

ANALYSIS OF NATURAL GAS CONSUMPTION AND ENERGY SAVING MEASURES
FOR SMALL AND MEDIUM-SIZED INDUSTRIES IN THE GREATER TORONTO AREA

by

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A thesis

presented to Ryerson University

in partial fulfillment of the
requirements for the degree of

MASTER OF APPLIED SCIENCE

In the program of

Mechanical and Industrial Engineering

Toronto, Ontario, Canada, 2014

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ANALYSIS OF NATURAL GAS CONSUMPTION AND ENERGY SAVING MEASURES FOR SMALL AND MEDIUM-SIZED INDUSTRIES IN THE GREATER TORONTO AREA

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Abstract

A total of 15 energy (natural gas) audits were conducted for industrial sites from food processing, packaged goods and finishing processes (powder coating) sector. Natural gas consumptions, performances of major gas consuming equipment and savings from proposed energy measures were analyzed for the audited sites. Proposed energy saving measures included reduction in non-productive consumption, tune-up of gas-fired equipment, optimization of boiler loads, heat recovery through feedwater economizer and reduction in oven exhaust using variable frequency drives (VFDs). Gas savings achieved by employing VFDs showed great potential ranging from 13% to 49% of oven consumptions while savings for feedwater economizer ranged from 3.4% to 18.4% of boiler consumptions. Other measures mentioned above, though relatively simpler to implement, also showed potential of considerable savings. Associated fuel cost savings and the reduction in greenhouse gas emissions were also estimated. Furthermore, a MATLAB program was created to calculate boiler efficiencies.

Acknowledgements

The author would like to express his deepest appreciation to Dr. Alan S. Fung for his kind support, guidance and encouragement throughout the project. The author also expresses his gratitude to Mr. Peter Goldman, Mr. Daniel Johnson and especially Mr. Paul Morrison of Enbridge Gas Distribution Inc. for providing energy audit training and acting as liaison between Enbridge's industrial customers and the author.

The author would also like to acknowledge the financial support provided by Connect Canada, Mitacs-Accelerate Ontario, and Enbridge Gas Distribution Inc.

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List of Acronyms

BTU	British Thermal Unit
CDD	Cooling Degree Days
CFM	Cubic Feet per Minute
CV	Coefficient of Variation
DFG	Dry Flue Gas
DSM	Demand Side Management
EEAP	Enterprise Energy Audit Program
EGD	Enbridge Gas Distribution
ESA	Energy Saving Activity
GHG	Greenhouse Gas Emission
GWh	Gigawatt hour
GTA	Greater Toronto Area
HDD	Heating Degree Days
HFC	Hydrofluorocarbon
HO	Heating Only
HVAC	Heating, Ventilation and Air Conditioning
IAC	Industrial Assessment Centre
kW	Kilowatt
MW	Mega Watt
NAC	Normalized Annual Consumption
NDA	Non Disclosure Agreement
NRDC	National Development and Reform Commission
OEB	Ontario Energy Board
PRISM	Princeton Scorekeeping Method
SME	Small and Medium Enterprise
VFD	Variable Frequency Drive

Nomenclature

%BD	Percentage of steam flow rate leaving the boiler as blowdown (%)
BL	Blowdown loss (BTU/h)
M_{bd}	Mass flow rate of blowdown (lb/h)
c	Speed of light (ft/s)
$CFM_{current}$	Exhaust rate of fan at full speed (ft ³ /min)
CFM_{new}	Exhaust rate of fan at reduced speed (ft ³ /min)
$c_{p,dfg}$	Specific heat of dry flue gas (BTU/lb-°F)
$c_{p,fg}$	Specific heat of flue gas (BTU/lb.°F)
\dot{Q}_{fg}	Heat carried away by flue gas (BTU/h)
$CO_{dry,}$	Percentage concentration of carbon monoxide by volume of dry flue gas (%)
CO_{2dry}	Percentage concentration of carbon dioxide by volume of dry flue gas (%)
$C_o(\tau_c)$	Long-term average cooling degree-days per year for the PRISM estimated reference temperature (°F-day)
EI	Energy input to the boiler (MMBTU/h)
F	Column vector comprised of coefficients of linear terms in the objective function
$f(X_k, Y_k)$	Natural gas consumption of the k-th boiler, as a function of the steam load (m ³ /h)
H	Hessian matrix for the objective function
h_{bd}	Enthalpy of blowdown (BTU/lb)
h_{fw}	Enthalpy of feed water (BTU/lb)
HHV_m	Higher heating value of natural gas on mass basis (BTU/lb)
HHV_v	Higher heating value of natural gas on volume basis (BTU/ft ³)
H_{liquid}	Enthalpy of water at combustion air temperature (BTU/lb)
$H_o(\tau_h)$	Long-term average heating degree-days per year for the PRISM estimated reference temperature (°F-day)
h_s	Enthalpy of steam (BTU/lb)
H_{vapor}	Enthalpy of saturated steam at 1 psia and flue gas temperature determined (BTU/lb)
$L_{k \max}$	Maximum load capacity of k-th boiler when the boiler is running (lb/h)
$L_{k \min}$	Minimum load capacity of k-th boiler when the boiler is running (lb/h)

MF_C	Mass fraction of carbon in natural gas
\dot{m}_{fg}	Mass flow rate of flue gas (lb/h)
MF_H	Mass fraction of hydrogen in natural gas
MF_N	Mass fraction of nitrogen in natural gas
MF_O	Mass fraction of oxygen in natural gas
\dot{m}_{fw}	Mass flow rate of feedwater (lb/h)
M_{ng}	Mass of one mole of natural gas (lb)
M_i	Molecular mass of i-th constituent of natural gas (lb)
\dot{M}_{steam}	Mass flow rate of steam produced by boiler (lb/h)
n	Number of boilers
N_{2dry}	Percentage concentration of nitrogen by volume of dry flue gas (%)
N_{Ci}	Number of carbon atoms in the i-th constituent in natural gas
$NG_{savings}$	Natural gas savings (m^3)
N_{Hi}	Number of hydrogen atoms in the i-th constituent in natural gas
O_{dry}	Percentage concentration of oxygen by volume of dry flue gas (%)
R^2	Coefficient of correlation
RL	Radiation loss (BTU/h)
SL	Stack loss (BTU/h)
T_{air}	Temperature of combustion air ($^{\circ}F$)
T_{fg}	Temperature of dry flue gas ($^{\circ}F$)
T_{dfg}	Temperature of flue gas ($^{\circ}F$)
t_f	Time of flight (sec)
$T_{fw\ in}$	Temperature of feedwater entering the economizer ($^{\circ}F$)
$T_{fw\ out}$	Temperature of feedwater exiting the economizer ($^{\circ}F$)
\bar{T}_{od}	Long-term average outdoor temperature ($^{\circ}F$)
T_{sat}	Saturation temperature of water at 1 psia ($^{\circ}F$)
V_i	Percentage by volume of the i-th component in dry flue gas (%)
X	Vector of variables
X_i	Percentage by volume of the i-th constituent of natural gas (%)
X_k	Steam demand load allocated to the k-th boiler (lb/h)
$\%XA$	Percentage excess air (%)

Y_i	Specific heat of the i-th constituent of dry flue gas (BTU/lb-°F)
Y_k	Represents the decision to switch on k-th boiler (it is a binary variable with a value of "1" for "on" and "0" for "off")

Greek letters

α	Daily base level consumption (m ³ /day)
β_h	Daily consumption per heating degree day (m ³ /day)
β_c	Daily consumption per cooling degree day (m ³ /day)
ε	Relative uncertainty (%)
$\eta_{\text{equipment}}$	Thermal efficiency of make-up air unit (%)
η_{comb}	Combustion efficiency of boiler (%)
$\eta_{\text{comb,baseline}}$	Combustion efficiency of boiler before tune up (%)
$\eta_{\text{comb,new}}$	Combustion efficiency of boiler after tune up (%)
$\eta_{\text{ewuipment}}$	Thermal efficiency of make-up air unit (%)
$\eta_{\text{comb,baseline}}$	Combustion efficiency of boiler before tune up (%)
$\eta_{\text{comb,new}}$	Combustion efficiency of boiler after tune up (%)
θ	Function of fuel analysis
σ	Standard uncertainty
τ	Reference temperature from PRISM analysis (°F)

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1 Introduction

1.1 Energy Conservation and Energy Efficiency

Energy conservation means saving energy by avoiding excessive or wasteful uses. Efficiency, on the other hand, means using less energy while getting the same results [1]. Efficient use of energy results in saving energy. Energy efficiency is therefore, a subset of energy conservation. Energy conservation and energy efficiency are sometimes used interchangeably. The distinguishing factor between the two is that energy efficiency is generally considered to involve the use of technology while energy conservation involves more of a behavioral change [2].

Both energy conservation and energy efficiency have received great attention and support in the past few decades. Since the energy crisis of the 1970s, a lot of research and technological advancement has taken place with the intention of reducing wasteful energy consumption in transportation, industrial, commercial and residential sector. Policies and programs have been created to mitigate the impacts of any future energy crises. Efforts to educate public about the benefits of energy conservation have steadily intensified over the years.

1.1.1 Benefits of Energy Conservation

In addition to mitigating the impact of energy shortage, energy conservation has other benefits as well. One obvious benefit of reduced energy consumption, resulting from energy conservation, is the financial savings in energy cost. These savings are beneficial for all energy users but especially for industrial sector which uses 37% of world's total energy [3, 4]. In the industrial sector the cost of energy is an unavoidable and ever-present part of overall operational cost. Reducing energy use and subsequently operational costs would result in higher profits and an increased ability to stay competitive in the market.

Energy conservation is also beneficial from the point of energy supply and distribution. A steady, predictable and manageable energy demand ensures that there is less pressure on the infrastructure and sudden breakdowns and blackouts are less likely to occur. Energy conservation when applied to fossil fuel fired systems also results in lower greenhouse gas

emissions. Global carbon dioxide emissions are rising more than 2% annually and are expected to rise 50 % above 1997 level by the year 2015, because of increasing energy demand and inefficient energy use [3, 4]. Energy conservation could be one of the methods of dealing with increased greenhouse gas emissions.

1.1.2 Barriers to Implementation

Despite the financial and environmental benefits, energy conservation measures have not been widely implemented in industry, especially in small and medium-sized enterprises (SMEs). There are a number of barriers which explain the lack of implementation of energy saving measures in industry.

One of the key barriers in the implementation of energy conservation measures in industry could be the lack of awareness about the benefits of energy conservation at the top management level. Plant managers in SMEs do not realize that if they are able to manage energy consumption they would be able to save money normally spent on energy and use it for other purposes such as improving quality of products, training of personnel, expanding their industrial facilities, etc, which would allow them to be more competitive in a globalized production environment that is prevalent today. Because of this lack of awareness, energy conservation is not on top of the list of priorities for industries. The management is more interested in production, quality and regular operation of industrial plants.

Furthermore, investment decisions in SMEs are made with short term goals in mind. Management is usually concerned about the high investment costs and tends to avoid energy conservation measures with high initial capital costs and long payback period.

Limited access to and availability of technical information and expertise is another key barrier to the implementation of energy conservation measures in SMEs. Even though the operation and plant managers may be interested in energy conservation, yet they may struggle to build a business case for the owners and stakeholders to justify the costs of implementing energy conservation measures. There may not be enough appropriately skilled personnel in the plant to track down energy losses, recommend remedial measures and develop a business plan to be

presented to decision-makers. This lack of specialized skills requires that SMEs hire external contractors for energy conservation, which adds extra costs to their budgets.

1.2 Energy Audit

In order to overcome the technical and financial barriers to energy conservation implementation in industry, energy supply companies in Canada provide energy audits of facilities to their customers at no cost. Energy audit is the analysis of energy consumption of a building for the purpose of identifying opportunities for saving energy [3]. Energy audit is the first step in energy conservation. Energy consumption can be managed efficiently only if it can be measured efficiently. For this reason, energy audit is an essential step in improving energy efficiency.

Energy audits vary in level and complexity depending upon the depth of analysis. Generally the cost of conducting an energy audit increases with the level and complexity of the audit. The levels of energy audit [3] are as follows:

- Level 0: Benchmarking
- Level 1: Walkthrough Audit
- Level 2: Detailed Energy Audit
- Level 3: Investment Grade Audit

1.2.1 Benchmarking

This level of energy audit involves the analysis of historical energy consumption of a building and subsequent comparison of building performance with other buildings which are similar in size, type, function, age, location, etc. Benchmarking helps in determining if further analysis is required.

1.2.2 Walkthrough Audit

This level of audit involves identification of energy end-use inside the building, study of energy consuming equipment along with their operational parameters. It also involves identification of simple and low cost energy conservation measures for future detailed audit.

