs. all-electric injection molding machines as a function of process rate [44]](image)

Another recommended strategy is the increase of material throughput rates of specific manufacturing process, where possible [44]. Maximizing production rates (where feasible) ensures that machinery is used to its full-capacity and that idle time energy losses are avoided as much as possible. Likewise, regularly monitoring and updating production schedules will ensure that equipment is being shut down during periods of reduced production within facilities.

Lastly, companies must conduct studies to ensure the most appropriate manufacturing processes are being utilized to generate a specific product or carry out a certain step within an overall manufacturing process. Certain processes are more energy-intensive than others and being able to switch from a more “modern” technology to a traditional or conventional process may often prove to be the more energy-conscious choice [44]. In cases where a higher level of dimensional tolerancing can be sacrificed for a reduction in energy intensity, the processes being utilized in that production stream should be re-evaluated, particularly instances where non-vapour phase techniques can be successfully used as a processing alternative.
2.3 Auxiliary Equipment Requirements

One of the largest industrial energy requirements comes from auxiliary equipment consumption, which includes pumping systems, fans and blowers, compressed air systems, and motor/drive systems. The enormous energy consumption by auxiliary equipment is due largely to the use of inefficient equipment and designs. In fact, the U.S. Hydraulics Institute estimates that most industrial pumps in use are only operated from 15%-40% efficiency and that working to increase pump efficiency could result in a reduction in global energy consumption by 7%, a considerable enormous amount of energy savings [46].

It should also be noted that for this portion of the literature review, while additional sources were consulted, the U.S. DOE’s sourcebooks pertaining to each individual type of industrial auxiliary equipment were used as a primary source. The sourcebooks were created specifically for industrial users as a way to have important information pertaining to auxiliary equipment available from a single source. The handbooks offer general explanations for how the equipment works and basic underlying system principles, tips on how to appropriately size equipment, common issues that arise with over and undersized auxiliary equipment, as well as advice on how to modify system configurations to improve efficiency, and where to turn for additional resources. The sourcebooks are an excellent tool for industry users and offer a thorough overview of the broad field of auxiliary equipment energy consumption. As well, because pumping systems are ubiquitous, the following section has been outlined in the greatest level of detail.

2.3.1 Pumping systems

Most manufacturing plants, commercial buildings, and municipalities rely heavily on pumping systems for their daily operation. 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 [46]. Since they serve such a diverse range of needs, pumps range in size from fractions of a hp (horsepower) to several thousand hp. They come in several different types,
classified by the way they transfer energy to a fluid, and many factors go into determining the suitability of a pump for a specific application [46]. Since several different pump types may meet the same service requirements, it is important that an appropriate analysis is conducted prior to pump selection and installation for a system. Typical pumping systems contain 5 basic components: 1) Pumps, 2) Prime movers, 3) Piping, 4) Valves, and 5) End-use equipment (e.g. heat exchanger, tank, hydraulic equipment) [46]. A basic arrangement of a typical pumping system (and its components) is outlined in Figure 19 below.

![Figure 19: A typical pumping system and its components](image)

2.3.1.1 Pumping System Principles

Pumps are sized and configured according to the flow rate and pressure requirements of a system or service. After the service needs of a pumping system are identified, the pump/motor combination, layout, and valve requirements must be engineered [46]. Selecting the appropriate type of pump and its speed and power
characteristics requires an understanding of its operating principles [46]. The most challenging aspect of the design process is cost-effectively matching the pump and motor characteristics to the needs of the system, which is often complicated by wide variations in flow and pressure requirements [46]. The flow/pressure relationship of many pumps is described in performance curves which plot flow rate as a function of head (pressure) [46]. Understanding this relationship is essential to properly sizing a pump and designing a system that performs efficiently. An example of a pump performance curve can be seen Figure 20 below.
2.3.1.2 Pump Reliability

As pumps are essential to the daily operations of many manufacturing facilities, reliability is extremely important. For example, in cooling systems, pump failure can result in equipment overheating and catastrophic damage [46]. Ensuring that system needs are met
during worst-case conditions can cause designers to specify equipment that is oversized for normal operation. By ensuring pumps are large enough to meet system needs, engineers often overlook the cost of oversizing pumps and err on the side of safety by adding more pump capacity [46]. This practice results in higher system operating and maintenance costs. As well, excess flow energy increases component wear and tear, resulting in valve damage, piping stress, and excess system operation noise [46]. 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. The key to improving system performance and reliability is to fully understand system requirements (peak demand, average demand, and the variability of demand) with respect to time of day and time of year and designing a pumping system to meet those specific needs [46].

2.3.1.3 Pump Efficiency [46]

Pumps have varying efficiency levels and are a function of many design characteristics. The operating point of centrifugal pumps at which their efficiency is highest is known as the best efficiency point (BEP). Operating a pump at or near its BEP not only minimizes energy costs, it also decreases loads on the pump and maintenance requirements. In reality, continuously operating a pump at its BEP is difficult because systems usually have changing demands. However, selecting a pump with a BEP that is close to the system’s normal operating range can result in significant operational cost savings.

2.3.1.4 Warning Signs of Inefficient Pumping Systems

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 and bearings), intermittent pump operation, and high energy costs [46]. 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 [46].

2.3.1.4.1 Excessive noise [46]

Oversized pumps tend to cause excessive levels of noise. However these problems are often disregarded as normal system operating characteristics as operators adjust to the system’s acoustic levels. Unless the noise levels worsen, the system is assumed to be performing normally. However, the cumulative damage that results from flow-induced pipe vibrations can significantly accelerate system wear. As well, pipe vibrations can loosen flanged connections and other mechanical joints. These vibrations also create fatigue loads on welds in both pipes and piping supports.

2.3.1.4.2 Highly throttled flow control valves [46]

In systems with oversized pumps, valves tend to remain in restrictive positions – with many operating at less than 50% open – which forces the pump to operate against a high backpressure. Since this backpressure is typically higher than the pressure associated with the pump’s BEP, the pump operates inefficiently and is susceptible to higher-than-normal bearing wear. Many control valves are oversized to ensure adequate flow with unknowns, such as pump performance, pipeline fouling and scaling, creating a bias toward oversizing. Proper sizing of the pump and control valve provides a more uniform response to flow changes and reduces process variability, thereby improving both efficiency and overall pump performance.

2.3.1.4.3 Heavy use of by-pass lines [46]

In some systems, excess flow is handled by using by-pass lines around system equipment. By-pass lines prevent the build-up of damaging pressure differentials, and are used for temperature control in many heat exchangers. By-pass lines may allow pump(s) to operate closer to their BEP and improve reliability, although the energy needed to push fluid through by-
pass lines is often wasted. When a system normally operates with a large number of open by-pass valves, this is usually a key indicator that the system is performing inefficiently because of improper balancing, oversized pumps, or both.

2.3.1.4.4 Heavy maintenance requirements [46]

The penalties for excess system flow can extend beyond high energy costs to include frequent pump maintenance. Since oversized pumps generate high backpressures, they often operate far to the left of their BEP and tend to experience greater bearing and seal wear. As well, higher back-pressure caused by increased flow velocity creates high radial-bearing and thrust-bearing loads, and exerts greater pressure on mechanical seals and packing glands. An oversized pump also generates higher friction losses during operation because it pushes fluid through the piping at higher velocities.

2.3.1.4.5 Intermittent pump operation [46]

Pumps are often used to maintain fluid levels in tanks, either by filling or draining them as needed. Many systems rely on a level control system to activate the pumps automatically. The cumulative effect of energizing and de-energizing a pump shortens the lives of the motor controller and the pump assembly and often contributes to poorer pump performance.

2.3.1.5 Corrective Measures for Inefficient Pumping Systems [46]

In systems served by oversized pumps, several corrective measures can be taken to lower system operating costs and extend equipment maintenance intervals. The correct measure to choose will depend on the system in question and on the particular indicator that points to the oversized pump problem. 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).

2.3.1.5.1 Impeller adjustment [46]

Most pumps can be assembled using more than one impeller diameter and pump manufacturers standardize their pump models as much as possible so that casings and pump shafts can accommodate multiple impeller sizes. This characteristic often allows a smaller impeller to be used when an existing impeller is generating excessive flow or head.

When a smaller impeller is not available or the performance of the next smallest impeller is insufficient, impeller trimming can be an alternative. Impeller trimming reduces the impeller diameter (and consequently the impeller tip speed) so that the same constant-speed pump motor can be used. Since the head generated by a pump is a function of its tip speed, impeller trimming shifts the entire performance curve of the pump downward and to the left, allowing the pump to operate closer to its BEP, improving performance.

2.3.1.5.2 Use variable frequency drives [46]

Pumps that experience highly variable demand conditions are often good candidates for ASDs (adjustable speed drives). The most popular type of ASD is the VFD (variable frequency drive). VFDs use electronic controls to regulate motor speed, which, in turn, adjusts the pump’s output. The principal advantage of VFDs is better matching between the fluid energy that the system requires and the energy that the pump delivers to the system. As system demand changes, the VFD adjusts the pump speed to meet this demand, reducing the energy lost to throttling or bypassing excess flow. The resulting energy and maintenance cost savings often justify the investment in the VFD. However, VFDs are not practical for all applications. For example,
systems that operate with high static head and those that operate for extended periods under low-flow conditions are not suitable for VFD use.

2.3.1.5.3 **Using smaller pumps to supplement larger pumps [46]**

Since the requirements of worst-case conditions are often significantly higher than those of normal operating conditions, many pumps are oversized relative to the demands of their application for most of their operating lives. Adding a smaller pump (also referred to as a pony pump) to handle normal system demand relieves the burden on the larger pump, which can be energized as needed during higher load conditions. A pony pump can operate more efficiently and require less maintenance, making investing in smaller pumps well worth it.

2.3.1.6 Piping Configurations to Improve Pumping Efficiency

In addition to making alterations to pumps, the piping configuration within a system can also be adjusted to make operations more efficient. There are several steps which should be taken during the design stage to ensure the optimal pumping system configuration is chosen, including determining the proper pipe size, designing a piping system layout that minimizes pressure drops, and selecting low-loss components [46].

2.3.1.6.1 **Determining the proper pipe size [46]**

To determine the proper pipe size, designers must balance the initial cost of the pipe against the cost of pushing fluid through it. Larger pipes create less friction loss for a given flow rate; however, larger pipes also have higher material and installation costs. The example below outlines the cost of pumping water through 1000 feet of steel piping with varying diameters. As can be seen, larger pipes often provide the most cost-effective design for a system due to the large reduction in initial pump and operating costs and despite higher up-front material costs. Unfortunately, designers often overlook the energy costs of using small piping and focus on the initial cost when sizing for a system.
2.3.1.6.2 Minimizing system pressure drops [46]

When designing a piping system, an awareness of the energy costs associated with poor flow profiles must always be taken into consideration. Although piping system layouts are typically dictated by space constraints, there are often opportunities to minimize unnecessary pressure drops by avoiding sharp bends, expansions and contractions, and by keeping piping as straight as possible. One useful rule of thumb is to orient valves and system equipment so that they are in line with the pipe run, as can be seen in Figure 22 below, to insure the piping runs as straight as possible to reduce pressure losses along the way.
2.3.1.6.3 Selection of low loss components [46]

Low-loss components provide another opportunity to minimize energy requirements within a system. As with pipe sizing, it is necessary to balance initial costs with future energy costs. In fact, one of the main ways designers can improve system life-cycle costs is to consider the cost of flow losses. A common example of this can be seen with the selection of valves for a pumping system, which are often sized incorrectly. Ensuring components are appropriately sized to meet the needs of a system is a key way to improve efficiency.

2.3.1.7 Pump Concerns [46]

Since centrifugal pumps operate most effectively when the inlet flow has a uniform profile, systems should be designed to avoid non-uniform flow at the pump inlet. In centrifugal pumps, as fluid moves from the suction piping into the eye of the impeller, it gets caught by an impeller vane and then accelerates to the tip. If the flow into the eye is uneven, the impeller will transfer energy to the fluid less efficiently. In addition, uneven flow at the pump suction promotes excessive vibrations, which shortens pump life and weakens pipe welds and mechanical joints.
An improper flow profile, vapor collection, and vortex formation are three common pipe configuration problems that result in poor pump performance.

2.3.1.7.1 Poor flow profile [46]

Piping configurations often promote uneven flow. Elbows and valves that are placed just before a pump disrupt fluid flow and degrade pump performance. This problem is particularly significant when the flow velocity is high and the suction pressure is low. Under these conditions, a dramatic redirection in flow, commonly created by a small-radius elbow or a globe valve, results in a highly turbulent flow that diminishes pump performance.

2.3.1.7.2 Vapour collection [46]

Vapour entrapment can be another consequence of poor piping layout. If the suction piping leading to the pump does not have a constant slope, vapour can collect at the high points. Vapour pockets limit flow through the pipe and cause pressure pulsations that degrade the pump’s performance. Figure 23 shows examples of piping installations that encourage vapor collection.

2.3.1.7.3 Vortex formation [46]

In tank applications, if a fluid surface drops close to the suction inlet, a vortex can form, potentially creating a loss of suction head or allowing air into the pump. In severe cases, the pump will lose its prime, which can cause severe degradation in performance and may even damage the pump. A centrifugal pump is not designed to run without fluid; mechanical seals, packing, and impeller wearing rings are susceptible to damage if they are not lubricated. Most centrifugal pumps are not self-priming; if a pump loses its prime, it must be filled and vented to be restarted. The centrifugal pumps that are self-priming tend to be less efficient than conventional centrifugal pumps and should be used only when necessary.
Figure 23: Examples of correct vs. incorrect piping system layouts [46]

2.3.1.8 Rules of Thumb for Improving Piping Configurations [46]
There are 2 primary rules of thumb for improving pipe configurations: 1) Establish a uniform-velocity flow profile upstream of a pump and 2) Ensure proper support infrastructure is in place for suction and discharge piping.

2.3.1.8.1 Establish a uniform-velocity flow profile upstream of a pump [46]

Manufacturers should make sure that a straight run of pipe leads into the pump inlet to ensure a uniform-velocity flow profile is maintained upstream. If space constraints require an elbow just upstream of the pump, a long radius elbow should be selected. In some cases, a flow straightener, such as a baffle plate or a set of turning vanes, should be installed with an elbow to correct any disruption in flow, shown in Figure 24 below. By smoothing out the flow, a flow straightener creates a more even velocity profile. Care must be taken, however, to ensure that the pressure drop across the straightener does not cause cavitation.

![Figure 24: Example of a flow straightener](image)

2.3.1.8.2 Ensure proper support of suction and discharge piping [46]

Likewise, installers should be used to make sure that transition pieces and joints between pipes and fittings are kept as smooth as possible. In particular, suction and discharge piping close to a pump should be properly supported, as can be seen in Figure 25 below. Many pump/motor problems are caused by pipe reactions that pull the pump out of alignment. For example, when a pump is installed, the connecting piping is rarely aligned perfectly with the pump; rather, some amount of mechanical correction is needed to make the connections. If the piping is pulled too far from its relaxed position to make the fit, it can force the pump and motor out of alignment,
excessively straining the pump casing. Properly supporting piping near pumps allows the pipe reaction to be carried by the pipe hangers rather than by the pump itself. Also, proper support of the piping near the pump stiffens the system, helping reduce system vibrations.

![Figure 25: Proper support of suction and discharge piping [46]](image)

### 2.3.2 Compressed air systems

Another vital piece of auxiliary equipment within the manufacturing sector is compressed air. Like pumps, compressed air systems are ubiquitous throughout industry and are considered to be a vital part of daily operations within many manufacturing facilities. Almost every industrial plant, from a small machine shop to a large-scale facility, has some type of compressed air system [49]. Industrial facilities use compressed air for many operations including powering pneumatic tools, packaging and automation equipment, running conveyors, and combustion and process operations such as oxidation, filtration, dehydration, and aeration [49]. Like pumps, plant air compressor systems come in a wide range of sizes, from smaller units on the order of 5 hp to huge systems with more than 50,000 hp capacity [49].

In fact, in many industrial facilities, air compressors use more electricity than any other type of equipment [49]. As a result, inefficiencies arising from improperly designed compressed air systems can correspond to significant energy losses and added operational costs. Investing in compressed air upgrades or improvements can result in electricity consumption savings from 20-50% or more for a system [49]. For many companies, that is equivalent to thousands, or even
hundreds of thousands of dollars of potential annual savings, depending on how heavily compressed air is used within a facility [49].

There are many benefits which accompany a properly managed compressed air system, including energy savings, reduced maintenance, decreased downtime, increased production throughput, and improved product quality [49]. This is why it is extremely important for manufacturers to understand their facilities’ overall compressed air needs and be able to identify inefficient compressed air system warning signs. Fortunately, a number of simple steps can be taken to improve efficiency levels within most compressed air systems.

2.3.2.1 Compressed Air System Basics

In general, compressed air systems can be thought of as 2 different sub-systems, consisting of a supply side and a demand side. The supply side, which includes the compressor and air treatment components, allows for the delivery of clean, dry, stable air at a specified pressure in a dependable, cost-effective manner (if appropriately designed and managed) [49]. A properly designed demand side will utilize compressed air for applications in an efficient manner, while minimizing generated waste air streams [49]. In order for a compressed air system to operate effectively, peak system performance requirements must address the needs of both the supply and demand sides and appropriately account for the interaction between the two.

A modern industrial compressed air system is comprised of several major sub-systems and sub-components, including a compressor, prime mover, control system, treatment equipment and accessories, and a distribution system [49]. A standard compressed air system is outlined in Figure 26 below.
Figure 26: Components and layout of a standard compressed air system [49]

2.3.2.2 Wasteful Compressed Air Practices

Compressed air is used in many industrial applications; however it is not always the best choice. Compressed air is clean, readily available, and simple to use, resulting in it often being chosen for applications in which other energy sources may be more economical [49]. This is due to the fact that compressed air is one of the most expensive forms of energy available in a manufacturing plant and typical compressed air systems are only 10-15% efficient overall [49]. Companies should therefore consider more cost-effective forms of power before utilizing compressed air.

As a general rule, compressed air should only be used if safety enhancements, significant productivity gains, or labor reductions will result from its use [49]. If compressed air is to be used for an application, the amount of air used should be the minimum necessary quantity/pressure and
should be used for the shortest possible duration [49]. The use of compressed air should also constantly be monitored and re-evaluated periodically to ensure it is the most feasible option for certain applications.

Compressed air is often used inappropriately within the industrial sector, particularly manufacturing facilities which utilize large quantities of compressed air for their daily operations. Some common examples of potentially inappropriate uses of compressed air include open blowing, sparging, aspirating, atomizing, vacuum generation, personal cooling, and diaphragm pumps [49].

Open blowing, or the use of compressed air through an open, unregulated tube, hose, or pipe to provide cooling, drying, cleaning, line draining, or clearing of conveyor jams, is one of the most common misuses of compressed air in industry [49]. While compressed air is very convenient to use in these scenarios, it is very inefficient and costly. Fortunately, a vast number of alternatives to open blowing exist, including brushes, brooms, dust collection systems, blowers, electric fans, mixers, and nozzles [49].

Sparging, or the aerating, agitating, oxygenating, or percolating of a liquid with compressed air, is another common misapplication of compressed air [49]. Its use is particularly inappropriate because liquid can be wicked into a gas that was originally dry, significantly increasing its dew point. This wicking effect is more strongly seen in compressed air with lower dew points and it can occur with many different types of liquids, including oil, caustics, and water rinse materials [49]. A useful alternative to sparging using a compressed air system is a low-pressure blower or mixer [49].

Similarly, vacuums are commonly used in manufacturing processes and are often generated using compressed air in conjunction with a venture, eductor, or ejector to produce a negative-pressure mass flow [49]. Typical applications are for the creation of compressed air vacuum cleaners. This is by far the most inefficient application in industry with less than 4% total
efficiency, although for very intermittent use (less than 30% load factor), compressed air can be a reasonably efficient solution [49]. However, an alternative to compressed air usage is often a vacuum pump. In the event that a compressed-air-generated vacuum is still required, installing a solenoid valve on the compressed air supply line to allow for the air to be shut off when it is not needed is an important addition to the system for efficiency improvement [49].

2.3.2.3 Compressed Air Load Profiles

Oversized air compressors are extremely inefficient because most compressors use more energy per unit volume of air produced when operating at part-load. One of the most important considerations to be taken when designing a compressed air system is the variation in demand for air over time, also known as a load profile [49].

Taking data at a single point, or even during various shifts, can provide some answers, but not the complete picture. The use of data loggers is important in determining how a system operates over time. Data logging system pressures and flow can indicate intermittent loads, system disruptions and general system conditions [49]. It can also indicate system changes (e.g. production process changes or air leaks) that can affect the compressed air system operation and efficiency [49]. These variations in pressure and flow can be managed through system control strategies and storage to minimize their impact on production.

2.3.2.4 Compressed Air System Leaks

Leaks are a significant source of wasted energy in industrial compressed air systems, sometimes wasting up to 20-30% of a compressor’s output [49]. A typical plant that has not been well maintained will likely have a leak rate equal to 20% of its total compressed air production capacity, while proactive leak detection and repair can reduce leaks to less than 10% [49]. The presence of leaks within a compressed air system not only increases maintenance requirements and reduces efficiency, it is also extremely costly for manufacturers. The cost related to various leak sizes can be seen in Figure 27 below.
In addition to being a source of wasted energy, leaks can also contribute to other operating losses. They cause drops in system pressure, which can make air tools function less efficiently, adversely affecting production and by forcing equipment to run longer, leaks shorten the life of almost all system equipment (including the compressor package itself) [49]. Increased running time can also lead to additional maintenance requirements and unscheduled downtime [49]. Leaks can also add unnecessary compressor capacity. The most common problem areas within a compressed air system include couplings, hoses, tubes, and fittings, pressure regulators, open condensate traps and shut-off valves, and pipe joints, disconnects, and thread sealants [49].