1.2.3 Detailed Audit

This level of audit includes energy end-use break down, detailed analysis of the building and equipment and cost and savings calculations for energy conservation measures.

1.2.4 Investment-Grade Audit

This level of audit includes refined analysis of energy conservation measures that require considerable capital investment. The audit often requires rigorous engineering study, simulation analysis, additional measurements and tests.

1.3 Electricity vs. Natural Gas

Electricity and natural gas are the most common sources of energy used in industrial plants. Even though both electricity and natural gas supply companies provide support for energy conservation in the form of financial incentives and energy audits, the implementation of energy saving measures for natural gas saving, lags behind that of electricity greatly.

There can be a number of reasons for the disparity between electricity and natural gas conservation efforts, such as a higher energy content and relatively lower price of natural gas. One billing unit of natural gas (cubic metre, m^3) provides approximately 37.3 MJ of energy [5] and costs approximated 22 cents [6]. On the other hand, one billing unit of electricity (kilo-watt-hour, kWh) provides only 3.6 MJ of energy and costs approximately 13 cents [7]. This means natural gas costs 0.6 cents per MJ while electricity costs 3.6 cents per MJ. For the same amount of energy the price of electricity is six times that of natural gas. Therefore, when it comes to energy conservation, saving electricity is given more attention than saving natural gas.

On the basis of energy content per unit natural gas may be less expensive than electricity but its environmental impact is far greater. Natural Resources Canada's greenhouse gas emission guidelines for the province of Ontario state that the combustion of one cubic metre of natural gas results in the greenhouse gas emissions equivalent to 1879 g of carbon dioxide [8]. Emissions resulting from the generation and distribution of one kWh of electricity in the province of

Ontario are equivalent to 100 g of carbon dioxide [9]. This means that natural gas consumption produces 50.4g of carbon dioxide per MJ while the consumption of electricity produces 27.8g of carbon dioxide per MJ. This implies that natural gas has nearly twice the GHG emission per MJ as that of electricity. Hence, natural gas conservation cannot be ignored completely. The environmental impact of burning natural gas makes its conservation deserving of attention from government, industry, natural gas suppliers and academia.

1.4 Enbridge Gas Distribution Inc.'s Demand Side Management Program

This study is being conducted as a part of Enbridge's demand side management program (DSM) which is one of the well established, utility-funded energy conservation programs in Ontario. Enbridge Gas Distribution (EGD) is the largest natural gas utility in Canada. The company offers DSM programs to all customer rate classes and across all sectors. Activities in Enbridge's DSM include the following tasks.

Assessment:

Energy assessments are conducted focusing on process equipment, boiler performance, steam systems, and heating and ventilation. Combustion tests, analyses, thermal imaging tests, benchmarking and statistical assessments of historical gas consumption data are also performed.

Analysis:

Energy improvement opportunities are identified. Also changes are proposed that can be made to increase the energy efficiency with no-cost or low-cost energy efficiency measures. Fuel cost savings achieved by proposed energy savings measures are also calculated.

Business case development:

Feasibility and cost benefit analyses are conducted to provide a cost and profit rationale for energy efficiency measures. This helps the plant managers, owners, stakeholders and decision makers in deciding whether or not to implement proposed energy saving measures.

This study would be conducted in collaboration with Enbridge Gas Distribution and would include assessments and analyses which could form the basis for business case development in the future.

1.5 Thesis Objective

This study is being conducted as a part of Enbridge's demand side management program and involves conducting energy audits for small and medium-sized industrial plants in the Greater Toronto Area (GTA), identifying opportunities for natural gas savings, consolidating the data obtained from the audits and developing software tools for facilitating energy audits and analyses. The level '2' energy audits case studies, will not only serve as reference but also as motivation for other similar industrial plants. The consolidated analysis will provide a range of estimated savings achievable by implementing specific energy efficiency measures and the software tools will allow plant managers to get estimates for their own industrial plants. Such a study has not been undertaken for small and medium-sized enterprises in Canada. This study would be limited to the analysis of energy consumption analysis and energy saving measures. The results from the analyses of energy saving measures can subsequently lead to detailed economic analysis in the future. Economic analysis of energy saving measures would not be dealt with in this thesis

The industrial sites for which energy natural gas consumptions were analyzed in the study belong to three specific sectors, which are food processing, packaged goods and powder coating. The limitation in the variety of industrial sectors allows making comparisons and drawing conclusions among similar industries in each of the three groups. Energy conservation measures most applicable to a specific sector could then be identified. The energy conservation measures would focus on the major gas consuming equipment and energy saving technologies by sector. For example, major gas consuming equipment in food industry are boilers and baking ovens while in the powder coating industry, these are curing ovens, washers and dry-off ovens etc. Therefore, when investigating each sector the above mentioned equipment would be considered. From the consolidated results of the analysis, software tools for facilitating analysis are to be created using MATLAB. The tools would make it more convenient for plant managers and owners to visualize the benefits of natural gas conservation.

1.6 Structure of the Thesis

This thesis is organized into seven chapters as outlined with brief contents as follows:

Chapter 1: Introduction to the thesis and main objectives of the study

Chapter 2: Literature review on industrial energy efficiency programs, practices, technologies and barriers to implementation of energy efficiency measures in small and medium-sized industries

Chapter 3: Energy audit methodology and analysis of major gas fired equipment

Chapter 4: Energy saving measures for audited sites

Chapter 5: Results and discussion on energy consumption of audited sites

Chapter 6: Software tool and uncertainty analysis

Chapter 7: Conclusion and recommendations

2 Literature review

The published research in the field of industrial energy conservation comprises mainly of energy audits and standalone case studies of energy efficiency improvements in industrial plants conducted by energy services companies and suppliers as well as government agencies. Over the years, a consolidation of these energy efficiency improvement case studies has made it easier to generalize energy consumption and energy conservation measures in industry with respect to specific industrial sector, energy conservation technology and location of industrial plants, and to generate policies and strategies. In addition to general trends, the consolidation of energy efficiency case studies has also resulted in development of software tools by energy supply companies and government agencies. A review of standalone case studies, consolidated research and software available, to facilitate energy conservation and manage energy consumption in industry is presented below. This review would highlight any gaps in understanding or application.

2.1 Energy Efficiency Programs

Energy efficiency and conservation programs have been developed all around the world. These programs have been quite effective in reducing wastage of energy. These programs and their effectiveness have been intensely studied.

2.1.1 USA: Department of Energy's Industrial Assessment Centre (IAC) Program

"Since its establishment in 1976 the Department of Energy's Industrial Assessment Centre (IAC) has been conducting energy audits for small and medium-sized industries" [10]. In the two decades from 1981 to 2000 energy consumption of 9034 manufacturing plants were assessed. These manufacturing plants had average annual sales of US \$30 million. A total of 38,920 energy management projects were recommended which had an average implementation cost of US \$7400 and the estimated savings of US \$5600 per year. The average estimated payback period for the proposed projects was 1.29 years. Around 53% of the projects were implemented. Analysis of the implemented projects reveals that these projects represented US \$103 million in investment while the estimated savings were US \$100 million, resulting in a simple payback of

close to 1 year. On the other hand the projects not implemented represented investments of US \$186 million and energy savings of US \$117 million. Overall, the projects recommended by IAC program resulted in an estimated 20 trillion BTU per year energy savings [10].

Projections of savings from energy savings programs funded by gas and electricity utility companies in USA up to 2025 were estimated by Barbose et al. [8]. Three different scenarios of spending, i.e., low, medium, and high spending were analyzed. The analysis was based on detailed bottom-up modeling of demand side management programs and utility resource plans in the country. Assuming that no major changes in policy occur, Barbose et al. predicted that by 2025 the spending on energy efficiency programs for electricity and gas would increase to \$6.5 billion in the low spending case, \$9.5 billion in the medium spending case and \$15.6 billion in the high spending case.

2.1.2 Australia: Enterprise Energy Audit Program (EEAP)

A large scale energy efficiency project called the Enterprise Energy Audit Program was launched in Australia. The program offered energy audits at 50% discounts between 1991 and 1997. The program covered around 1200 firms with an average number of employees around 297 and an average of six proposed measures per firm. From all the measures proposed by the project approximately 82% were implemented [12].

2.1.3 Sweden: Project Highland

Project Highland is a Swedish program focused on energy efficiency in small and medium-sized industries. An evaluation of the last 15 years achievements of project Highland was conducted by Thollander et al. [13]. The evaluation showed that the adoption rate for energy efficiency measures proposed through this program was 40%. The adoption rate was calculated considering the projects that had already been implemented. Project Highland was also compared to another established program for energy efficiency which is geared towards energy-intensive industries in Sweden. The comparison showed that energy efficiency was relatively less prioritized in small and medium-sized enterprises than in large energy-intensive industries. The evaluation of project Highland showed that the option of using local authorities and regional energy experts to

provide energy savings was highly effective.

2.1.4 China: Top 1000 Energy–Consuming Enterprises Program

This program was launched in 2006 by the National Development and Reform Commission (NRDC) of China. Energy conservation activities undertaken through the program included energy benchmarking, energy audits, training workshops, monitoring and annual reporting of energy consumption [14, 15]. The energy consumption for the year 2004 of the 1000 highest energy consuming enterprises accounted for 33% of the national energy consumption and 47% of the industrial energy consumption

2.1.5 Canadian Industry Program for Energy Conservation (CIPEC)

Canadian Industry Program for Energy Conservation (CIPEC) was established in 1973. Under the mandate of this program sector task forces have been created which identify energy efficiency opportunities, review and address the barriers associated with industrial energy conservation, and develop implementation strategies for realization of savings from the identified energy saving measures. The program achieved a cumulated "energy savings per unit of production" of 26.1% and reduction in emissions of 30.4% from Canadian industries between 1973 and 1990 [16, 17].

In addition to CIPEC program, energy utilities in Canada run their own demand side management (DSM) programs for energy conservation. These programs are mandated by local government bodies on provincial or federal level. The targets of these programs vary by companies and also by type of energy supplied.

2.2 Energy Audit and Case Studies

Energy audits and energy efficiency improvement studies in industry have become very common in the recent years. Over the years numerous such studies have been conducted by energy services and supply companies, government agencies and academic institutions.

Energy-intensive industries such as the cement industries have been the main focus of energy

audits around the world. An energy audit was conducted by Kabir et al. [15] on the pyro-processing unit of a cement manufacturing plant in Nigeria. The thermal energy efficiency of the unit was found to be 41%, well below the 50% to 54% efficiency that is achievable in modern plants. It was found that utilizing waste heat to generate steam and to preheat the raw materials would be quite effective in conserving energy and reducing greenhouse gas emissions (GHGs).

Energy auditing for the rotary kiln systems of a dry type cement plant in Turkey was conducted by Engin and Ari [19]. It was estimated that around 40% of the total energy input to the plant was lost. Approximately, 19.2% of the total energy was lost through hot flue gases while 15.1% and 5.6% were lost through kiln shell and cooling stack respectively. Waste heat steam generator was proposed to recover the losses from hot flue gas and cooling stack resulting in an estimated energy saving of 1 MW. An extra shell to reduce losses from the hot kiln shell was designed. The savings expected by using an extra shell was estimated at around 3 MW. The overall savings for the plant were 4 MW which was 15.6% of the overall energy input. The payback period for the two proposed measures was estimated to be 1.5 years.

Kanan and Boie [20] conducted a case study of energy efficiency improvements for a small bakery in Germany. The authors investigated potential savings for recovering heat from bake oven exhaust, replacing induction choke exhaust of fluorescent lighting, heating pipe water rather than mixing hot and cold water, insulation of water pipes and recalibration of thermostat. A 6.5% reduction in overall energy consumption of the plant was expected as a result of better energy management practices. It was found that 10% to 15% savings in energy utilization could be achieved by recovering heat from flue gas leaving the bake oven. Flue gas from the 10 m² bake oven could be used to heat 300 liters of water to 70 °C daily. Furthermore, an estimated savings of 450 litres of oil in the boiler and 5400 kWh of electricity in the cold water system could be achieved if the practice of mixing cold water at 4 °C and hot water at 80 °C were to be substituted for direct heating of pipe water to 13 °C.

An energy assessment at a large carpet yarn plant in South Carolina was conducted by Brown et al. [21]. Energy saving measures for boilers, air compressors, HVAC equipment and yarn extruders were investigated. Also, the opportunities to improve energy management practices at the plant were analyzed. Overall, a total of 18 energy saving measures were recommended

which would result in an estimated 13.8% savings in the total annual energy cost of the plant.

"In the pulp and paper industry drying is one of the most energy intensive process" [22]. The potential for heat recovery from exhaust moist air which takes away latent heat with it, was analyzed by Abrahamsson et al. [22]. The analysis was conducted based on actual operating data collected from a major Swedish paper mill. Strategies for optimal energy conservation were investigated using various heat pump systems. Analysis was conducted for compressor and absorption based heat pump systems and the simulation results were compared. The results of the simulation run by using SHPUMP showed that 22 MW of thermal energy could be recovered by installing a mechanical heat pump. The results for the absorption chiller indicated a heat recovery of 12 MW. The pay back periods for compressor-driven and absorption heat pump was estimated to be 3.3 years and 2.9 years respectively.

An energy audit was conducted by Bergek [23] in Sweden to determine energy efficiency measures for powder coating industry. The first part of the project involved fact and data collection. After which energy audit was conducted. Subsequently, the potential savings from implementation of energy conservation measures was estimated and finally the results were benchmarked with a similar energy audit conducted in parallel. The audit showed that the plant under consideration consumed 2 GWh of energy derived from liquefied petroleum gas (LPG) and electricity. Most of the overall energy consumption in the plant could be attributed to the cure-oven, dry-off oven and pre-treatment unit. In terms of electricity the largest consumption was in the powder box because of its high ventilation. Pinch analysis was used to investigate three possible heat exchange networks for ovens and cooling zones. The results showed that an energy saving of 420 MWh could be achieved which was 21% of the total energy consumption of the plant. In addition to energy savings cost savings of 25% and carbon dioxide emission reduction of 30% could also be achieved. Comparison showed an energy savings of 30% for the parallel energy audit.

2.3 Energy Conservation Measures and Practices

The data and results obtained from the energy efficiency improvement studies have helped energy managers, energy efficiency experts and scholars in generalizing energy consumption and

energy conservation measures for specific industries, technologies and locations. A review of these energy saving measures is presented below.

An investigation regarding the improvement in productivity, pollution reduction and energy conservation was conducted by Kasten et al. [24]. The analysis was conducted by considering energy efficiency practices in three industrial plants. These plants were plastic foam cup production plant, glass bottle making plant, and tire making plants. The results of the analysis indicated that energy conservation practices not only reduce energy consumption but also improve productivity and reduce pollution.

Because the boiler is present in many industries as well as commercial and residential buildings, it has been widely studied for improvement in energy efficiency. Gonzalez [25] studied the improvement of boiler performance by using economizer. The results showed that up to 57% of the energy loss can be recovered by using a heat recovery system.

Saidur and Masjuki [26] presented energy efficiency measures that can be generally implemented to improve energy efficiency of an industrial boiler. The methods of energy saving studied by the authors were, use of variable speed drives to match boiler fan speed with the load and heat recovery from the flue gas. The payback period for heat recovery system in a boiler was found to be 1 year while that for a variable speed drive with 19 kW motor was three years.

Abdelaziz et al. [27] conducted a review of energy saving measures in industrial sector. They discussed the energy saving potential of energy saving measures such as the use of variable speed drives to match load requirements, use of feedwater economizer to recover waste heat from boiler flue gas, use of high efficiency electric motor, prevention of leak and reduction of pressure to optimized levels. The authors found the above mentioned measures to be economically and environmentally beneficial.

Building up on previous studies that identified potential for industrial energy efficiency through management practices, Thollander and Ottosson [28] analyzed energy management practices in two energy-intensive industries in Sweden. One of the industrial sectors selected for analysis was pulp and paper while the other one was foundry. It was found that around 33% of the paper mills and 20% of the foundries did not have sub-metering in their facilities. Also there was no

long term strategy in about 20% of the paper mills and 50% of the foundries. Only 40% of the paper mills and 25% of the foundries could be considered successful in effectively managing energy. These results were important because of the implication that if energy efficiency was not prioritized in highly energy-intensive industries, it was unlikely to be prioritized in other industries that are relative less energy-intensive. The degree of adoption was found to be greater for larger sized plants. Nevertheless a huge untapped potential of energy conservation was identified.

2.4 Barriers, Drivers and Policies for Energy Conservation in Industry

There has been extensive work done around the world in identifying barriers and drivers for industrial energy efficiency. Also, studies on the effectiveness of policy changes in driving adoption of energy efficiency have been conducted.

A review of energy saving measures for the cement industry was conducted by Madloul et al. [29]. Energy efficiency measures were categorized based on the parts of the steam plant and process for cement production. The measures reviewed were related to energy conservation for raw material preparation, clinker production and cement grinding.

Jaccard et al. [30] explored the impact of a compulsory greenhouse gas (GHG) reduction policy on industries. The effects of greenhouse gas tax and emissions cap were analyzed to generate useful policy information using a hybrid energy-economy model. From the results of the model it could be concluded that imposing a greenhouse gas tax or emissions cap would result in reduced energy consumption in industry. The model also predicted that a greater financial penalty would result in greater market dominance of equipment and technologies based on low-GHG energy sources like hydroelectricity compared to the technologies based on high-GHG energy sources like natural gas. However, until such a policy is put in place improvements in energy efficiency for natural gas would be the best way to reduce energy consumption and associated greenhouse gas emissions.

Kostka et al. [31] analyzed technical, financial and organizational barriers hindering adoption of energy-efficiency measures in small and medium-sized enterprises in China. The analysis was based on surveys of 480 industrial sites in Zhejiang province of China. The survey revealed that

only 21% of the surveyed companies were actively practicing energy efficiency. A lack of awareness amongst companies regarding energy saving equipment and technologies was also found. Around 40% of the companies participating in the survey were unaware of energy saving equipment for their respective businesses. Additional barriers include tax enforcement of government regulations, lack of government support and the lack of skilled labour. Furthermore, a lack of awareness about the technical aspects of energy efficiency among managers was observed.

An empirical analysis was conducted by Liu et al. [32] to measure the "energy saving activities (ESAs)" in "small and medium-sized enterprises (SMEs)" in the Taicang city of China. The findings from the survey indicated that internal training on energy conservation positively impacted company's involvement in "ESAs". It was suggested that energy saving regulatory requirements as well as financial incentives, mandatory audits and technical support of large companies should also be imposed on SMEs. The survey in Taicang can only be considered as a representative of companies in eastern coastal areas of China. Similar surveys for other parts of China would be required.

An empirical analysis was conducted by Fleiter et al. [33] on the implementation of energy conservation measures in small and medium-sized enterprises in Germany. A multivariable regression analysis was conducted to identify the influence of a variety of factors on adoption of energy conservation measures. It was found that high cost was a major barrier in implementation of energy conservation measures in industry. It was suggested that government subsidies or loans may be helpful in motivating small and medium-sized industries to adopt energy conservation measures.

Similar studies were undertaken in other countries as well. In Italy barriers to industrial energy efficiency were identified and evaluated by Trianni et al. [34]. The study was based on investigation of 48 small and medium-sized enterprises (SMEs) in Northern Italy. Financial and informational barriers were identified as the major obstacles in the implementation of energy conservation measures. In addition to financial and informational barriers a lack of interest in energy efficiency and the need to prioritize other projects were also identified as the most important barriers.

Trianni and Cagno [35] conducted an empirical investigation of 71 case studies in small and medium-sized enterprises in Italy. The investigation analyzed the influence of external factors such as increased energy prices or taxes on energy consumption and emissions, on adoption of energy-efficiency measures and technologies. The analysis revealed that industries are interested in adopting those energy-efficiency measures that not only reduce wasteful energy consumption but also result in strategic non-energy benefits such as improving long-term competitiveness.

2.5 Software Tools for Energy Conservation

Several software tools have also been developed to aid in conducting analysis and estimating the energy and cost savings. Some of these tools are focused entirely on particular energy intensive equipment in industry while others can be used for estimating the potential benefits of capital projects.

Mohanty and Manandhar [36] developed a software to analyze the performance of boilers and furnaces. The software could also be used to estimate energy savings for heat recovery through heat exchanger. The software had a library of fuel data and could carry out combustion analysis, basic heat exchanger design with the user's data options and an optimization of design configuration leading to the minimum heat exchanger cost.

Kudra et al. [37] developed an algorithm to examine the energy performance of convective dryers. This algorithm formed the basis of an Excel-based calculation tool. When provided with the data for an industrial dryer as inputs the tool returns specific energy consumption and energy efficiency of the dryer as the outputs. Furthermore, the tool also identifies major sources of inefficiency and quantifies energy savings for energy saving measures such as dryer insulation, partial recycling of exhaust air and feed pre-heating.

The RETScreen [38] software was developed by CanmetENERGY research centre of Natural Resources Canada's (NRCan). The software comprises of several case studies of large scale projects related to energy conservation and renewable energy. The case studies include projects involving wind energy, hydroelectric energy, photovoltaic power generation, combined heat and power generation and solar heating projects. The software is very useful for large-sized industries that require decision support for projects that involve considerable capital investment.

2.6 Relevance of the Thesis

There is a need to focus more on conservation of natural gas in industry. Natural gas is usually ignored in industrial energy conservation efforts because of its relatively low price. However, natural gas consumption results in considerable greenhouse gas emissions. If there are any policy changes in Canada resulting in strict financial penalties or constraints on greenhouse gas emissions, the industries would experience considerable increase in operation cost and would find it difficult to compete in the global market. This thesis attempts to provide decision makers and managers in small and medium-sized industries with studies of energy saving measures that can be adopted by SMEs to reduce wasteful natural gas consumption along with the reduction in greenhouse gas emission that could be achieved by implementing said energy conservation measures. In addition software tools will be developed which can be applied to specific ubiquitous equipment such as the boilers and furnaces.

This study would focus on the analysis of natural gas consumption in small and medium-sized industries in the Greater Toronto Area (GTA). In addition to analyzing natural gas consumption, measures to reduce wasteful natural gas consumption and improve energy efficiency will also be identified. This study would consist of three parts, i.e., conducting energy audits, consolidation of data, observation and results obtained from the audits, and software tool generation to facilitate analysis of energy performance of gas-fired equipment.

3 Energy Audit

An energy audit is a process to evaluate where a building or plant uses energy and identify opportunities to reduce consumption [39]. Energy audit aids an organization in analyzing its energy consumption and identifying wastage of energy which subsequently leads to identification and implementation of energy conservation measures and subsequently, energy and cost savings [39, 40]. Energy audit of an industrial site involves evaluating various sources of energy available in the plant and their consumption. Such site assessments are essential to identify the areas of highest and lowest consumption, as well as the energy wasted and the measures required to be implemented for saving or recovering the energy being wasted. The tasks completed during the audit along with their procedure are explained in detail in the subsequent sections.

3.1 Site Selection and Data Collection

Sites for energy audits were selected by Enbridge Gas Distribution Inc. All possible efforts were made to limit the participating sites to as few specific sectors as possible so that energy conservation opportunities applicable to a particular sector could be identified. The selected sites belonged to food industry, packaged goods or the finishing process (powder coating industry).

For confidentiality reasons a non-disclosure agreement (NDA) was signed for each industrial site. All identification information for the industrial sites participating in this study was removed. The sites in this study were referred to only by letter of the alphabet assigned to them, i.e., site A, site B, etc. Comprehensive energy audit reports containing detailed analysis of energy consumption, conservation opportunities and estimated savings were submitted to the respective plant managers.

3.2 Gas Consumption Analysis

Gas utility bills for the past years were gathered along with the information regarding plant operational hours, site area, energy end-uses and age of the industrial plants. For most plants one to three years data for natural gas consumption were available. From the gathered information

overall gas consumption, average annual gas consumption, average monthly gas consumption and gas consumption per unit area were calculated.

3.3 Productive and Non-Productive Consumption

The overall energy consumption in an industrial facility can be classified as either productive time or non-productive time consumption. Productive time refers to the operational hours and non-productive time refers to the non-operational hours. The operational hours are those when the production is taking place in the plant and the non-operational hours are when there is no production in the plant such as on holidays or weekly off-days.

With better house-keeping energy management practices, the non-productive time energy consumption can be greatly reduced or eliminated altogether. Non-productive time energy consumption has to be identified before it can be reduced. For this purpose, the operational hours of the plant as well as energy consumption data during operational time is required.

In cases where daily or hourly consumption data were available, energy consumption for productive and non-productive times were determined by corresponding the consumption with working days and operational hours.

3.4 Weather Normalized Energy Consumption

"The process of estimating energy consumption based on outside dry-bulb temperature is called weather normalization and the estimated energy consumption is known as weather normalized energy consumption" [41].