2.3.2.4.1 Leak detection

Air leaks are almost impossible to see and therefore are extremely difficult to detect, however a number of leak location methods exist. One of the most commonly used leak detection methods is an ultrasonic acoustic detector, which can recognize the high-frequency hissing
sounds associated with air leaks [49]. A simpler method is to apply soapy water with a paint brush to suspect areas [49]. Although reliable, this method can be time consuming.

Ultrasonic leak detection systems are portable units which consist of directional microphones, amplifiers, and audio filters and usually have either visual indicators or earphones to detect leaks [49]. They can be used to find mid- to large-sized leaks and offer many advantages including versatility, speed, ease of use, the ability to perform tests while equipment is running, and the ability to find a wide variety of leaks [49].

2.3.2.4.2 Fixes [49]

There are a number of available fixes for compressed air leaks, with many being both cheap and easy to implement. Since leaks occur most commonly near joints and connections, a common example is to ensure connections and joints are sufficiently tightened. As well, in many cases, leaks are caused by failing to clean the threads or by bad or improperly applied thread sealant. Selecting high quality fittings, disconnects, hose, 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. Another way to reduce leaks is to lower the air pressure of the system. The lower the pressure differential across an orifice or leak, the lower the rate of flow, so reduced system pressure will result in reduced leakage rates. Stabilizing the system header pressure at its lowest practical range will minimize the leakage rate for the system. In some cases, the replacement of aging or faulty equipment, such as couplings, fittings, pipe sections, hoses, joints, drains, and traps may be required in order to reduce the leak rate of a system.

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.

2.3.2.5 Compressed Air System Pressure Drops

Pressure drops occur as compressed air travels through the various treatment elements and distribution system. A properly designed system should have a pressure loss of much less than 10% of the compressor’s discharge pressure, as measured from the receiver tank output to the point-of-use [49].

Excessive pressure drop not only results in poor system performance, but also causes excessive energy consumption. Minimizing differentials in all parts of the system is an important part of efficient operation. Pressure drop upstream of a compressor signal requires higher compression pressures to achieve the control settings on the compressor [49]. Pressure drop in distribution systems and in hoses and flexible connections at points-of-use result in lower operating pressure at the points-of-use [49]. If the point-of-use operating pressure has to be increased, it is best to try reducing the pressure drop in the system before adding capacity or increasing the system pressure, as increasing the compressor discharge pressure or adding compressor capacity will result in significant increases in energy consumption. Typical problem areas include aftercoolers, lubricant separators, and check valves [49]. A rule of thumb for systems in the 100 psi (pounds per square inch) range is that for every 2 psi increase in discharge pressure, energy consumption will increase by approximately 1% at full output flow [49].

2.3.2.5.1 Causes [49]

Any type of obstruction, restriction, or roughness in a compressed air system will cause resistance to air flow, resulting in pressure drop. Within a distribution system, the highest pressure drops are usually found at the points-of-use, including undersized or leaking hoses, tubes, disconnects, or filters, regulators and lubricators (FRLs). On the supply side of the system, air/lubricant separators, aftercoolers, moisture separators, dryers and filters can be the main items
causing significant pressure drops. The maximum pressure drop from the supply side to the points-of-use will occur when the compressed air flow rate and temperature are highest. As a result, system components should be selected based upon these conditions and the manufacturer of each component should be requested to supply pressure drop information under these conditions. When selecting filters, dirt loading characteristics must be taken into consideration, as filters which frequently clog can act as an obstruction within the system.

2.3.2.5.2 Fixes [49]

Some of the most common ways to minimize pressure drop within a compressed air system include properly designing air distribution systems, operating and maintaining air filters and drying equipment to reduce the effects of moisture (e.g. pipe corrosion), selecting aftercoolers, separators, dryers and filters having the lowest possible pressure drop for the rated conditions, reducing the distance air travels through the distribution system, and specifying pressure regulators, lubricators, hoses, and connections having the best performance characteristics at the lowest pressure differential. It is important to note that these components must be sized based upon the maximum actual rate of flow and not the average rate of flow.

2.3.2.6 Compressed Air System Controls

Compressed air system controls are used to match the compressed air supply with system demand and are one of the most important determinants of overall system energy efficiency. The objective of any control strategy is to shut off unneeded compressors or delay bringing on additional compressors until needed [49]. Over the years, compressor manufacturers have developed a number of different types of control strategies.

2.3.2.6.1 Start/stop control [49]

Start/stop is the simplest control system available and can be applied to both reciprocating and rotary screw compressors. The motor driving the compressor is turned on or off
in response to the discharge pressure of the machine. Typically, a simple pressure switch provides
the motor start/stop signal. This type of control should not be used in an application that has
frequent cycling, because repeated starts will cause the motor to overheat and other compressor
components to require more frequent maintenance. Start/stop control is typically only used for
applications with very low-duty cycles for compressors with a 30 hp or lower capacity. A main
advantage of this control system is that power is used only while the compressor is running,
however this is offset by having to compress to a higher receiver pressure to allow air to be drawn
from the receiver while the compressor is stopped.

2.3.2.6.2 Load/unload control [49]
Load/unload control, or constant-speed control, allows motors to run continuously, but
unloads the compressor when the discharge pressure is adequate. Compressor manufacturers use
different strategies for unloading their compressors, but in most cases, an unloaded rotary screw
compressor will consume 15-35% of full-load hp while delivering no useful work. As a result,
some load/unload control schemes can be inefficient and in some cases it may be more effective
to use an alternate control system.

2.3.2.6.3 Modulating (throttling) inlet control [49]
Modulating or throttling inlet control allows the output of a compressor to be varied to
meet flow requirements. Throttling is usually accomplished by closing the inlet valve, thereby
restricting inlet air to the compressor. This control scheme is applied to centrifugal and lubricant-
injected rotary screw compressors. This method cannot be used on reciprocating or lubricant-free
rotary screw compressors and when applied to lubricant-injected rotary screw compressors, is an
inefficient means of varying compressor output. When used on centrifugal compressors, more
efficient results are obtained, particularly with the use of inlet guide vanes, which direct the air in
the same direction as the impeller inlet. However, the amount of capacity reduction is limited by
the potential for surge and minimum throttling capacity.
2.3.2.6.4 Dual-control/Auto-dual [49]

For small reciprocating compressors, dual-control allows the selection of either start/stop or load/unload. For lubricant-injected rotary screw compressors, auto-dual control provides modulation to a preset reduced capacity followed by unloading with the addition of an overrun timer to stop the compressor after running unloaded for a pre-set time.

2.3.2.6.5 Variable speed drives [49]

Variable speed is accepted as an efficient means of rotary compressor capacity control, using integrated variable frequency AC (alternating current) or switched reluctance DC (direct current) drives. Compressor discharge pressure can be held to within +/- 1 psi over a wide range of capacity, allowing additional system energy savings.

Rotary screw compressors with fixed-speed drives can only be stopped and started a certain number of times within a given time frame. Depending on the control scheme used, instead of stopping the compressor, it will be unloaded, throttled, or the compressor displacement will be varied in applications where the demand for air changes over time. In some cases, these control methodologies can be an inefficient way to vary compressor output. Compressors equipped with variable speed drive controls continuously adjust the drive motor speed to match variable demand requirements.

2.3.2.7 Multi-stage Compression and Multiple Compressors [49]

While there are many different types of compressors, all compressor types theoretically operate more efficiently if they are designed to include multiple stages. With multiple stages, the final discharge pressure is generated over several steps, thereby saving energy. Many multi-stage compressors save energy by cooling the air between stages, reducing the volume and work required to compress the air. In spite of this, many industrial compressors only have a single stage because equipment manufacturing costs are lower.
In many cases, it makes sense to use multiple, smaller compressors with sequencing controls to allow for efficient operation at times when demand is less than peak, thereby allowing plants with wide variations in air demand to operate efficiently under part-load.

2.3.3 Motor and drive systems

The last and perhaps the most important topic to discuss with regards to auxiliary equipment within the manufacturing sector is that of motors and drive systems. 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. Electric motors, taken together, make up the single largest end use of electricity in the U.S., accounting for roughly 60% of electricity consumption in industry [50]. Electric motors provide efficient, reliable, long-lasting service, and most require comparatively little maintenance. However, because they are such large consumers of electricity, there is a potential for high levels of CO₂ to be produced during their use – especially within electrical grids that use fossil fuels to generate electricity.

Unfortunately, operators are often so focused on the immediate demands of their equipment that they overlook how various system parameters can affect the operation of that equipment [50]. Oversizing a motor, for example, ensures that the motor is strong enough to meet the needs of the application, even at peak loading. However, an oversized motor can create performance problems with the driven equipment, especially in turbomachinery, such as fans or pumps. In fact, in certain circumstances, an oversize motor can compromise the reliability of components and the entire system. This leads to highly inefficient operations and enormous energy wastage with concomitant higher CO₂ emissions. Understanding the requirements of a system and how to size a motor accordingly is an important first step in the motor selection process [50]. The sections that follow are designed to outline the basic principles behind motor operation, provide some common motor inefficiency warning signs, and offer some suggestions on how motor efficiency can be improved depending on the system in question.
2.3.3.1 Indications of Poor System Design [50]

Motor efficiencies vary according to several factors, but generally range from 85-97% at full load. 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.

A number of indicators of poor system design and inefficient motor operation exist which are important for manufacturing companies to continuously watch for. These include, but are not limited to, high energy costs, abrupt or frequent system start/stops, high noise levels, hot work environments, and frequent maintenance requirements.

High energy costs can be the result of inefficient system design as well as inefficient motor operation. Not selecting or designing a proper motor and drive system for an application can also lead to power quality problems, such as voltage sags. In many material handling systems, the work-in-process moves roughly from one work station to the next. The banging that often accompanies sudden accelerations and decelerations is symptomatic of stress on the motor and drive system. The consequences of this stress can be more frequent maintenance and poor operating efficiency.

High noise levels are also common in inefficient fluid systems. Since energy losses in fluid flow often dissipate as noise, systems with large flow losses tend to be loud. Likewise, inefficient equipment operation often greatly increases the temperature of the workspace, especially if the added heat load was not included in the original design specifications for a HVAC system. As well, equipment that is not properly matched to the requirements of a certain application tends to require more maintenance. The primary causes of increased maintenance requirements are the added stresses on the system and the increased heat that accompanies inefficient operation. Ironically, system designers often specify oversized motor and drive and
end-use equipment in order to improve reliability. An oversized motor might be more reliable, but it might also make other parts of the system less reliable. 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.