There are two important factors affecting weather normalization i.e., Heating Degree Days (HDDs) and Cooling Degree Days (CDDs) [42]. "The summation of difference (in degree) between inside temperatures and outside weather temperatures when it drops below a specified reference temperature is referred to as the heating degree day" [43]. On the other hand, cooling degree day is the "summation of the difference (in degree) between inside temperatures and outside weather temperatures when it rises above a reference temperature" [43]. Heating degree days (HDDs) reflect the weather conditions and space heating requirement in the winter while

cooling degree days (CDDs) reflect summer weather conditions and cooling requirement of the building. Since, this study is focused on natural gas which is primarily used for heating, only heating degree days (HDDs) were used for normalization.

"The base or reference temperature is the temperature at which neither cooling nor heating is required in a building" [43]. The reference temperature varies depending on the building type, occupancy level, wall thickness of the building, building envelope, and internal heat generation of the building [44, 45]. The reference temperature affects the number of heating or cooling degree days in a given data sample. The variation of heating degree days with reference is shown in Figure 3.1. It is evident from Figure 3.1 that a high reference temperature results in a higher number higher number of heating degree days and a lower number of cooling degree days.

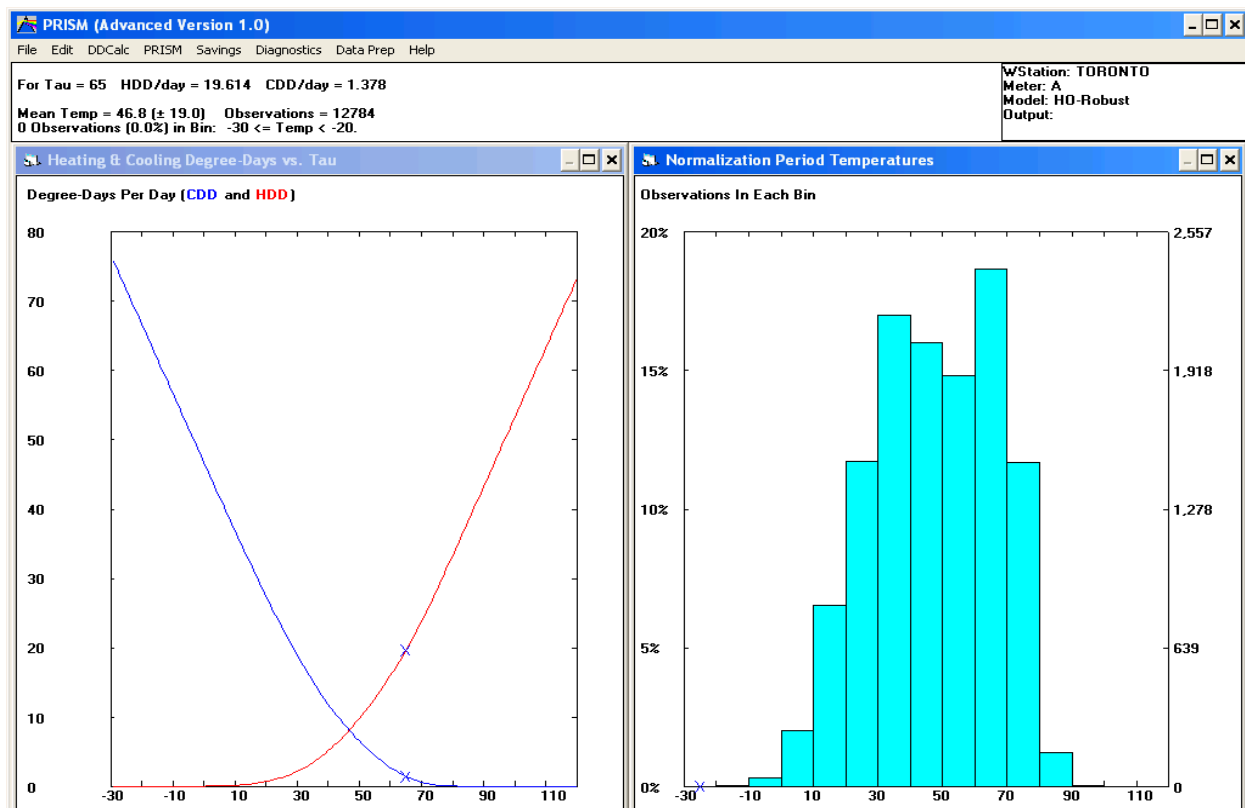


Figure 3.1 Screenshot of PRISM output for (degree-days)/day for different reference temperatures

Energy consumption was weather normalized by conducting linear regression analysis using PRISM software. PRISM considers that the overall energy consumption is the sum of a base load

(the non-weather related energy consumption of a building) and the weather-dependant energy consumption [46, 47]. In the regression model, energy consumption was the dependant variable while heating degree day was the independent variable. The extent to which one variable can be correlated with the other is determined using the coefficient of correlation, R^2 . The range of R^2 value varies from '0' to '1', in which '0' shows that two variables have no relationship and '1' indicates the perfect correlation between the two variables. In PRISM, for a reliable estimate of normalized annual consumption (NAC) the R^2 should be higher than 0.7 and coefficient of variation (CV) should be less than 7% [48].

Data for daily mean temperatures for the weather station located at Toronto Lester B. Pearson International Airport from January 1, 1978 to May 31, 2013, were retrieved from Environment Canada's Climate Data and Information Archive [49]. Daily mean temperatures were used to calculate long-term heating degree days. Data were converted to Fahrenheit for the PRISM analysis. Since, the analysis was for natural gas, the heating only (HO) model of PRISM was used to calculate normalized annual consumption. In order to determine reference temperature of for each site HO–Robust model was selected.

The, normalized annual consumption (NAC), can be determined using Equation 3.1 [50, 51].

$$\text{NAC} = 365 \alpha + \delta_h \beta_h H_o(\tau_h) + \delta_c \beta_c C_o(\tau_c) \quad (3.1)$$

where,

α is the daily base level consumption
 β_h is the daily consumption per heating degree day
 β_c is the daily consumption per cooling degree day

$H_o(\tau_h)$ is the "long-term average heating degree-days" per year for the PRISM estimated reference temperature

$C_o(\tau_c)$ is the "long-term average cooling degree-days" per year for the PRISM estimated reference temperature

δ_h is '1' for heating only (HO) and "combined heating and cooling" (HC) model, otherwise zero

δ_c is '1' for cooling only (CO) and "combined heating and cooling" (HC) model, otherwise zero

For the heating only model, Equation 3.2 was used.

$$NAC = 365 \alpha + \delta_h \beta_h H_o(\tau_h) \quad (3.2)$$

Equation 3.2 could be rewritten in terms of base level (process) and seasonal consumption as shown in Equation 3.3.

$$NAC = \text{Process Consumption} + \text{Seasonal Consumption} \quad (3.3)$$

The seasonal consumption could be further classified as consumption for ventilation and consumption for space heating. The consumption for ventilation could be determined using Equation 3.4.

$$\text{Consumption for ventilation} = \frac{1.08 * CFM * (\tau - \bar{T}_{od}) * \text{hours of operation}}{\eta_{\text{equipment}} * HHV_v} \quad (3.4)$$

where

CFM is the ventilation rate (ft³/h)

τ is the reference temperature from PRISM analysis (°F)

$\eta_{\text{equipment}}$ is the thermal efficiency of make-up air unit (%)

HHV_v is the higher heating value of natural gas on volume basis (BTU/ft³)

\bar{T}_{od} is the long term average outdoor temperature (°F)

The consumption for space heating could be calculated as a difference between total seasonal consumption and the consumption for ventilation

$$\text{Consumption for space heating} = \text{Seasonal consumption} - \text{Consumption for ventilation} \quad (3.5)$$

3.4 Marginal Cost of Natural Gas

In order to estimate the monetary value of natural gas savings it was necessary to determine the change in total gas utility bills resulting from the change in natural gas consumption. This change

in cost per unit of gas consumption is called marginal cost of natural gas. Marginal cost was calculated through summation of all consumption dependant charges on the gas utility bill such as gas supply charge, cost adjustment charge, transportation charge, storage and delivery charges. Fixed charges are not part of marginal cost. Therefore, fixed charges were not considered in the calculation of marginal cost.

Enbridge Gas' Rate-6 for commercial and industrial customers was used for this study. The applicable monthly charges under rate-6 are shown in Table 3.1.

Table 3.1 Monthly charges and rates for industrial customers of Enbridge Gas [6]

Monthly Charges	Monthly Rates January 1, 2014
Customer Charge	\$70
Gas Supply Charge	12.7159 ¢/m ³
Delivery to Customer	See breakdown in Table 3.2
Transportation to Enbridge	3.15665 ¢/ m ³

The delivery charges to the customer vary with the natural gas consumption. For the first 500 m³ of natural gas consumed the delivery charge is 8.1357 ¢/m³ but falls to 3.9853 ¢/m³ for natural gas consumption of over 28300 m³. A complete breakdown of the variation of delivery charges is shown in Table 3.2. Since, the industrial customers most likely consumed well over 28300 m³ the delivery charge used in the study for the calculation of marginal cost were 3.9853 ¢/m³.

Table 3.2 Breakdown of delivery charges [6]

Delivery to Customer Breakdown	
Amount of gas used per month in cubic metres	Cost in cents per cubic metre (¢/m³)
First 500	8.1357
Next 1050	6.4065
Next 4500	5.1958
Next 7000	3.10177
Next 15250	4.0721
Over 28300	3.9853

In addition to monthly charges there is also a cost adjustment charge which includes the cost of gas supply, transportation and delivery to the industrial customer. The breakdown of cost adjustment charge is shown in Table 3.3.

Table 3.3 Cost adjustment along with the individual components [6]

Cost Adjustment Breakdown	
Gas Supply	0.9021 ¢/m ³
Transportation	0.1660 ¢/m ³
Delivery	– 0.2061 ¢/m ³
Total Cost Adjustment	0.8620 ¢/m ³

An assumption was made that the utility bills were paid on time and there were no late fees. From the assumption and rates described above the marginal cost of natural gas to industrial customers of Enbridge gas was 22.5 ¢/m³ as shown in Table 3.4. This implies that an increase or decrease of 1 m³ in the consumption of natural gas would result in an increase or decrease of 22.5 cents respectively, in the fuel cost for the customer.

Table 3.4 Marginal cost to industrial customers of Enbridge Gas

Charge	Rate
Gas supply charge	12.7159 ¢/m ³
Transportation to Enbridge	3.15665 ¢/ m ³
Cost adjustment	0.8620 ¢/m ³
Delivery to Customer	3.9853 ¢/m ³
Total Marginal Cost	22.5297 ¢/m ³

3.5 Greenhouse Gas Emission Factor

An added benefit of energy conservation is the associated reduction in greenhouse gas emissions. The greenhouse gas emission factors in terms of grams of carbon dioxide per m³ of natural gas in Canada based on the Canada's National Inventory Report (1990–2009) [8] are shown in Table 3.5. The greenhouse gas emission factor for Ontario was taken as 1879 g CO₂/m³

Table 3.5 Carbon dioxide (CO₂) emission factors for natural gas [5]

Province	GHG Emission Factor (gCO ₂ /m ³)
Newfoundland and Labrador	1891
Nova Scotia	1891
New Brunswick	1891
Quebec	1878
Ontario	1879
Manitoba	1877
Saskatchewan	1820
Alberta	1918
British Columbia	1916
Yukon	2389
Northwest Territories	2454

3.6 Energy Audit Tools

The instruments used for tests and measurements are described below.

3.6.1 Temperature Gun

A temperature gun is a type of infrared thermometer that uses a laser to help aim the thermometer. The working principle behind temperature guns or other infrared thermometers is the measurement of infrared radiation emitted from the object under consideration [52]. A temperature gun is shown in Figure 3.2 [53]. Temperature guns are useful for measuring temperatures where other contact type thermometers, thermocouples and probes cannot be used.



Figure 3.2 Temperature gun (courtesy Extech Instruments, www.extech.com) [53]

3.6.2 Propeller Anemometer

Propeller anemometer is also called a wind mill anemometer. "In this type of air flow meter which has the axis of rotation parallel to the direction of flow" [54]. The blades of the anemometer rotate similar to the blades of a windmill. The speed of rotation is proportional to the speed of air flow. These types of anemometers can be made with sufficiently small sized blades to make them easy to carry and mobile. A small propeller type anemometer is shown in Figure 3.3 [54].