2.3.3.2 Matching Motors to Applications [50]

As mentioned previously, in order to select a motor for a particular application, an understanding of the basic service requirements is needed. Applications in which normal operating loads are much smaller than the worst-case load often forces a motor to operate at part-load for significant periods of time, leading to poor system performance. This is a common industry problem, with a U.S. Industrial Electric Motor Systems Market Opportunities Assessment finding that more than 40% of motors in industrial applications operate at or below 40% of their load rating [50]. This means that large amounts of energy are being wasted by many industrial facilities.

In designing a motor to meet a specific system’s needs, it is important to note that almost 60% of the energy consumed by industrial motor-driven applications is used to drive pumps, fans, and compressors [50]. As well, within these auxiliary equipment applications, common relationships between speed, flow rate, pressure, and power (or the affinity laws) exist.

An important implication of these laws is that power consumption is highly sensitive to operating speed. As a result, increasing the speed of a fan or a pump requires a relatively large increase in the power required to drive it. For example, doubling the speed of a machine requires eight times more power. Similarly, decreasing the speed of a fan or pump removes a significant load from the motor. These considerations must be made when designing systems and selecting motors for varying applications.

One way to take into account the effect of various parameters on power requirements is to utilize what is known as a load duty cycle. Similar to the way pumps and fans use performance
curves and compressed air systems use load profiles to determine the best operating point for a system, motors and drives can also track their performance over time. A load duty cycle maps the amount of time that a motor operates at various loadings, relative to its rated capacity. They are extremely useful for determining the maximum requirements of a system and provide a clear outline of what normal operating conditions will entail. They can also be combined with pump, fan, or other auxiliary equipment performance curves to show how the various system elements will interact from a power requirement point of view.

2.3.3.3 Common Motor Selection Problems [50]

Electric motors are relatively inefficient when they are operated at very light loads, that is, below 40% of the rated load. They are usually most efficient at about 70% to 80% load. A good rule of thumb is to size motors to operate at about 75% load. This will also take into account occasional operational changes that require a higher load, such as voltage unbalances which require motor de-rating and any errors in the calculation of the motor load.

2.3.3.3.1 Oversized motors [50]

Since motors are often specified according to worst-case operating conditions, applications in which normal operating loads are much smaller than the worst-case loading force motors to operate at part-load much of the time. Engineers frequently specify motors that are larger than needed to meet system requirements in order to ensure that the existing motor/drive assembly can support anticipated increases in capacity. However, the consequences of oversizing motors include lower efficiency, higher motor/controller costs, higher installation costs, lower power factor and increased operating costs.

2.3.3.3.2 Undersized motors [50]

Another type of motor selection problem is undersizing the motor for the intended application. Motors should be sized to operate from 75% to 100% of rated load. The principal
consequence of operating a motor above its rated load is a higher winding temperature, which shortens the operating life of the motor. If the motor has a service factor of 1.0, the motor lifetime may be only a few months if it is operated above rated load or if it is operated at rated load when there is a power quality problem. As a rule of thumb, every 10°C rise in winding temperature reduces insulation life by half. Although motor efficiency drops off slightly at higher-than-rated loads, the increase in energy cost is usually not as severe as the cost associated with shorter intervals between repairs or replacements.

2.3.3.4 Efficiency Improvement Strategies

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 [50]. As well, since many industrial applications require accurate control of a motor’s operating speed, the addition of a speed-adjusting device improves performance overall [50]. Historically, DC motors have been used in these applications because of their effective speed control characteristics, however, improvements in power semiconductor technology has resulted in increased use of VFDs with AC motors within industry [50].

One particular area where the use of speed controlling devices has been beneficial is within machining and fabrication. Since tool and cutting bit operating life is highly sensitive to how well constantly changing cutting speed and pressure are maintained during operation, the use of VFDs offer several advantages [50]. They can allow for continuous control of cutting speed during machining operations and can shift to different speeds without requiring the machine to be reconfigured [50]. As well, in many machining operations, VFDs can improve process control
and speed of production, demonstrating that energy savings are not the only benefit of this technology [50].
Chapter 3
Available Tools and Programs

As noted in the literature review above, there are numerous energy efficiency strategies available for companies to implement. It is important to keep in mind that those solutions focus on only 3 sources of inefficiency, when, in reality, there could be dozens of other sources of energy loss within a plant or facility. With so many individual processes, pieces of equipment, or production stages to monitor it is easy to understand why so many companies feel overwhelmed by the thought of pursuing energy efficiency initiatives.

It takes a considerable amount of time and resources to initially identify the primary sources of inefficiency within a facility, as each has its own unique requirements. It is the unique nature of energy consumption that makes a blanket solution for energy efficiency practically impossible. Varying production schedules, production levels, and equipment types all play a significant role in determining the overall energy requirements of a facility and can also affect the feasibility of certain energy efficiency projects.

It is important that energy efficiency projects target the major areas of concern within a facility in order to achieve maximum economic and environmental impacts. But with so many factors influencing a facility’s specific energy requirements, how can a company begin to pinpoint the best area to focus their efficiency efforts?

Currently, a growing trend has emerged among industry in which many companies try to grasp a better understanding of their energy needs and sources of inefficiency by performing internal energy audits or hiring third party contractors to conduct audits for them. While this process is effective in generating a concise list of actions (ranked according to potential impact) for companies to pursue, it can be quite costly and time consuming. As well, there is often a trade-off depending on what route is pursued.
Internal audits require trained auditors to already be on staff, which is not always possible, and utilizes personnel hours to conduct the necessary surveys. If resources are limited within an organization, it may be best to contract the auditing process to an external company and allow personnel hours to remain focused on tasks pertaining to major company projects. While the use of external contractors will allow personnel hours to be reserved for key project work, the cost of hiring professional auditors to conduct the work may be an added expense many companies cannot afford. This is especially true in the case of SMEs, which are typically limited in terms of both their financial and human resources. This can lead to companies simply pursuing what they think is the best solution for their facility, which can result in ineffective solutions, wasted resources, and, in some cases, escalate the problem. It is for this reason that a thorough understanding of a facility’s primary energy users, production schedules, and essential system interactions is required before attempting to implement any plant modifications or efficiency strategies.

Fortunately, a cheaper alternative to conducting formal energy audits does exist so that companies are able to pinpoint areas of concern without expending considerable resources. Oftentimes software programs or tools have been created which can be used to determine the impact of a proposed system modification or efficiency project. This means that companies can focus their efforts on the most critical areas within their facility. While these programs are not a complete substitute for energy audits, they do offer an excellent support system for companies that are looking to pursue projects. As well, if used properly, they offer the added benefit of reduced cost and implementation time. However, if a company is intending to pursue wide-scale changes within a plant or facility, it is still highly recommended that an energy audit be conducted, as it provides a more holistic view of the potential impact of any proposed system changes.
A number of programs and resources exist which can aid companies with the implementation of efficiency improvement strategies. Many are free or require only a small subscription fee to access. They offer extensive resources to companies and platforms through which to analyze planned efficiency projects. By importing data into these programs, companies have an opportunity to “preview” a project. Overall impacts can then be identified and a project’s feasibility determined.

Such tools 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 to use these programs to identify their main improvement areas. It saves both time and resources, and allows companies, both large and small, to focus their efficiency programs on the most effective areas.

A popular series of energy efficiency tools is available through the U.S. DOE and universities around the world are focused on developing software to better enable companies to track their energy consumption and model the outcomes of energy efficiency projects. As well, many governments worldwide, including here in Canada, have made energy efficiency a primary environmental strategy. As a result, they offer numerous rebates and support tools to companies that are interested in pursuing efficiency projects. These tools are outlined in further detail below.

3.1 DOE Energy Efficiency Tools

3.1.1 Pumping system assessment tool (PSAT)

As previously mentioned, enormous energy savings can result by improving the efficiency of industrial pumping systems. Prior to implementing some of the techniques presented within this thesis, companies must first be able to identify their system needs and issues. One software program of particular use to manufacturers looking to get a better understanding of their system needs and identify areas of inefficiency is the Pumping System Assessment Tool (PSAT),
available through the U.S. DOE’s ITP [46]. The program is designed to help industrial users assess the efficiency of their pumping system operations. PSAT uses achievable pump performance data from the American Hydraulic Institute standards as well as motor performance data from the MotorMaster+ database (an energy-efficient motor selection and management software tool also created by the ITP) to calculate potential savings in energy and associated costs [51].

The software is available to download online and is free to all users. In order to be able to use the software successfully, companies must be able to accurately provide system data, including: pump type, system of units, number of stages within the pump, pump and motor speed(s), motor nameplate ratings, operating duty (fraction of time the equipment runs at the specified condition), energy costs on site, flow rate, pump head, and electric power or current and voltage of the system [51]. While this may seem like an extensive list of data inputs, in reality, it is the bare minimum of what would be required to perform general energy calculations on a typical pumping system. As well, most of the information should be readily available or easily collected from the pump itself or the pump manufacturer.

If a company is able to provide this information, PSAT will in return generate an estimated efficiency for both the pump and motor, as well as the shaft power for both the existing and commercially available “optimal” equipment for the system [51]. It will also provide the annual energy use and costs for the existing versus the optimal system, as well as the potential annual energy savings which would result from any system modifications [51]. The PSAT also offers an optimization rating for the system so that its efficiency level can be compared with that of a completely optimal system (which corresponds to a rating or grade of 100) [51].

As a result, through the collection of basic system information, PSAT can be utilized by companies looking to improve the overall efficiency of their pumping systems to determine the effect of anything from a simple modification to a complete system overhaul [51].
3.1.2 AIRMaster+ Program

As with pumping systems above, utilizing available software tools and programs to identify inefficiencies and develop energy conservation strategies remains one of the best ways for companies to improve the operation of their compressed air systems. An example of one such software tool is the AIRMaster+ program, a free online tool available through the DOE. The program helps users analyze the energy use of current compressed air systems, as well as identify potential savings opportunities [52]. It provides comprehensive information for assessing compressed air systems including modeling existing and future system upgrades and evaluating the potential savings and effectiveness of energy efficiency modifications made to the system [49].

AIRMaster+ is a stand-alone, Windows-based software tool used to analyze industrial compressed air systems [49]. There is an additional LogTool that can be used to help industrial users determine the operating dynamics of a compressed air system. The LogTool is used first to collect data, which is then input into the AIRMaster+ program in order to model the existing system and any future upgrades [52]. Much like PSAT, a minimum amount of data from the system is required to operate the AIRMaster+ program, including the type of facility the compressed air system is used in, utility rates, the number of air compressors and the end uses for each system, typical operational day types, compressor performance and operating details (which can be gathering using the provided LogTool), and metered hourly energy use or air flow for each day type and for each compressor [52]. As well, unlike PSAT, the AIRMaster+ tool requires users to define an energy efficiency enhancement goal, which can include anything from reducing leaks and shortening run time to improving system efficiency targets overall [52].

While the information required to use the AIRMaster+ program is more detailed than that of PSAT, it is necessary in order to fully understand a facility’s compressed air needs and where improvements can be made. In some cases, if a compressed air audit was recently completed at
the facility, it may be able to be used in conjunction with the LogTool to provide most of the required information.

The AIRMaster+ program requires more input and system monitoring than most efficiency software tools, however the benefits of the program can be quite substantial considering the effect that eliminating compressed air wasteful practices can have on energy consumption trends. Current users of the program include distributors of compressed air equipment, compressed air system auditors, industrial plant personnel, and utility representatives [52]. However, AIRMaster+ does not model dynamic effects of distribution and end uses and such issues should be addressed through consultation with an experienced auditor before any efficiency recommendations are pursued [52].

3.1.3 MotorMaster+

In terms of motors and drive systems, an excellent tool available for manufacturers is the MotorMaster+ software, which is free and available through the National Electrical Manufacturers Association (NEMA) [53]. The software is available to assist industry in managing electric motor systems and help users find the most energy-efficient motors that meet their requirements and compare the life-cycle costs of potential replacements with the cost of a typical repair [50]. Through the program companies can access performance data from nearly 30,000 industrial electric motors and perform several tasks to help with system management, including a comparative benefits analysis of existing motors with possible alternatives, maintaining a plant’s electric motor inventory, keeping a historical record of motor maintenance, and calculating the life-cycle costs of a motor project [50].

MotorMaster+ is designed for industrial energy coordinators, facility managers and engineers, plant electricians, maintenance staff, and procurement personnel who are interested in improving the energy efficiency of motor systems at an industrial facility [53]. Users who want to create an in-plant motor inventory must first collect the following information for entry into the
system: utility and rate schedule, operational schedules, motor nameplate information, operating and load profiles, as well as various life cycle economic details (depreciation method, capital investment, financing plan, utility usage and costs, and expected equipment life) [53].

The program is designed to help companies choose the most reliable motor for a particular system in a way that is also cost-effective. It allows companies to optimize their drive systems by offering a ‘repair versus replace’ comparison between hundreds of similar motor models [53]. It also provides payback period and return on investment information for potential system modifications. Energy accounting, conservation savings tracking, and greenhouse gas emissions reduction reports can also be generated using the program [53]. The versatility of the tool means that companies can receive expertise in numerous areas all from one source, saving both money and resources.

3.1.4 Process Heating Assessment and Survey Tool (PHAST)

The DOE’s Industrial Technologies Program, through its Technology Delivery Strategy and the Industrial Heating Equipment Association (IHEA), a trade association for process heating equipment manufacturers, have excellent resources available to manufacturers looking to improve the performance of their industrial process heating. One tool available for process heating systems is the Process Heating Assessment and Survey Tool (PHAST), which provides an introduction to process heating methods and tools to improve the thermal efficiency of heating equipment [54]. The tool can be used to survey process heating equipment that uses fuel, steam, or electricity, and identify the most energy-intensive equipment [55].

The tool is designed for industrial energy coordinators, plant managers, and engineers who are looking to identify energy-saving opportunities for process heating equipment and systems [55]. Much like the AIRMaster+ program, PHAST requires a considerable level of data input, mostly pertaining to energy usage. General manufacturing plant information, in addition to available energy sources for the plant and fuel heating costs are compulsory [55]. Energy use data
for any furnaces or heaters within the system, auxiliary equipment associated with furnace operation, as well as energy used in various parts of the furnace under given operating conditions are all necessary for successful simulation [55]. Additionally, commonly used materials for charging and fixturing and the makeup of the process atmosphere within the heating system are also required [55]. As a result, it is important for companies to have a thorough understanding of their heating systems before attempting to simulate modifications or improvement measures. Sub-monitoring of individual heating system components and material composition is critical to developing an accurate model within the PHAST framework.

The tool also enables users to perform an energy (heat) balance on selected equipment in order to identify and reduce non-productive energy use [54]. The performance of a furnace under various operating conditions can also be compared and ‘what-if’ scenarios can be simulated and tested using this software [55]. The software can report the annual energy use of each piece of equipment within the system and suggest methods to save in areas where energy is used excessively or wasted [55]. As a result, for companies that have sound background data on their process heating systems, PHAST is a useful tool, whether the facility in question is small or large-scale.

3.2 Modelling Programs

The DOE has committed numerous resources to developing programs for industries to use when developing energy efficiency initiatives. However, numerous universities and companies around the world are also committed to improving energy efficiency through the development of cutting edge software tools and simulators. One of these tools is further highlighted in the section below.

3.2.1 e!Sankey

A Sankey diagram is a directional flow chart where the magnitude of the arrows is proportional to the quantity of flow [56]. Sankey diagrams are a useful way of visualizing
material flows, energy efficiency or costs [56]. They are used commonly by academics to visualize system interactions and identify energy hot spots or sinks. The development of a Sankey diagram can be quite time consuming depending on the complexity of the system in question and requires a considerable breakdown of energy usage in terms of individual systems and components.

However, a program which has been developed at the Institute for Environmental Computer Science (IECS) in Hamburg, Germany has recently enabled Sankey diagrams to be utilized by industry and has allowed this useful energy visualization tool to spread beyond the boundaries of academia. The IECS has been developing this tool for over a decade and has partnered with numerous companies to ensure its accuracy, as well as its applicability to industry [57].

The software enables companies to optimize process streams and make production more efficient through the visualization of material and energy flows throughout the entire system and the identification of key process system interactions. The program is available to download online in a free trial version format for a 2 week period, after which it can be purchased by paying a modest access fee [57]. The program is relatively straight forward to use and has been utilized by numerous corporations around the world [57]. However, like any model, energy usage data is still required to be input into the e!Sankey environment, so companies must either have such data on file or be willing to install meters at various points throughout their system to gather the necessary information.
It can be seen from the example given in Figure 28 that accurate data is required to model a system. As a result, proper, inexpensive monitoring equipment, placed appropriately throughout a system can offer considerable aid in controlling energy use.

**3.3 Matching Inefficiencies and Software Programs**

For convenience purposes, the information pertaining to various sources of industrial energy inefficiency and their subsequent warning signs from Chapter 2 have been summarized in the table below and matched with a suitable software program or tool outlined in Chapter 3 above. Due to the large amount of information which was presented on each inefficiency source, it is believed that this table could serve as a good starting point for facilities which are experiencing specific inefficiency symptoms but do not have the resources available to do an in-depth audit or system analysis. Once their primary source of inefficiency has been identified they
can then use the suggested tool to complete a high-level analysis and begin implementation of solutions as outlined by the software program.

**Table 5: Inefficiency sources, warning signs, and software tools**

| Source of inefficiency | Warning signs | Suitable software program |
|------------------------|---------------|---------------------------|
| Waste heat             | • High fuel costs  
                          • Decreased production  
                          • Reduced profit  
                          • Hot work spaces  
                          • Hot equipment or piping surfaces  
                          • Warn or missing insulation | PHAST |
| Idle power losses      | • Long wait times between production batches  
                          • Continuous running equipment  
                          • Low production rates | e!Sankey |
| Inefficient pumps      | • Excessive noise in pipes and across valves  
                          • Highly throttled control valves  
                          • Heavy use of by-pass lines  
                          • Heavy maintenance requirements  
                          • High energy costs | PSAT |
| Compressed air losses  | • Excessive pressure drop in system  
                          • High energy costs  
                          • Reduced production | AirMaster+ Program |
| Inefficient motors     | • High energy cost  
                          • Abrupt system start/stop  
                          • High noise levels  
                          • Hot work environments  
                          • Heavy maintenance requirements | MotorMaster+ |
3.4 Government Programs

A number of programs and initiatives have recently been developed by the Canadian government, through its Department of Natural Resources, to encourage more wide-scale deployment of energy efficiency projects. As a result, the number of resources available to Canadian manufacturers has grown considerably. Some of these recently-developed industrial efficiency programs include the introduction of the CAN/CSA-ISO 50001 Energy Management System standard, CIPEC (Canadian Industry Program for Energy Conservation), the ecoENERGY and CanmetENERGY programs, and the Canadian Energy Efficiency Act, which includes government-regulated MEPS (minimum energy performance standards).

3.4.1 CAN/CSA-ISO 50001 Energy Management System

This Canadian Standard Association (CSA) standard corresponds to the International Standards Association’s (ISO) 50001 Energy Management System standard. It is a voluntary standard which companies can choose to enrol in, which indicates their commitment to environmental performance once they become certified [58].

The implementation of this standard is designed to help organizations reduce their energy consumption and carbon footprint, while at the same time making them more competitive and environmentally responsible [58]. The standard specifies requirements applicable to energy use and consumption – including measurements, documentation, reporting, and design and procurement practices for equipment, systems, processes, and personnel [58].

3.4.2 CIPEC [59]

CIPEC is a voluntary program implemented by NR (Natural Resources) Canada’s Office of Energy Efficiency. The program is a partnership between private industry and the Federal government. It aims to promote and improve Canada’s industrial energy efficiency and reduce greenhouse gas emissions from energy use in the industrial sector. An important aspect of the program is the creation of sector task forces, which has set targets and developed action plans for
improving energy efficiency in over 25 different industrial sectors. These specialized task forces also allow members to share information and identify common needs and best practices, which has proven to be an invaluable asset to many small-scale companies. To date, more than 1400 companies across Canada have registered with the CIPEC program.

3.4.3 ecoENERGY

The ecoENERGY Efficiency Program was recently established by the Canadian government in order to help improve energy efficiency within Canadian homes, offices, industries, and roads. Between 2011 and 2016, the program will invest $195 million dollars to make energy performance within Canada more visible and to help make industry and vehicle operations more efficient [60]. Under this program, there are 5 target areas within which the government hopes to address specific efficiency issues: 1) ecoENERGY Efficiency for Buildings, 2) Housing, 3) Equipment Standards, 4) Industry, and 5) Vehicles.

The ecoENERGY Industry Program is designed to aid companies in the adoption of the new ISO 50001 Energy Management Systems standard by establishing both a framework and the necessary processes to adopt a systematic approach to improving energy efficiency, use, and intensity [61]. The program is also designed to support CIPEC efficiency efforts. The program also provides ‘Dollars to Sense Energy Management Training’ workshops for industrial companies, as well as biweekly newsletters and reports, guides, manuals, and other publications to increase industrial energy efficiency awareness [61].

3.4.4 CanmetENERGY [62]

The CanmetENERGY program helps support NR Canada’s clean energy research and technology development. The program is the largest energy, science and technology organization working on clean energy research, development, demonstration, and deployment, with over 450 scientists, engineers, and technicians working to develop more energy efficient and cleaner technologies. Their research areas include buildings and communities, clean fossil fuels, bio
energy, renewables, industrial processes, oil sands, and transportation. The program offers
science and technology programs and services, supports the development of energy policy, codes,
and regulations, and acts as a window to federal financing. As with the other programs mentioned
above, the CanmetENERGY program is also voluntary and companies must choose to become a
CanmetENERGY industrial partner.