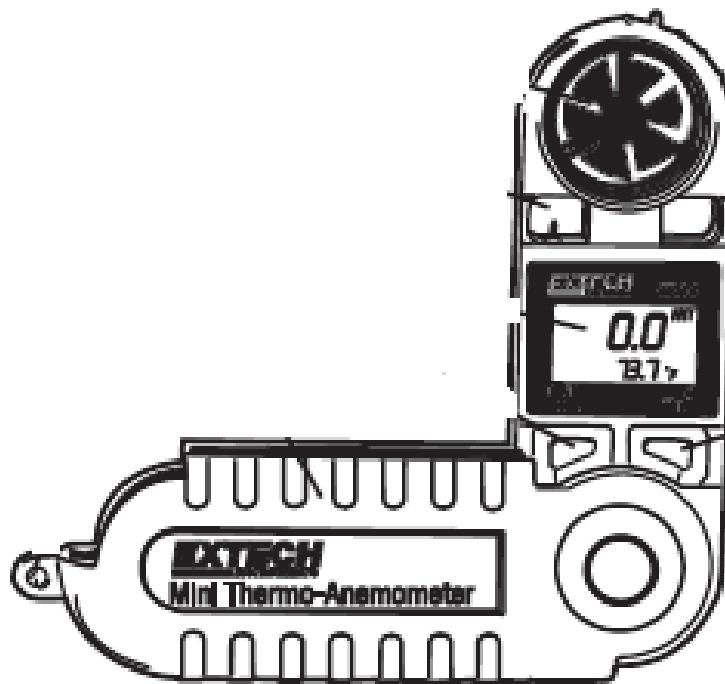


Figure 3.3 Mini anemometer (courtesy Extech Instruments, www.extech.com) [54]

3.6.3 Laser Distance Meter

Laser distance meters measure distance by emitting a beam of laser and noting the time it takes for the reflected beam to return. Lasers are monochromatic, intense beams of light that do not diverge as much as ordinary light rays and hence, can be considered to have uniform velocity. This velocity together with the time of flight is used to measure distance. The distance (D) can be determined by Equation 3.6.

$$D = \frac{ct_f}{2} \quad (3.6)$$

where

t_f = time of flight

c = speed of light

Laser distance meters are useful as they provide measurements much quicker than ordinary tape measure. Their range is also greater than the tape measure and they also be used where using tape measures is difficult or inconvenient. A laser distance meter is shown in Figure 3.4.



Figure 3.4 Laser distance meter (courtesy Extech Instruments, www.extech.com) [55]

3.6.4 Hybrid Ultrasonic Flow Meter

Hybrid ultrasonic flow meters utilize both Doppler and transit time sound techniques to calculate the flow rate. In transit time mode, the flow meter works on the principle that a sound wave introduced into the flow stream takes longer to travel upstream than downstream. Frequency modulated pulses of sound are introduced into the pipe in upstream and downstream and the difference in travel time (transient time) is measured. Transit time flow meters are used mostly for water and liquids [56]. The operation of transit time flow meter is shown in Figure 3.5.

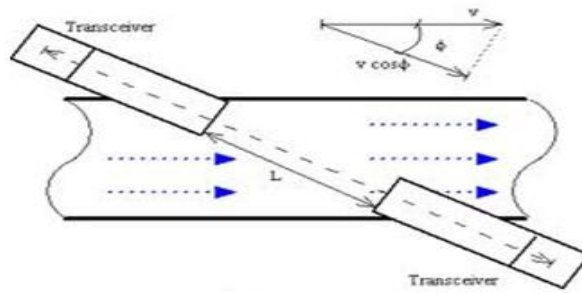


Figure 3.5 Flow measurement using transient time

(courtesy of the Engineering Tool Box, www.engineeringtoolbox.com) [57]

Doppler flow meters are used for solids-bearing or gaseous liquids. In Doppler mode, the flow meter works on Doppler's effect or Doppler's shift which is an apparent shift in the frequency of sound due to the motion of the source or observer of the sound relative to each other. For the purpose of flow measurement ultrasonic sound waves are transmitted in to the flow. The sound is reflected by particulates or gas bubbles in the flow. Particulates or gas bubbles act as the source for the reflected sound. A receiving transducer acts as the observer and experiences the difference of frequency between transmitted and reflected sound depending on how fast the source of reflected sound is moving in the pipe. The shifted frequency is interpreted by the instrument as the rate of flow. The operation of Doppler flow meter is shown in Figure 3.6.

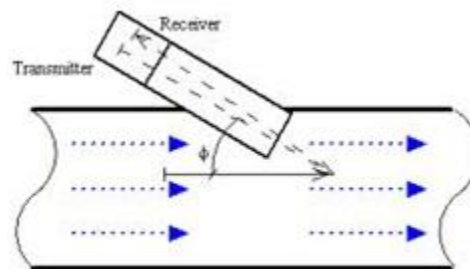


Figure 3.6 Flow measurement using Doppler flow meter

(courtesy of Engineering Toolbox, www.engineeringtoolbox.com) [57]

When the operator selects the correct type of flow in the pipe the measurement technique is automatically selected by the flow meter and accurate measurements for flow rates can be taken.

3.6.5 Combustion Analyzer Kit

A combustion analyzer is a tool used to determine the combustion efficiency of thermal equipment such as furnaces, burners and boilers by measuring the composition of dry flue gas leaving the exhaust (stack). The analyzer takes a variety of readings including the temperature of the stack and combustion air, the concentration of oxygen, carbon dioxide, carbon monoxide, nitrous oxide, sulphur dioxide and unburned hydrocarbons

3.6.6 Infrared Camera

Infrared cameras use thermal radiation to form images [58]. Infrared cameras are useful in detecting leakage of thermal energy from building or equipment. Other uses may include identification of the need for insulation. They can also be used to visualize thermal stratification and the effectiveness of mixing of hot and cold air in a conditioned environment. Figure 3.7 shows the images captured on-site of a dry-off oven.

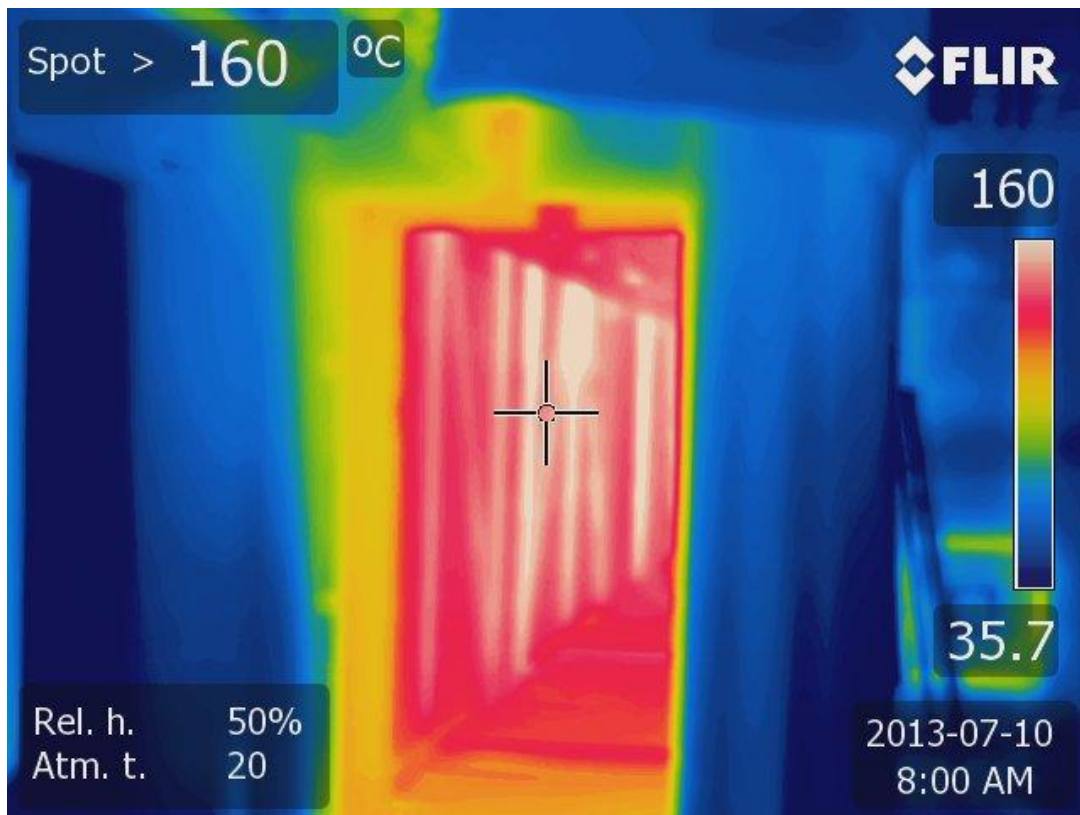


Figure 3.7 Dry-off oven image taken on-site by infrared camera

3.7 Major Gas-Consuming Equipment

The major gas-consuming equipment observed at audited sites were boilers and ovens. These equipment were analyzed to determine their natural gas consumption as well as losses.

3.7.1 Boilers

Boilers are widely used in industrial buildings to supply steam and hot water for processes. Figure 3.8 shows a generalized schematic of boiler rooms at industrial sites.

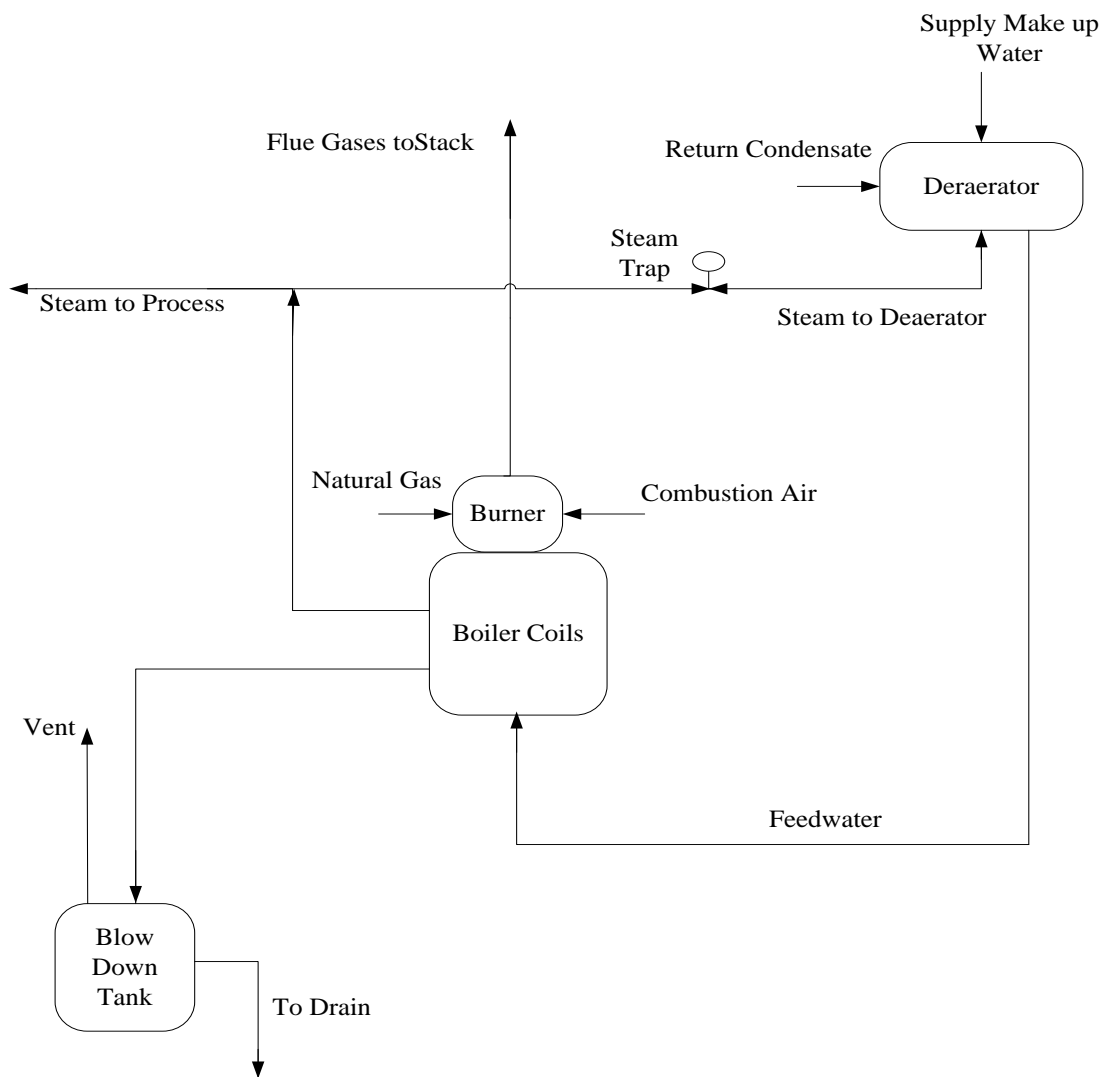


Figure 3.8 Generalized schematic diagram of an industrial boiler room

The procedure for testing boiler performance has been defined by the "American Society of Mechanical Engineers (ASME)" in ASME Power Test Code 4.1 (PTC-4.1-1964) [59], first established in 1964. It was later revised in 1974 [60] and 1998 [61].

There are two methods of determining boiler efficiency (also referred to as gross thermal efficiency or fuel to steam efficiency). These are "input-output method" and "heat loss method". The input output method is also called the "direct method" while the heat loss method is also called the "indirect method" [62]. In the direct method measurement of energy streams coming into and going out from the boiler are required. On the other hand, in the indirect method only the measurement of energy losses are required. The heat loss method is generally considered to be the more accurate method because it only requires the measurement of losses which are only a fraction of the overall energy input. The magnitude of error in thermal efficiency resulting from a small error in measurement would be smaller in comparison to the thermal efficiency calculated by direct method [62]. Therefore, indirect method is considered to be more accurate compared to the direct method [62]. In this study boiler efficiencies were determined using the indirect method or heat loss method.

Heat loss method calculates boiler efficiency as 100% minus the percentage losses from the boiler. The losses from the boilers are:

- Stack losses
- Blow down loss
- Radiation, convection and unaccountable losses

The stack losses represent the inefficiency in the combustion process. Therefore, subtracting percentage stack loss from 100% provides the combustion efficiency.

The composition of the exhaust flue gases leaving the equipment through the stack was determined using a combustion or flue gas analyzer.

The composition of natural gas supplied by Enbridge is given in Table 3.6 [63].

Table 3.6 Volumetric composition of natural gas [63]

Component	Chemical Formula	Percent by Volume in Fuel	Molecular Mass
Methane	CH ₄	95	16.040
Ethane	C ₂ H ₆	2.5	30.07
Propane	C ₃ H ₈	0.2	43.16
n-Butane	C ₄ H ₁₀	0.06	58.12
n-Pentane	C ₅ H ₁₂	0.01	72.10
Decane	C ₁₀ H ₂₂	0.01	142.28
Nitrogen	N ₂	1.6	28.010
Carbon Dioxide	CO ₂	0.7	44.011

3.7.1.1 Fuel Analysis

Since, the products of combustion depend on the composition of the fuel (natural gas) therefore it was necessary to first analyze the fuel. The mass of one mole of natural gas was determined using Equation 3.7.

$$M_{ng} = \sum_{i=0}^N (M_i) (\% X_i) \quad (3.7)$$

Where

M_{ng} is the mass of one mole of natural gas

M_i is the molecular mass of i-th constituent of natural gas and

X_i is the percentage by volume of the i-th constituent of natural gas

Similarly, other properties of the flue gas such specific volume, higher heating value (per unit mass) and higher heating value (per unit volume) were calculated in the same way.

The mass of carbon, hydrogen, nitrogen and oxygen per mole of natural gas was found by using the percentage of carbon containing molecules in the fuel and the atomic mass of carbon (12.011) as shown by Equation 3.8.

$$M_C = 12.011 * \left\{ \sum_{i=0}^N (N_{C_i}) * (\% X_i) \right\} \quad (3.8)$$

Where

N_{Ci} is the number of carbon atoms in the i-th constituent in natural gas

Similarly for hydrogen Equation 3.9 was used while for nitrogen and oxygen Equations 3.10 and 3.11 were used.

$$M_H = 1.008 * \left\{ \sum_{i=0}^N (N_{Hi}) * (\% X_i) \right\} \quad (3.9)$$

where

N_{Hi} is the number of hydrogen atoms in the i-th constituent in natural gas

$$M_N = 14 * \left\{ \sum_{i=0}^N (N_{Ni}) * (\% X_i) \right\} \quad (3.10)$$

where

N_{Ni} is the number of nitrogen atoms in the i-th constituent in natural gas

$$M_O = 16 * \left\{ \sum_{i=0}^N (N_{Oi}) * (\% X_i) \right\} \quad (3.11)$$

The masses of carbon, hydrogen, oxygen and nitrogen obtained from Equations 3.8 through 3.11 were used to determine the mass fractions of these elements in natural gas by dividing them by the mass of one mole of natural gas as shown in Equations 3.12 through 3.15.

$$MF_C = \frac{M_C}{M_{ng}} \quad (3.12)$$

$$MF_H = \frac{M_H}{M_{ng}} \quad (3.13)$$

$$MF_N = \frac{M_N}{M_{ng}} \quad (3.14)$$

$$MF_O = \frac{M_O}{M_{ng}} \quad (3.15)$$

3.7.1.2 Excess Air

The percentage of excess air can be determined by using the percentage oxygen by volume in dry flue gas as shown by Equation 3.16 [64].

$$\%XA = \frac{8.52 * \% O_{2dry} / 100}{2 - (9.52 * \% O_{2dry} / 100)} * 100 \quad (3.16)$$

where

O_{dry} is the percentage volume of oxygen in dry flue gas from combustion test

3.7.1.3 Analysis of Dry Flue Gas

The ratio of volumes of dry flue gas per unit volume of fuel could be determined using the composition of flue gas obtained from the combustion analyzer as shown in Equation 3.17 [65].

$$\begin{aligned} \frac{\text{Volume of DFG}}{\text{Volume of Fuel}} = & (0.0289 * CO_{dry}) + (0.0856 * \%CH_4) + (0.1523 * \%C_2H_6) \\ & + (0.2190 * \% C_3H_8) + (0.2857 * \%C_4H_{10}) + (0.01 * \text{inerts}) - (0.0378 * O_{2dry}) \\ & + 0.0239 * \theta * \left(\frac{\%XA}{100} \right) \end{aligned} \quad (3.17)$$

where

$\%CH_4$, $\%C_2H_6$, $\%C_3H_8$, $\%C_4H_{10}$ are known from the composition of fuel

CO_{dry} and O_{dry} are percentage concentrations of carbon monoxide, and oxygen by volume of dry flue gas determined from the emission test

Inerts include CO_2 , H_2 and SO_3 , SO_2 argon and helium

$\%XA$ is Percentage Excess Air

θ is a function of fuel analysis determined using Equation 3.18 [65].

$$\theta = \%CO + (4 * \%CH_4) + (7 * \%C_2H_6) + (10 * \%C_3H_8) + (13 * \%C_4H_{10}) - (2 * \% O_{2dry}) \quad (3.18)$$

where

%CH₄, %C₂H₆, %C₃H₈, %C₄H₁₀, are known from the composition of fuel

The volume of carbon dioxide per unit volume of fuel was determined using Equation (3.19) [65].

$$\frac{\text{Volume of CO}_2}{\text{Volume of Fuel}} = [(0.01 * \% \text{CO}) + (0.01 * \% \text{CH}_4) + (0.02 * \% \text{C}_2\text{H}_6) + (0.03 * \% \text{C}_3\text{H}_8) + (0.04 * \% \text{C}_4\text{H}_{10}) + (0.01 * \% \text{CO}_2)] \quad (3.19)$$

where

%CH₄, %C₂H₆, %C₃H₈, %C₄H₁₀, %CO and % CO₂ are known from the composition of fuel

The percentage of carbon dioxide by volume of dry flue gas was determined using Equation 3.20.

$$\text{CO}_{2\text{dry}} = \left(\frac{\text{Volume of CO}_2}{\text{Volume of Fuel}} \right) * \left(\frac{\text{Volume of Fuel}}{\text{Volume of DFG}} \right) * 100 \quad (3.20)$$

The volume of nitrogen per unit volume of fuel was determined using Equation 3.21 [64].

$$\frac{\text{Volume of N}_2}{\text{Volume of Fuel}} = \left[\text{MF}_N + \left\{ 1 + \frac{\% \text{XA}}{100} \right\} (0.0189)(\theta) \right] \quad (3.21)$$

The percentage of nitrogen by volume of dry flue gas was determined using Equation 3.22.

$$\text{N}_{2\text{dry}} = \frac{\text{Volume of N}_2}{\text{Volume of Fuel}} * \left(\frac{\text{Volume of Fuel}}{\text{Volume of DFG}} \right) * 100 \quad (3.22)$$

The mass of dry flue gas per unit mass of fuel was determined using Equation 3.23 [66].

$$\frac{\text{Mass of DFG}}{\text{Mass of Fuel}} = \frac{11\text{CO}_{2\text{dry}} + 8\text{O}_{2\text{dry}} + 7(\text{N}_{2\text{dry}} + \text{CO}_{\text{dry}})}{3(\text{CO}_{2\text{dry}} + \text{CO}_{\text{dry}})} * \text{M}_C \quad (3.23)$$

When carbon monoxide in the exhaust is negligible the above equation can be rewritten as Equation 3.24 [66, 67].

$$\frac{\text{Mass of DFG}}{\text{Mass of Fuel}} = \frac{11\text{CO}_{2\text{dry}} + 8\text{O}_{2\text{dry}} + 7\text{N}_{2\text{dry}}}{3(\text{CO}_{2\text{dry}})} * M_C \quad (3.24)$$

where

O_{dry} is the percentage volume of oxygen in dry flue gas

CO_{dry} is the percentage volume of carbon monoxide in dry flue gas

$\text{CO}_{2\text{dry}}$ is the percentage volume of carbon dioxide in dry flue gas

$\text{N}_{2\text{dry}}$ is the percentage volume of nitrogen in dry flue gas

3.7.1.4 Stack Losses

The heat generated during the process of combustion is carried away by the products of combustion (flue gases). Major heat losses through the stack are:

- Heat loss due to dry flue gas
- Heat loss due to water vapor
- Heat loss due to carbon monoxide
- Heat loss due to unburned hydrocarbons

The heat loss due to dry flue gas per unit mass of fuel was determined by using Equation 3.25 [67].

$$\frac{\text{Heat Lost to DFG}}{\text{Mass of Fuel}} = \left(\frac{\text{Mass of DFG}}{\text{Mass of Fuel}} \right) (T_{\text{dfg}} - T_{\text{air}}) c_{p,\text{dfg}} \quad (3.25)$$

where

T_{dfg} is the temperature of dry flue gas

T_{air} is the temperature of combustion air

$c_{p,\text{dfg}}$ is the specific heat of dry flue gas and is given by Equation 3.26

$$c_{p,\text{dfg}} = \sum_{i=1}^N V_i * Y_i \quad (3.26)$$

Where

V_i is the percentage by volume of the i-th component in dry flue gas.

Y_i is the specific heat of the i-th constituent of dry flue gas

The percentage heat loss due to dry flue gas was calculated using Equation 3.27.

$$\% \text{ Heat loss to DFG} = \left(\frac{\text{Heat Lost to DFG}}{\text{Mass of Fuel}} \right) * \left(\frac{100}{\text{HHV of Fuel}} \right) \quad (3.27)$$

The heat lost due to water vapor per unit mass of fuel was found from Equation 3.28 [67].

$$\frac{\text{Heat lost to Water Vapor}}{\text{Mass of Fuel}} = 9 \text{ MF}_H [H_{\text{vapor}} - H_{\text{liquid}}] \quad (3.28)$$

where

MF_H is the mass fraction of hydrogen in natural gas

H_{vapor} is the enthalpy of saturated steam at 1 psia and flue gas temperature determined using Equation 3.29 [64].

H_{liquid} is the enthalpy of water at combustion air temperature BTU/lb

$$H_{\text{vapor}} = 1055 + 0.467 * (T_{\text{dfg}}) \quad (3.29)$$

The percentage heat loss due to water was calculated using Equation 3.30.

$$\% \text{ Heat loss to Water Vapor} = \left(\frac{\text{Heat lost to Water Vapor}}{\text{Mass of Fuel}} \right) * \frac{100}{\text{HHV of Fuel}} \quad (3.30)$$

Heat lost due to carbon monoxide was found using Equation 3.31 [64].

$$\frac{\text{Heat lost to CO}}{\text{Mass of Fuel}} = \frac{\text{CO}_{\text{dry}}}{\text{CO}_{2\text{dry}} + \text{CO}_{\text{dry}}} * 10160 * M_C \quad (3.31)$$

The percentage heat lost due to carbon monoxide was determined using Equation 3.32

$$\% \text{ Heat loss to CO} = \left(\frac{\text{Heat lost to CO}}{\text{Mass of Fuel}} \right) * \frac{100}{\text{HHV of Fuel}} \quad (3.32)$$

For calculating heat lost due to unburned hydrocarbons the density of dry flue gas was required which was determined by using Equation 3.33.

$$\text{Density of DFG} = \left(\frac{\text{Mass of DFG}}{\text{Mass of Fuel}} \right) * \text{Density of Fuel} * \left(\frac{\text{Volume of Fuel}}{\text{Volume of DFG}} \right) \quad (3.33)$$

Density of dry flue gas can be used to determine the heat lost due to unburned hydrocarbons as shown in Equation 3.34.

$$\frac{\text{Loss to UHC}}{\text{Mass of Fuel}} = \frac{1}{100} * \left(\frac{\text{HHV}_{\text{UHC}}}{\text{Density of DFG}} \right) * \left(\frac{\text{Mass of DFG}}{\text{Mass of Fuel}} \right) * \left(\frac{\text{Volume of UHC}}{\text{Volume of DFG}} \right) \quad (3.34)$$

The percentage heat loss due to unburned hydrocarbons (UHC) was determined using Equation (3.35)

$$\% \text{ Heat loss to UHC} = \left(\frac{\text{Loss to UHC}}{\text{Mass of Fuel}} \right) * \frac{100}{\text{HHV of Fuel}} \quad (3.35)$$

Density of fuel is given in [65] as the ratio of molecular mass and molecular volume. The molecular mass of was determined using Equation 3.7 and the molecular volume of natural gas is 379 cubic ft [65]. "Higher heating value" of unburned hydrocarbons was taken as 1014.2 BTU/lb [65].