3.4.5 Canadian Energy Efficiency Act and MEPS

Unlike the programs mentioned above, Canada’s Energy Efficiency Act is responsible for
the enforcement of regulations concerning MEPS (Minimum Energy Performance Standard) for
energy-using products within Canada, as well as the labelling of energy-using products and the
collection of energy use data [63]. These regulations establish efficiency standards for a wide
range of energy-using products, with the main objective being the elimination of least energy-
efficient products from the Canadian marketplace. Regulated industrial equipment in Canada
covers a broad range of processes and systems, including large air conditioners (19 kW), large
heat pumps, boilers, electric motors, pumps, compressors, arc-welding equipment, HVAC
(heating, ventilation, and air-conditioning) units, chillers, and steam distribution systems [63]. A
sample of the MEPS for gas-powered boilers can be seen in Table 5 below. A document
containing all the MEPS for industrial equipment within Canada can be found within the
Canadian Energy Efficiency Act and should be referenced when replacing or upgrading industrial
equipment, processes, and systems to ensure that a manufacturer is meeting the appropriate
regulations.

Canada’s Energy Efficiency Act is currently the only piece of legislation within the
country that is responsible for the enforcement of efficiency regulations. It is also important to
note that these regulations establish efficiency standards for energy-using products only and do
not provide standards for systems as a whole. The incorporation of a similar MEP standard for
system efficiencies could be a way to force corporations to improve the overall efficiency of the
process streams used throughout their facilities and encourage the utilization of wasted heat and energy sources.

Table 6: MEPS for gas powered boilers [63]

| Item # | Energy-using product | Standard/Legislative provision | Energy efficiency standard | Completion period |
|--------|----------------------|--------------------------------|---------------------------|-------------------|
| 46.    | Gas boilers intended for low pressure steam systems | CGA P.2 | Annual fuel utilization efficiency ≥ 75% | On or after December 31, 1998 until August 31, 2010 |
| 46.1   | Gas boilers intended for low pressure steam systems | CSA P.2 | Annual fuel utilization efficiency ≥ 80% | On or after September 1, 2010 |
| 47.    | Gas boilers intended for hot water systems | CGA P.2 | Annual fuel utilization efficiency ≥ 80% | On or after December 31, 1998 until August 31, 2010 |
| 47.01  | Gas boilers intended for hot water systems | CSA P.2 | Annual fuel utilization efficiency ≥ 82% | On or after September 1, 2010 until August 31, 2012 |
| 47.02  | Gas boilers intended for hot water systems not equipped with tankless domestic water heating coils | CSA P.2 | Annual fuel utilization efficiency ≥ 82% | On or after September 1, 2012 |
| 47.03  | Gas boilers intended for hot water systems with tankless domestic water heating coils | CSA P.2 | Annual fuel utilization efficiency ≥ 82% | On or after September 1, 2012 |
Chapter 4

Canadian Industrial Case Studies

This chapter provides detailed case studies from three companies within Canada: Pratt and Whitney Canada (PWC), Magna International Inc., and Van-Rob Inc. The companies were contacted throughout the research phase of the project in an attempt to collect energy consumption and efficiency data directly. Obtaining such data is often difficult due to the sensitive nature of energy consumption data, especially within industry.

Most of the research conducted for this study was done by meeting with industry representatives and discussing energy conservation. The lack of transparency toward energy consumption is evident within industry. It is practically impossible to find energy data on Canadian organizations, even by contacting them directly. Most organizations contacted were comfortable talking about energy consumption practices, about the projects they had recently implemented and the qualitative results they had seen from such strategies – however getting quantitative data was challenging.

It is hoped that by highlighting the benefits that accompanied the energy conservation projects within these case studies, that a conservation benchmark or baseline will be created. Using this benchmark as a guide, it is a primary goal of the study to encourage the development of further energy conservation projects within Canadian industry.

It is believed that SMEs would be more inclined to participate in larger-scale conservation strategies if they were presented with positive examples from within industry of companies who had successfully undertaken efficiency projects. Being able to provide positive industrial examples of successful conservation projects is one of the main objectives of the research undertaken for this project. The new data published in the above papers and within this
study can hopefully change the way energy efficiency opportunities are viewed in this country and an open discussion on the issue of energy conservation and overconsumption can begin.

Examples of successful energy conservation projects from the three companies mentioned above are discussed in-depth in the case studies below. The most detailed will be presented first. It is important to note that the energy consumption and cost analysis data has been collected directly from the organizations, while the GHG emissions stemming from these energy projects were tabulated separately by myself using the supplied energy consumption values and carbon footprint values pertaining to various fuel sources and regions within Canada.

4.1 Pratt and Whitney Canada

PWC is a jet engine manufacturer headquartered in Longueuil, QC. They are a large player in Canada’s industrial sector, having a number of facilities throughout the country. They are also an example of an organization which has been proactive in increasing its energy efficiency and overall environmental performance, having undertaken a number of energy efficiency initiatives at two separate manufacturing facilities in Halifax and Montreal.

4.1.1 Boiler consolidation – Halifax facility

Pratt and Whitney Canada recently consolidated the existing boiler system at its Halifax facility. The project involved the replacement of the plant’s original oil-fired boilers with natural gas fired. 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 showed the boilers were actually operating under 40% capacity for most of the year and were highly fouled and inefficient (less than 50%).
By consolidating the boiler system and converting from petroleum to natural gas, there will be an estimated reduction of annual CO$_2$e emissions of 680-780 tonnes. As well, the project, which cost roughly $450,000 to install, is estimated to save the company roughly $180,000-350,000 annually, with an estimated payback period of only 1.5-2 years. The project reduced both fuel costs and the cost to the environment through extensive CO$_2$ emission reduction. This project demonstrates the opportunities available to manufacturers to reduce both their cost and emissions, and is summarized in Table 7 below.

Table 7: Boiler consolidation project summary

| Project:                  | Project Cost: | Annual Cost Savings: | CO$_2$e Reduction: | Payback Period: |
|---------------------------|---------------|----------------------|--------------------|-----------------|
| Boiler Consolidation (Halifax) (completed) | $450,000 | $180,000-$350,000 | 680-780 t | 1.5-2 years |

4.1.2 Industrial cooling water plant heating project – Montreal facility

At its Montreal facility, PWC recently invested considerable resources into a WHR project. The project involves extracting heat from a waste water (i.e. cooling water) stream and using it to heat various shop areas. Installation of the project was completed last fall and, since its inception, the plant has noticed a considerable natural gas consumption decrease, and, as a result, cost and GHG emission savings. The plant has tracked and compared the consumption practices of this winter (2014) to that of last year (2013) and noticed remarkable improvements.

For the month of November, which was 2% warmer on average as compared to 2012, the plant used 22% less natural gas for heating than during the same time period in 2012. Likewise, December, which was 24% colder on average, saw a 13% reduction in natural gas consumption, January was 3% colder and saw a 13% reduction in consumption, while February was 13% colder and saw a 22% reduction in natural gas usage. During this period it is estimated that PWC were able to off-set 761 tCO$_2$e and that 355,100 m$^3$ less natural gas was consumed. As a result, on
average 17% less natural gas was used for heating, despite 10% colder temperatures throughout the winter season.

It is also estimated that during this period cost savings of roughly $290,000 occurred as a result of the project’s implementation. Due to increases in fuel prices, if PWC had continued heating their plant using strictly natural gas, using 2012-2013 consumption volumes, roughly $1,164,895 would have been spent on plant heating as opposed to the $875,476 which was actually spent. This project also demonstrates the opportunities available for companies to significantly reduce both their cost and emissions through WHR and energy recycling and is summarized in Table 8 below. It also serves as a positive example to companies who are considering implementing similar projects but are hesitant due to concerns of economic and other risks.

Table 8: Natural gas consumption and cost summary for PWC's WHR project

| Consumption period | Gas consumption (m³) | Average fuel price (CDN) | Heating cost (CDN) | Average temperature change (against 2012 reference year) |
|--------------------|----------------------|--------------------------|---------------------|---------------------------------------------------------|
| Nov-12             | 444,100              | $0.3278                  | $106,262            |                                                         |
| Dec-12             | 517,000              |                          | $112,077            |                                                         |
| Jan-13             | 553,000              |                          | $243,266            |                                                         |
| Feb-13             | 535,000              |                          | $210,101            |                                                         |
| Total              | 2,049,100            |                          | $671,706            |                                                         |
| Nov-13             | 346,000              | $0.5168                  | $81,447             | 1% warmer                                              |
| Dec-13             | 448,000              |                          | $188,824            | 24% colder                                              |
| Jan-14             | 481,000              |                          | $352,772            | 3% colder                                              |
| Feb-14             | 419,000              |                          | $252,434            | 13% colder                                              |
| Total              | 1,694,000            |                          | $875,476            | 10% colder                                              |

Table 9: Summary of PWC's WHR project

|                | GHG reduction (tonne CO₂e) | Consumption comparison | Cost comparison |
|----------------|--------------------------|------------------------|-----------------|
| Nov-13         | 210                      | -22%                   | -23%            |
4.2 Magna International Inc.

Magna International Inc. is a global automotive supplier headquartered in Aurora, ON. With 316 manufacturing operations around the world and 46 plants in Canada alone, the company has invested numerous resources toward identifying areas of energy inefficiency and is continually improving their performance through the implementation of numerous energy conservation projects.

4.2.1 Hot stamp heat recovery:

A major project implemented at one of Magna’s Canadian facilities during 2013 involved reclaiming waste heat from the flue gas stream of a hot stamping process. The outcome of the project is summarized in Table 10 below. Originally, a direct usage approach for the flue gas stream was considered. However, it was later decided that bringing the air directly into the plant could pose too much of a contamination risk, even with adequate filters in place. As a result, it was decided that a heat exchange system would be installed to extract the waste heat from the flue stream and return it to the plant for heating purposes.

Through the project, Magna estimates that 240,000 m³ of natural gas will be saved at the plant, keeping approximately 514 tCO₂e out of the atmosphere annually. The project, with an initial investment of $180,000 is expected to have a payback period of 36 months (i.e. 3 years) and will save the company $52,800 annually. The company has also indicated that a number of government rebates and energy efficiency incentive programs could help them receive an additional $24,000 in rebates or almost 15% of the project’s original capital investment.

4.2.2 Air curtain installation:
Air curtains were added to three doors within the plant in an attempt to reduce heating requirements. The outcome of the project is summarized in Table 10 below. An air curtain is a fan-powered device that creates a barrier across an open doorway by blowing a continuous stream of air from the top to the bottom of the opening. In doing so, the stream of air insulates the door and prevents the climate on either side from coming into contact. It is generally installed to act as a second line of defense inside a closed door or to replace plastic hanging flaps in an open doorway. Air curtains, if installed properly, maintain a comfortable thermal environment by preventing excessive heat loss or gain inside a space and are capable of reducing heating or cooling costs up to 80% [64].