The combustion efficiency was determined by subtracting the sum of percentage losses from 100%.

$$\eta_{\text{comb}} = 100 - \text{Sum of \% Stack Losses} \quad (3.36)$$

The stack loss is the sum of losses as shown in Equation (3.37)

$$\text{SL} = \frac{(100 - \eta_{\text{comb}})}{100} * \text{EI} \quad (3.37)$$

3.7.1.5 Radiation, Convection and Unaccountable losses

It is assumed that radiation, convection and unaccountable losses are 1% of the energy input rate.

$$RL = 1\% * EI \quad (3.38)$$

3.7.1.6 Blowdown Loss

The blowdown loss can be calculated by using (3.39).

$$BL = M_{bd} * (h_{bd} - h_{fw}) \quad (3.39)$$

where

BL is blowdown loss (BTU/h)

M_{bd} is mass flow rate of blowdown (lb/h)

h_{bd} is enthalpy of blowdown (BTU/lb)

h_{fw} is enthalpy of feed water (BTU/lb)

Blowdown flow rate is usually expressed as a percentage of the steam production rate as shown in (3.40).

$$M_{bd} = \%BD * M_{steam} \quad (3.40)$$

where

$\%BD$ is percentage of steam flow rate leaving the boiler as blowdown

M_{steam} is mass flow rate of steam produced by boiler (lb/h)

The steam produced by the boiler is determined using (3.41).

$$M_{steam} = \frac{(EI - SL - RL - BL)}{(h_s - h_{fw})} \quad (3.41)$$

where

h_s is enthalpy of steam (lb/h)

Simultaneously solving (3.39), (3.40) and (3.41) the blowdown loss was determined.

$$BL = \frac{(EI - SL - RL - BL)}{(h_s - h_{fw}) + \%BD(h_{BD} - h_{fw})} \quad (3.42)$$

The percentage blowdown is determined by using (3.43).

$$\% BL = (BL / EI) * 100 \quad (3.43)$$

After determining the stack loss, blowdown loss and other losses the overall efficiency (boiler efficiency) can be determined using (37)

$$\eta_{\text{boiler}} = 100 - \% SL - \% RL - \% BL \quad (3.44)$$

3.7.2 Ovens

In addition to boilers ovens were the most frequently present equipment at the audited sites. The working of oven involves heating of the product. However, some of the heat is also taken away by the conveyor equipment carrying the product and also by the oven exhaust. The energy use for the oven could be represented by Equation 3.45.

$$Q_{\text{oven}} = (mc_p \Delta T)_{\text{product}} + (mc_p \Delta T)_{\text{conveyor}} + \frac{(1.08)(CFM_{\text{exhaust}})\Delta T}{\eta_{\text{comb oven}}} \quad (3.45)$$

The heat taken away by the product and conveyor cannot be avoided. However, the heat lost through the exhaust can be reduced. Therefore, oven exhaust was the focus of analysis of the oven.

4 Energy Conservation Measures

Energy conservation measures in industry vary depending on the size and type of industry. Large plants in energy intensive industries usually conserve energy through retrofitting of process equipment. On the other hand, energy saving measures with short paybacks are attractive for small and medium sized industrial plants [68, 69]. The energy conservation measures identified in this study fall under one of the three categories.

1. Energy conservation by management practices
2. Energy conservation by better maintenance and operation practices
3. Energy conservation by available technologies

4.1 Energy Conservation by Management Practices

Better housekeeping and management practices if implemented properly could result in significant energy savings without incurring much cost. In some cases there may not be any cost associated with energy saving practices. These management practices can include ensuring that all production equipment is turned off on holidays and weekends. The effects of such practices were investigated in the report.

The information collected during the energy audit regarding the daily or hourly gas consumption and the operation schedule of the plant was used to calculate energy consumption during productive time and non-productive time. Energy consumption on weekends, statutory holidays and during non-operational hours were considered as the non-productive time energy consumption. Estimates of savings achieved by reduction of non-productive time consumption were made. For this purpose energy savings achieved by reducing the non-productive time energy consumption by 25%, 50%, 75% and 100% were estimated along with the accompanying cost savings and reduction in greenhouse gas emissions.

4.2 Energy Conservation by Improving Equipment Performance

Energy (in this study natural gas) conservation by improving equipment performance involves implementing better maintenance and operation practices to keep the equipment running

efficiently and making sure that the equipment are operating at conditions where they are at their highest efficiencies. Energy efficiency measures related to maintenance and operation practices were tune-up of gas fired equipment and optimization of load management of boilers.

4.2.1 Tune-up of Gas Fired Equipment

In order to quantify the savings achieved by implementing this measure, it is first necessary to determine the current energy consumption of the equipment. This combustion efficiency can then be used as the baseline to compare with the efficiency achieved after tune-up. The method in this study used to determine the baseline combustion efficiency and stack losses has been detailed in Chapter 3.

$$\text{Percentage fuel savings} = \frac{\eta_{\text{comb,new}} - \eta_{\text{comb,baseline}}}{\eta_{\text{comb,baseline}}} \quad (4.1)$$

where

$\eta_{\text{comb,baseline}}$ combustion efficiency before tune up
 $\eta_{\text{comb,new}}$ combustion efficiency after tune up

After tune-up the equipment would operate with optimal level of excess air. For natural gas fired equipment the optimum level of excess air is around 20% to 30% excess air (characterized by a 4% to 5% oxygen in dry flue gas) [68]. For estimates of savings the combustion efficiency was re-calculated using 5% oxygen in the flue gas at the same exhaust temperature as measured during the combustion test. Additional improvement in efficiencies due to the decreased temperature can only be determined by conducting combustion tests again after tune-up and therefore, were not considered. The annual savings were determined by taking the difference in efficiency for the baseline and new analysis as shown by Equation 4.2.

$$\text{Annual energy savings} = \text{Current fuel consumption} * \text{Percentage fuel savings} \quad (4.2)$$

4.2.2 Optimized Load Allocation

Optimized load allocation is a very useful and effective method of reducing energy consumption

in plants that have similar equipment that may not have the same operational efficiencies. Examples of such cases are boiler rooms that have more than one boiler sharing the steam demand load of the plant. Optimized load allocation has been studied in [71-74]. However, in this study a novel optimization algorithm based on mixed integer non-linear programming (MINLP) was developed for minimizing energy (natural gas) consumption.

The algorithm was developed for a boiler room with "n" number of boilers. Since, natural gas consumption only changes to satisfy the steam demand therefore, the steam load allocated to each of the boilers (represented by 'X') was taken as the independent variable. Also the decision to run a particular boiler was represented by the binary variable 'Y' which could be assigned values of "1" or "0" for "on" or "off" respectively. The natural gas consumption of each of the boilers was determined by conducting tests at different loading conditions. Natural gas consumption was expressed as a function, $f(X)$, of steam demand. It has been shown in [71] that observed boiler data fitted on a second order polynomials could be used to represent boiler efficiencies at different loads. In this study quadratic expressions were used for natural gas consumption of the boilers as shown by Equation (4.3). These expressions were obtained by performing regression analysis on the boiler test data.

$$f(X_k, Y_k) = Y_k * [a_k * (X_k)^2 + b_k * X_k + c_k] \quad (4.3)$$

X_k is the steam demand load allocated to the k-th boiler

Y_k represents the decision to switch on k-th boiler (it is a binary variable with a value of "1" for "on" and "0" for "off")

n is the number of boilers

$f(X_k, Y_k)$ is the natural gas consumption of the k-th boiler, as a function of the steam load

Since, there is no need to run a boiler if there is no steam demand therefore, there will be no natural gas consumption. Hence, the intercept (c_k) would be zero, as shown in Equation (4.4).

$$f(X_k, Y_k) = Y_k * [a_k * (X_k)^2 + b_k * X_k] \quad (4.4)$$

The steam demand of the boiler plant was taken as the constraint for the optimization problem. Furthermore, it was necessary to ensure that the solution of the optimization problem did not

return a load allocation for boiler which corresponds to a firing rate less than the minimum firing rate of the boiler. This was achieved by adding an extra constraint that the steam load for a boiler could only be between the minimum and maximum load capacity of the boiler.

The optimization problem for 'n' number of boilers was set to minimize natural gas consumption of the boiler plant (Z)

Minimize

$$Z = \sum f(X_k, Y_k) \quad (\text{For } k \text{ ranging from } 1 \text{ to } n)$$

Subject to

$$\sum X_k = \text{Steam load demand of the boiler room} \quad (\text{Constraint 1})$$

$$L_{k \min} \leq X_k \leq L_{k \max} \quad (\text{Constraint 2})$$

and

$$Y_k = \{1, 0\} \quad (\text{Constraint 3})$$

where

$L_{k \max}$ is the maximum load capacity of k-th boiler when the boiler is running

$L_{k \min}$ is the minimum load capacity of k-th boiler when the boiler is running

For the solution of the optimization problem Branch and Bound technique [75] combined with nonlinear programming (NLP) was used. At each node of the variable (Y) was assigned a value of either "1" or "0". This reduced the mixed integer non-linear programming (MINLP) problem to a quadratic programming (QP) problem of the form shown in Equation (4.5)

$$\text{Minimize: } Q = \frac{1}{2} X^T H X + F^T X \quad (4.5)$$

where

X is the vector of variables

H is the hessian matrix for the objective function

F is the column vector comprised of coefficients of linear terms in the objective function

The problem was solved by using algorithm based on the solution of Karush-Khun-Tucker (KKT) conditions [76]. At each node the corresponding quadratic programming problem was solved to obtain the lower bound for the objective function. For generating branches, depth first technique was used (i.e., nodes on a branch was solved all the way to the last node). For finding candidate solution or fathoming nodes (i.e., "determination that it is not necessary to explore the descendants of a particular node in the search tree" [75]), best lower bound method was used. If the optimal solution did not return a result better than the current lower bound, no further branches from that node were generated).

The boilers which were to be 'on' and the load allocation for those boilers were determined by solving the MINLP optimization problem. The baseline natural gas consumption was determined by using the load allocation in the boiler room at the time of the audit. The natural gas saving was determined as the difference between the baseline and the optimal.

$$\text{Energy Savings} = \text{Operational hours} * (Z_{\text{baseline}} - Z_{\text{optimal}}) \quad (4.6)$$

4.3 Energy Conservation by Available Technologies

Available technologies considered in this study included, equipment that could either recover the waste heat or reduce energy consumption at reduced loads. Examples of such technologies are feedwater economizers and variable frequency drives for fan motors, running at constant volume.

4.3.1 Feedwater Economizer

Feedwater economizer is equipment that recovers heat from the exhaust flue gases exiting the boiler through the stack and heats the feedwater coming into the boiler using the recovered heat. The schematic feedwater diagram is shown in Figure 4.1.

Since, this study involved small and medium-sized industries that were less likely to bear the extra cost of condensing economizer, therefore, only conventional economizer was considered.