While the actual savings encountered by Magna will depend on the temperature differential between the 2 spaces the air curtain separates, the company is estimating that roughly 45,000 m³ of natural gas will be saved as a result of heat loss prevention. The initial cost of the air curtain installation was $62,050, with the company receiving an additional $4,500 in rebates. Through the implementation of this project, the company will save an estimated $9,900 annually, giving a payback period of 70 months (almost 6 years) and keeping 96 t of CO₂e out of the atmosphere.

4.2.3 Hot water heater replacement:

Magna is also continually replacing outdated equipment with newer, more efficient products. This is an important aspect of their energy conservation strategy and will result in long-term savings for the company. This year, Magna replaced 2 existing hot water heaters at one of its facilities. The outcome of the project is also summarized in Table 10 below. The units were replaced with high-efficiency (96.3%) condensing hot water heaters rated at 168.8 PJ/hr. The project required minimal capital investment ($2,860) and as much as 25% of the upfront cost ($750) was redeemed through conservation rebates. The replacement of the old hot water heaters is expected to save the company $1,430 annually, with a payback period of only 18 months. The
new units will also keep an additional 14 tCO₂e out of the atmosphere by reducing natural gas consumption by roughly 6,500 m³/year. This project demonstrates the potential benefits and rebates which are available to companies who are looking to improve their overall system efficiency through the installation of high-efficiency equipment and offers a feasible way for organizations to achieve considerable energy reduction.

4.2.4 Compressed air pressure reduction:

The Energy Efficiency Manager for the Americas Branch of Magna International identified compressed air leaks as the number one source of inefficiency within their plants during a conference call that was held to discuss the company’s energy conservation strategy. Magna has large, industrial facilities which utilize hundreds of air compressors. A compressed air audit was recently completed at one of its facilities and a compressed air leak repair program initiated.

As noted in the compressed air section above, air leaks are a primary source of wasted energy within industry and a number of steps can be taken to repair detected leaks and to reduce leakage rates overall. One of the main ways which Magna has chosen to address the issue of compressed air leaks is through the reduction of overall system air pressure from 114 psi to 107 psi. The outcome of the project is summarized in Table 10 below. When it is possible for organizations to reduce their system air pressure it can result in wide-scale energy reduction and greatly improve system efficiency by reducing the flow rate across any leaks present in the system.

The specific savings encountered at the facility will obviously depend on the compressed air flow rate and demand, however Magna estimates the approximate savings through the reduction of system air pressure by 7 psi to be 240,000 kWhr which equates to 185 tCO₂e. This is a positive example of an organization expending no capital and receiving major economic benefits in the long-term. It is estimated that through this reduction in pressure and compressed
air leakage rates the company will save $21,600 annually – a considerable return for simply analyzing their plant’s compressed air requirements and modifying system set-points as a result.

**Table 10: A summary of Magna's key 2013 energy conservation projects**

| Project               | Annual natural gas reduction (m³) | Annual CO₂e reduction (Tonnes) | Initial capital investment | Projected annual savings |
|-----------------------|----------------------------------|-------------------------------|----------------------------|--------------------------|
| Hot stamp WHR        | 240,000                          | 514                           | $180,000                   | $52,800                  |
| Air curtain          | 45,000                           | 96                            | $62,050                    | $9,900                   |
| Heater replacement   | 6,500                            | 14                            | $2,860                     | $1,430                   |
| Air pressure reduction | 240,000                          | 185                           | $0                         | $21,600                  |

A summary of cost and GHG reductions experienced by Magna in 2013 as a result of these energy efficiency projects can be seen in Table 10 above. Magna International Inc., like PWC, has successfully demonstrated the economic and environmental benefits available to Canadian companies through the implementation of WHR and other energy efficiency initiatives, including assessing compressed air requirements and upgrading outdated equipment with more energy-efficient models.

### 4.3 Van-Rob Inc.

Van-Rob Inc. is a tier-one supplier of automotive manufacturing facilities within North America. Its Corporate Centre and Engineering Department is headquartered in Aurora, ON. In recent years, the company has invested in a number of retrofitting and energy conservation projects. They are working to continually improve their environmental performance, but, like many industrial facilities, have been finding it challenging to monitor progress and track specific GHG reduction numbers.

#### 4.3.1 Chiller replacement project
In September 2009, Van-Rob Inc. finalized the replacement of the chiller system at their Aurora facility. The original system consisted of 2 chillers (one continually in service and a back-up), with a capacity of 628t (tonnes) each, and 2 motors, with a capacity of 501 and 469 hp respectively. The equipment used in the 35 year-old facility is outdated, including the chiller units. The refrigerant used in the system – Freon R-11 – was being phased out under the Montreal Protocol (an international treaty designed to reduce the production and consumption of ozone depleting substances to mitigate their abundance in the atmosphere and in order to protect the Earth’s fragile ozone layer [65]) and although the chiller could continue running under current legislation, in the event of a system breakdown the plant had been informed it would not be able to be repaired under the refrigeration management guidelines of the protocol.

The Facilities Team at Van-Rob took this as an opportunity to remove outdated refrigerants from their plant, while simultaneously improving the performance and reliability of the chillers. The old system was replaced with two 300t chillers with two 192 hp capacity motors. What is different about the new system is that the chillers are comprised of 6 individual stages or 6 compressor units in series so the chiller capacity can come online as needed. Not only does this system improve reliability by allowing the chillers to continue to run if one or more of the compressor units are down for maintenance or repair, it also reduces the need for a large back-up chiller. As well, the new system runs on R-401a and is fully compliant under the Montreal Protocol.

In addition to the energy savings which result from eliminating the need for a back-up chiller and the reduction in the required motor capacity, during the winter cold, outside air is used to cool the glycol/water mix in the chiller loop so that the refrigeration cycle does not run, resulting in even more energy savings. Unfortunately, Van Rob does not use sub-metering to monitor the energy consumption of specific equipment and systems and so the exact savings resulting from the chiller replacement project cannot be determined.
It is important to note that this retrofitting project cost Van-Rob Inc. approximately $719,000 in initial capital investment. However, through the ERIP (Electricity Retrofit Incentive Program) offered by HydroOne, they were able to receive $280,000 in rebates. The program offers rebates to companies who upgrade large, power-consuming equipment to more energy-efficient models. The value of the rebate received is based on the kW savings between the new and old system, with $800/kW reduction being returned to the company at a maximum of 40% of the original project cost.

This project demonstrates the benefits that are available to companies who are looking to upgrade their systems as a result of legislation or regulatory requirements. In addition to receiving a large rebate for the project, Van-Rob is also able to obtain the added benefits of cost and energy savings through the use of smaller auxiliary motors and improvement in system reliability by upgrading their chiller system to include individual compressor stage units.

4.3.2 Compressor control unit:

A compressor control unit was also recently installed at Van Rob’s main engineering facility, with the intent of reducing its energy usage during times of low compressed air demand. The unit was designed to automatically shut down compressors during times of low demand so that only 1 of the 4 units would be running, with the others being restarted as needed. The specific savings from this project, like many in an industrial setting, will vary depending on production demand. However, during times of low demand, shutting down 3 of the units is expected to save approximately 150 kW/hr, a respectable reduction in energy consumption for the system. Using basic emission calculations, the project is estimated to reduce more than 180 tCO$_2$e over the course of a year, assuming low demand occurs 25% of the time at the production facility, which operates 24/7, year-round.
Chapter 5

A Discussion of the Need for Better Monitoring and the Creation of an Open Dialogue Surrounding Energy Consumption in Industry

As outlined numerous times throughout this study – via the discussion of current energy efficiency strategies and techniques in the literature review and the inclusion of industrial case studies demonstrating their successful implementation – energy efficiency presents considerable opportunities for Canadian industry – saving money, stimulating economic growth, increasing productivity, and offering a significant reduction in environmental impact. Unfortunately, many companies – especially SMEs – are reluctant to implement most energy efficiency strategies due to a lack of in-house expertise, inadequate resources, or positive reinforcement through industrial feedback on the use of such techniques. Until organizations and government become more transparent about consumption practices within the industrial sector, little will change. Companies must be more willing to share their energy consumption data and an open dialogue regarding best practices must begin. Despite all the potential benefits, a single barrier still exists to wide-scale industrial energy efficiency progress: confidentiality.

As mentioned in the Available Tools and Programs chapter, the government has begun to create a number of platforms aimed at improving industrial energy consumption dialogue. Programs such as CIPEC and CanmetENERGY have begun to allow companies to share information and identify common needs and best practices [62] – an invaluable asset for many small-scale companies. Each year the program expands to include more members and engage a broader audience; however, despite this, the programs remain a voluntary initiative and have no power to enforce transparency in the area of energy consumption data.

It is the intent of this study to demonstrate the benefits that are possible through conversation strategies and to encourage more Canadian organizations to share their conservation
success stories in order to begin to remove the taboo industry has placed on the discussion
surrounding energy consumption.

In total 10 companies were contacted for the case study portion of the project: Pratt and
Whitney Canada, Invista, Utilities Kingston, Ontario Power Generation, Procter and Gamble
(P&G), Mana Steel, Van-Rob Inc., Mirarco Mining Innovation, DuPont, and Magna Inc. Initial
responses were received from seven of the companies, with follow up conversations leading to
successful data collection from only three.

Several of the organizations were unable to provide project details due to expressed
confidentiality concerns, while others who were contacted, such as P&G, said that they would
like to contribute but that resources were simply not available to allow them to do so and that
tracking conservation data was not currently a priority within the organization. This is often the
case within many organizations. It is well known that during times of economic downturn,
companies are less likely to focus on conservation projects when budgets, resources, and
personnel hours become limited. Anything outside of the scope of primary maintenance and
upgrading required to sustain production will likely be viewed as an extravagance, which the
company has neither the money nor the person-hours to implement. As well, when budgets begin
to tighten, conservation projects are the first to be cut or put on hold until a more suitable
economic environment has been restored.

If the time period following the 2008 economic recession is considered, it can be noted
that most energy conservation efforts among organizations shifted toward behavioural programs
and scheduling – encouraging turning off lights, turning off computers at the end of the work day,
etc. While these strategies are important in creating a positive change in the mindsets of workers
and getting them to view energy conservation as a corporate value, it does little to actually
improve the efficiency of the physical equipment and systems in use throughout a facility.
It is difficult to pledge thousands of dollars toward a new energy-efficient piece of equipment or retrofitting an outdated processing system when the company is trying to reduce costs and cut back on new project spending. However, many companies are rewarded substantially for retrofitting old systems and purchasing more efficient equipment through government or industry rebates, helping offset upfront project costs significantly. As a result, the long-term benefits of implementing system upgrades and improving energy efficiency are numerous – both economically and environmentally speaking.

Ironically, if organizations continue with the implementation of efficiency projects they are more likely to remain economically competitive than those who do not. The fuel and maintenance savings resulting from such projects often far outweighs initial capital investment and favourable payback periods are usually possible, as demonstrated in the case studies above.

A clear distinction in an organization’s willingness to discuss energy consumption was also noted during the data collection process. Both organizations which talked most openly about energy consumption and shared the data related to several of their efficiency projects had energy managers with an open mind about sustainability and the need for industry to play its part. These managers were eager to talk about their respective organization’s success stories and share positive examples with other companies. They understand the important role that open dialogue plays in energy consumption and creating the necessary changes within industry to curb emissions. This mindset is not found as often as one would hope within industrial energy managers. Many people are often transitioned to the role of energy manager within a company with little to no technical experience in the area and who are focused solely on the economics surrounding efficiency projects, particularly the length of payback periods. One of the best ways to begin to enact change within industry is to ensure that the right individual, with the right mindset and background, is placed in the position of energy manager. It is a critical
environmental role with the greatest potential to change an organization’s energy consumption practices.

Another issue that was discovered while collecting data for this research project was the lack of data currently available. Before companies were contacted directly, preliminary research was conducted using academic papers and online sources. It quickly became apparent that the data was not just difficult to find, it was non-existent. Companies have placed a taboo on openly discussing consumption records, most likely out of fear of being branded as wasteful or inefficient among industry competitors.

However, appropriate tracking of industrial energy consumption is not just lacking at the facility or company-level, it is also missing from many government energy programs. In recent years, governments across the globe have identified improved efficiency as a fundamental component of their energy and environmental strategies. While identifying the need for improved efficiency is imperative, it is not enough to enable wide-scale change. In order to truly capture gains in efficiency it is necessary to have a baseline energy target to compare against, which includes a breakdown of consumption by end use. Tracking of this information is practiced much more widely within the residential and commercial/institutional sectors, while industrial consumption tends to be lumped together and recorded as a single value, with no indication of the percentage of energy consumption responsible for each end use (i.e. space cooling, space heating, lighting, water heating, motors, pumps, etc).

As an example, within Canada, the Energy Efficiency Act is responsible for the enforcement of regulations concerning MEPS for energy-using products, as well as the labelling of energy-using products and the collection of energy use data [63]. As part of this legislative act, the Canadian government publishes an annual document entitled “Improving Energy Performance in Canada.” The report summarizes energy consumption trends within the country across various sectors and indicates where improvements have been made and which areas are lagging or have
seen a drop in efficiency [7]. What is important to note about these reports is that they offer a comprehensive breakdown of consumption for both the residential and commercial sectors, but offer little to no information on the breakdown of industrial usage [7], as seen in Figure 29 below. Unfortunately, this indicates that when it comes to industrial energy, little is known about the exact consumption of individual systems.

Figure 29: Breakdown of residential and commercial energy usage by purpose (industrial sector unavailable) [7]

One of the largest gaps in existing consumption monitoring is the area of ancillary or auxiliary system energy requirements [18]. Auxiliary equipment forms the backbone of many of
our day-to-day operations. Monitoring the specific energy requirements of these systems tends to go largely unchecked since their use is often “behind the scenes” and is not as prominently displayed [18]. However, despite this, their wide-scale usage means they account for a large percentage of energy consumption, especially within the industrial sector. Effective monitoring of these systems will allow prominent sources of inefficiency to be identified and could be a key step toward improving energy efficiency globally [18].

Unless governments do more to enforce sub-metering at the industrial level, the consumption of key ancillary systems will remain unknown in terms of energy trending and a comprehensive energy map for individual countries will be difficult to develop [18]. Likewise, within industry, many companies try to grasp a better understanding of their own energy needs and sources of inefficiency by performing internal energy audits or hiring third party contractors. Magna, as mentioned previously, has identified compressed air leaks as their number one source of inefficiency. The company has invested numerous resources toward identifying air leaks within their compressor systems and monitoring the effectiveness of repairs. Additionally, by conducting follow-up audits, they are able to determine if their reduction strategies are effective and are better able to track efficiency gains within their compressed air ancillary systems.

While energy audits are an excellent way for organizations to prioritize their energy efficiency targets, their effectiveness is lessened considerably without a firm commitment to consumption sub-metering to determine if implemented projects are achieving desired results [18]. It is unfortunate, but the reality remains that the main driver for most energy efficiency projects is the economic benefit which often accompany them rather than the reduction in environmental impact. Unless a source of inefficiency is quite costly or effects operational performance, it is unlikely to be pursued. It is also true that in many small-scale organizations resources and personnel are simply not available to dedicate to energy performance monitoring. This often means that the performance of ancillary systems such as pumps and compressors is not
regularly tracked and inefficiencies stemming from these systems can go unnoticed for extended periods of time [18]. If an efficiency project is implemented, its overall reduction capacity is often undocumented [18].

The compressor control unit project implemented by Van-Rob Inc. and discussed in the Case Study section above demonstrates this issue. Following the control unit’s installation no tracking of the actual reduction in consumption for the compressor system was completed. As well, the company’s electricity bills only record total monthly consumption, with no breakdown of individual end uses. As a result, without appropriate follow-up measures, it is difficult for project effectiveness to be demonstrated or actual savings to be tracked within an organization. This remains a key issue in achieving effective energy conservation within the industrial sector. While it is important for companies to pursue energy efficiency strategies, without proper follow-up and due diligence in consumption tracking even greater opportunities for energy reduction may be missed or inefficiencies may continue to go unnoticed within large facilities [18].

While making strides in the area of energy efficiency is important, so too is the approach taken to achieve such gains. It is important that reduction strategies remain effective and focused on the most promising solutions. Determining what these efficiency “best practices” are can only be achieved through effective consumption sub-monitoring, both pre and post-project implementation [18]. In no other area is this more true than for ancillary systems. The fact that these systems remain largely hidden from us in our day-to-day routines, even at the industrial facility level, means that the need to monitor their exact usage is even higher. When it comes to auxiliary energy, the old adage out of sight, out of mind can no longer apply. If we are to make considerable improvements in the efficiency levels of these systems in the next decade, we must make auxiliary energy requirements a key element of major energy reduction strategies, monitor implemented efficiency project results more stringently, and make consumption trends and data more visible.
While it is true that companies and organizations have made a shift toward environmental stewardship and improving energy efficiency, much work still remains. To date, one of the greatest barriers to developing more sustainable products and processes is the lack of information available on the energy consumption of current equipment and processing techniques [18]. Without appropriate monitoring of energy consumption, it is practically impossible to know where the greatest sources of inefficiency are stemming from and how they can be remedied. Most engineered systems require feedback control to determine if they are performing optimally or achieving set targets – energy consumption is no different [18]. Even if organizations begin to overhaul their existing systems with new equipment, design layouts, or maintenance regimes, if consumption is not adequately monitored before an alteration, it is difficult to pin-point specific savings and whether or not the new system is performing effectively.

5.1 Application of System Dynamics

Although not part of this thesis, one of most rapidly developing areas in the field of energy consumption monitoring is the idea of using system dynamics as a possible way to monitor and influence energy use and decrease CO₂ emissions. It has been proposed to use system dynamics (SD) to connect system monitoring to energy use in ancillary systems. SD has been used, since its inception in the 1950’s, as way of understanding the behavior of complex systems over time [18]. The 2 progenitors of SD are Forrester who used SD in industrial dynamics (1961) and Sterman who used it in business dynamics (2000) [18]. It is used for policy analysis, by both the public and private sector, and uses “causal loop diagrams” for system dynamic models which examine phenomena that may be responsible for a growth or decline [18]. SD can refer to the behavior of groups that result from the interactions of individual group members as well to the study of the relationship between individual interactions and group level behaviors [18].
The SD modelling Process consists of 5 steps: (1) Problem Articulation; (2) Formulation of Dynamic Hypothesis; (3) Formulation of Simulation Model; (4) Testing; (5) Solution Design and Evaluation [18]. The problem articulation for energy consumption monitoring and influence includes: (a) Fossil fuel energy (b) GHG emissions (environmental cost), (c) Energy cost ($), and (d) Ancillary equipment energy consumption. Into this mix, the notion of machine condition monitoring is also introduced. A preliminary SD diagram for ancillary systems and monitoring, as seen in Figure 30 has been proposed, but requires further work [18]. If this tool becomes more thoroughly developed it has the potential to create an efficient, cost-effective energy optimization tool which can be tailored to meet the needs of individual facilities, plants, and companies and could prove to be a game-changer in the field of energy conservation.
Figure 30: Proposed SD diagram for auxiliary systems and monitoring [18]
Chapter 6
Conclusions and Recommendations

As a result of the research undertaken for this study, it can be concluded that energy efficiency improvement strategies present multiple opportunities for Canadian industry – saving money, stimulating economic growth, increasing productivity, and offering a significant reduction in environmental impact. The case studies presented within this thesis highlight some of the major energy consumption and GHG emission reduction opportunities that are available to industry through the implementation of various efficiency projects.

Though research into new energy-saving technologies should continue, it is also clear that many of the techniques and strategies needed to begin to significantly lower global GHG emissions already exist. Unfortunately, many companies – especially SMEs – still shy away from the opportunities that are available to them from energy conservation due to a lack of in-house expertise, inadequate resources, or positive reinforcement through industrial feedback on the use of such techniques. Additionally, energy efficiency is still largely viewed as a problem rather than an opportunity. A number of broad recommendations have been created from the results of this study. They are summarized below.

(1.) Despite all the potential benefits, a single barrier still exists to wide-scale industrial energy efficiency progress: confidentiality. Until organizations and government become more transparent about consumption practices within the industrial sector, very little will change. Companies must be more willing to share their energy consumption data and an open dialogue regarding best practices must begin. Governments should encourage more organizations to share their conservation success stories in order to begin to remove the taboo industry has placed on the discussion surrounding energy consumption.
(2.) Organizations must begin to avail of the resources and tools (from government agencies, technological societies, and universities) that have been created to better equip industrial users to improve the efficiency of their systems, equipment, and tools. These resources have been specifically created to aid industrial users with their energy efficiency projects and many of them are free of charge. The notion that not enough information or expertise exists will soon no longer be an acceptable excuse for why energy efficiency is not promoted within an organization.

(3.) Individuals who are chosen as energy managers within their respective organizations should come from a strong sustainability background. They must be open to the notion that all three (3) spheres of sustainability are equally important and they must understand the importance that open dialogue plays in energy consumption and creating the necessary changes within industry to curb emissions. By placing the appropriate personnel in energy management roles, energy efficiency projects will likely be implemented more frequently and with less opposition within organizations.

(4.) Lastly, it is important that energy reduction strategies remain effective and focused on the most promising solutions. Determining what these efficiency "best practices" are can only be achieved through effective consumption sub-monitoring, both pre and post-project implementation. Without appropriate monitoring of energy consumption it is practically impossible to know where the greatest sources of inefficiency are stemming from and how they can be remedied. Even if organizations begin to overhaul their existing systems with new equipment, design layouts, or maintenance regimes, if consumption is not adequately monitored before an alteration, it is quite difficult to pin-point specific savings and whether or not the new system is performing effectively. Accurate and sufficient energy monitoring is a key component to energy reduction success.
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