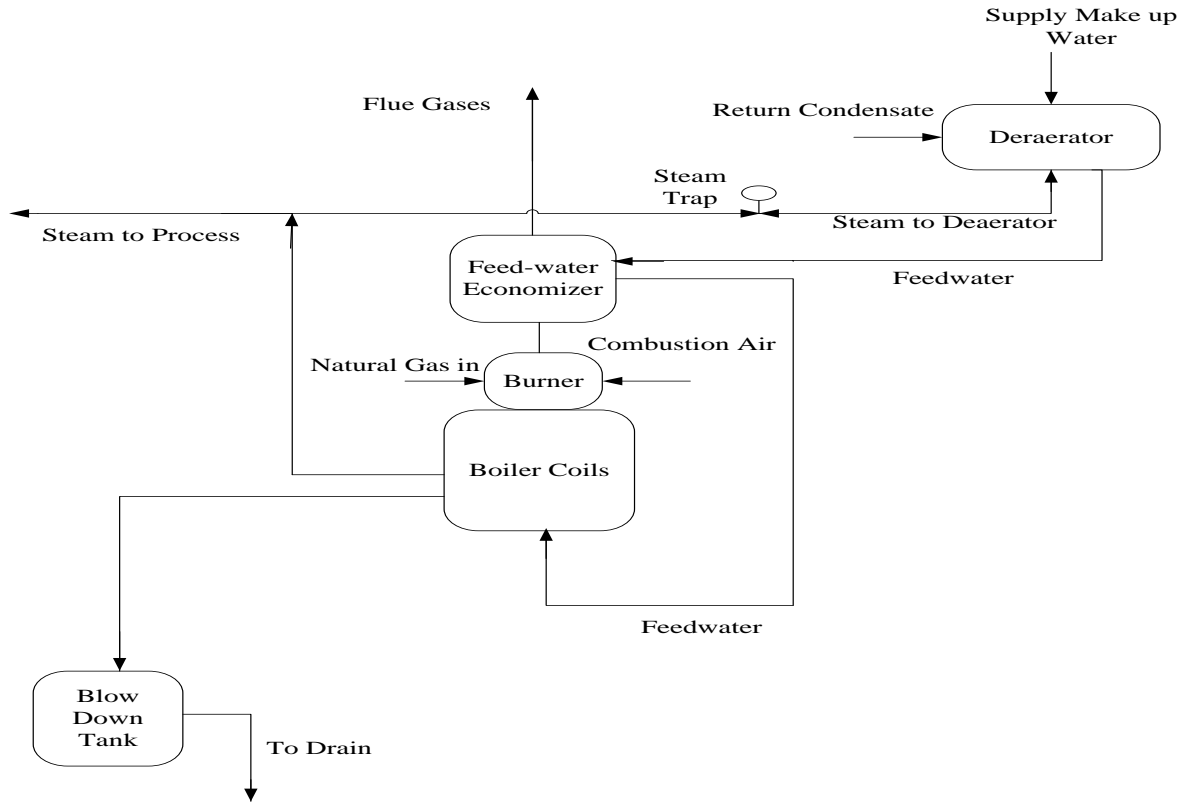


Figure 4.1 Schematic of a conventional feedwater economizer

In order to estimate the heat recovery potential of flue gas it is necessary to analyze flue gas as a whole (dry as well as wet products of combustion) not just the dry flue gas [65].

$$\frac{\text{Mass of FG}}{\text{Volume of Fuel}} = (0.002558 * CO_{\text{dry}})(0.00770 * \%CH_4) + (0.01353 * \%C_2H_6) + (0.01936 * \%C_3H_8) + (0.02518 * \%C_4H_{10}) + (0.01 * \text{inerts}) - (0.0378 * O_{2\text{dry}}) + (0.0239 * \theta * \%XA / 100) \quad (4.7)$$

The mass of flue gas per unit mass of fuel is given by Equation 4.8.

$$\frac{\text{Mass of FG}}{\text{Mass of Fuel}} = \frac{\text{Mass of FG}}{\text{Volume of Fuel}} * \frac{HHV_m}{HHV_v} \quad (4.8)$$

where

HHV_m is the "higher heating value" of natural gas on mass basis

HHV_v is the "higher heating value" of natural gas on volume basis

The mass flow rate of flue gas is therefore,

$$\dot{m}_{fg} = \frac{\text{Mass of FG}}{\text{Mass of Fuel}} * \frac{EI}{HHV_m} \quad (4.9)$$

The heat carried away by the flue gas is

$$\dot{Q}_{fg} = \dot{m}_{fg} * C_{pfg} * (\Delta T_{fg}) \quad (4.10)$$

ΔT_{fg} is the temperature difference between the temperature of flue gases entering and leaving the flue gas economizer.

The temperature of flue gases leaving the economizer is constrained by the lowest temperature flue gases can be cooled without condensation and possible corrosion of the stack. This lowest temperature depends on the type of fuel. For natural gas the lowest temperature flue gases can be cooled without condensation is 250 °F.

The feedwater flow rate is calculated using the Equation (4.11)

$$\dot{m}_{fw} = \frac{M_{\text{steam}}}{(1 - \%BD)} \quad (4.11)$$

The temperature of feed water exiting the economizer is found using Equation 4.12.

$$T_{fw,out} = \frac{Q_{fg}}{\dot{m}_{fw} C_{fw}} + T_{fw,in} \quad (4.12)$$

where

$T_{fw,out}$ is the temperature of feedwater exiting the economizer

$T_{fw,in}$ is the temperature of feedwater entering the economizer

The annual natural gas saving in terms of m³/year is calculated using Equation 4.13.

$$NG_{\text{savings}} = \frac{Q_{\text{fg}}}{35.31 * HHV_V * \eta_{\text{boiler}}} * \text{annual hours of operation} \quad (4.13)$$

The annual monetary savings was calculated by multiplying the natural gas savings by the natural gas price.

4.3.2 Reduction of Oven Exhaust using Variable Frequency Drive

It was observed that the ovens were equipped with exhaust fans for purging during daily start up. The exhaust fans are run at full speed during purging. However, after purging the speed of exhaust fans cannot be reduced. The rate of energy consumed (in BTU/h) while running the fans at full speed is expressed in Equation 4.14.

$$Q_{\text{current}} = \frac{(1.08)(CFM_{\text{current}})\Delta T}{\eta_{\text{comb oven}}} \quad (4.14)$$

where

CFM_{current} is the exhaust rate of fan at full speed

It was recommended to reduce the speed of exhaust fans after purging so that the ovens operate with a lower exhaust rate. The rate of energy consumed (in BTU/h) while running the fans at reduced speed is expressed in Equation 4.15.

$$Q_{\text{new}} = \frac{(1.08)(CFM_{\text{new}})\Delta T}{\eta_{\text{com oven}}} \quad (4.15)$$

where

CFM_{new} is the exhaust rate of fan at reduced speed

ΔT is the difference in temperature of air leaving and entering the oven (°F)

The natural gas savings (in m³/year) achieved using variable frequency drive is

$$NG_{\text{savings}} = \frac{Q_{\text{current}} - Q_{\text{new}}}{35.31 * HHV_V * \eta_{\text{com oven}}} * \text{annual hours of operation} \quad (4.16)$$

4.4 Cost Savings

The annual monetary savings were calculated by multiplying the natural gas savings by the marginal cost of natural gas.

$$\text{Annual cost savings} = \text{Annual energy savings} * \text{Marginal cost} \quad (4.17)$$

4.5 Reduction in Greenhouse Gas Emission

The reduction in greenhouse gas emissions were calculated using Equation (4.18)

$$\text{Annual cost savings} = \text{Annual energy savings} * \text{GHG Emission Factor} \quad (4.18)$$

5 Results and Discussions

The results obtained from energy audits of small and medium-sized industries are presented in this chapter. The results have been distributed into three main sections. These are:

1. Natural gas consumption
2. Major gas fired equipment
3. Energy saving measures

In order to maintain confidentiality the names of industrial sites were removed. All the industrial sites are referred to by the letters of the alphabet. Furthermore, the results were tabulated in manner to allow similar industrial sites to be arranged together. For instance sites 'A' through 'D' belong to food manufacturing sector, sites 'E' and 'F' belong to the packaged goods sector while the remaining sites belong to finishing process industry. The results of energy audits from all these sites are presented in the following sections.

5.1 Natural Gas Consumption

Natural gas consumptions at the audited sites were analyzed to assess performance indicators such as annual natural gas consumption, energy intensity, annual cost of natural gas, yearly emission of greenhouse gases, natural gas consumption during operational and non-operational hours of the plant, base level energy consumption and weather dependent energy consumption.

5.1.1 Natural Gas Consumption from Utility Bills

Average annual gas consumption as well annual cost and annual greenhouse gas emissions are shown Table 5.1. These are the preliminary results obtained from the utility bills data. Site 'A' is by far the biggest consumer of natural gas amongst all the sites averaging close to 3.4 million m³. Therefore, site 'A' not only has the largest annual cost but also the largest greenhouse gas emissions.

Figure 5.1 illustrates the average annual natural gas consumption. Site 'A' is visibly the largest consumer of natural gas. Excluding site 'A' the audited sites belonging to the food sector had

annual natural gas consumption ranging between 500,000 m³ to 1,000,000 m³. Annual consumption for sites belonging to the packaged goods sector (i.e. 'E' and 'F' remained below 1,000,000 m³. Annual gas consumption for finishing process industries was found to vary from 153,529 m³ for site 'O' to 1,283,047 m³ for site 'L'. The audited sites vary in size, operational hours and performance of the equipment. The effects of these parameters were studied and are presented in the subsequent sections.

Table 5.1 Average annual natural gas consumption, annual cost and greenhouse gas emissions

Site	Type of Industry	Average Annual Natural Gas Consumption (m ³ /yr)	Cost (\$/yr)	GHG Emission (tonnes CO ₂ /yr)
A	Food	3,369,563	759,152	6,331
B	Food	676,090	152,321	1,270
C	Food	1,040,399	234,399	1,955
D	Food	544,200	122,607	1,023
E	Packaged Goods	987,794	222,547	1,856
F	Packaged Goods	628,339	141,563	1,181
G	Finishing Process	625,765	140,983	1,176
H	Finishing Process	340,017	76,605	639
I	Finishing Process	447,889	100,908	842
J	Finishing Process	492,795	111,025	926
K	Finishing Process	290,981	65,557	547
L	Finishing Process	1,283,047	289,067	2,411
M	Finishing Process	886,747	199,781	1,666
N	Finishing Process	373,955	84,251	703
O	Finishing Process	153,529	34,590	288

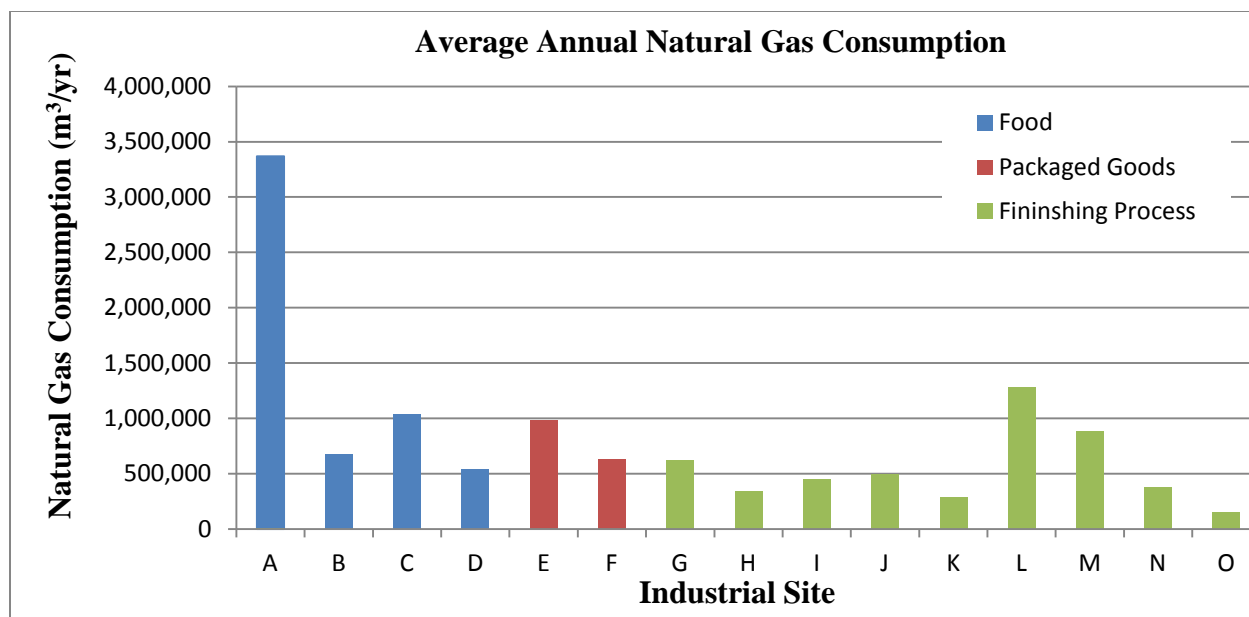


Figure 5.1 Average annual natural gas consumption for audited sites

The annual natural gas consumption of any facility is dependent on the size of the plant and its internal processes and equipment. The greater the size of the plant, the greater the natural gas consumption. The energy (natural gas) consumption per unit area, also called as energy intensity was calculated. The energy intensities of the audited sites are presented in Table 5.2 and Figure 5.2. Site 'A' had the highest energy intensity at $17.73 \text{ m}^3/\text{ft}^2$ while site 'F' had the lowest energy intensity at $2.33 \text{ m}^3/\text{ft}^2$.

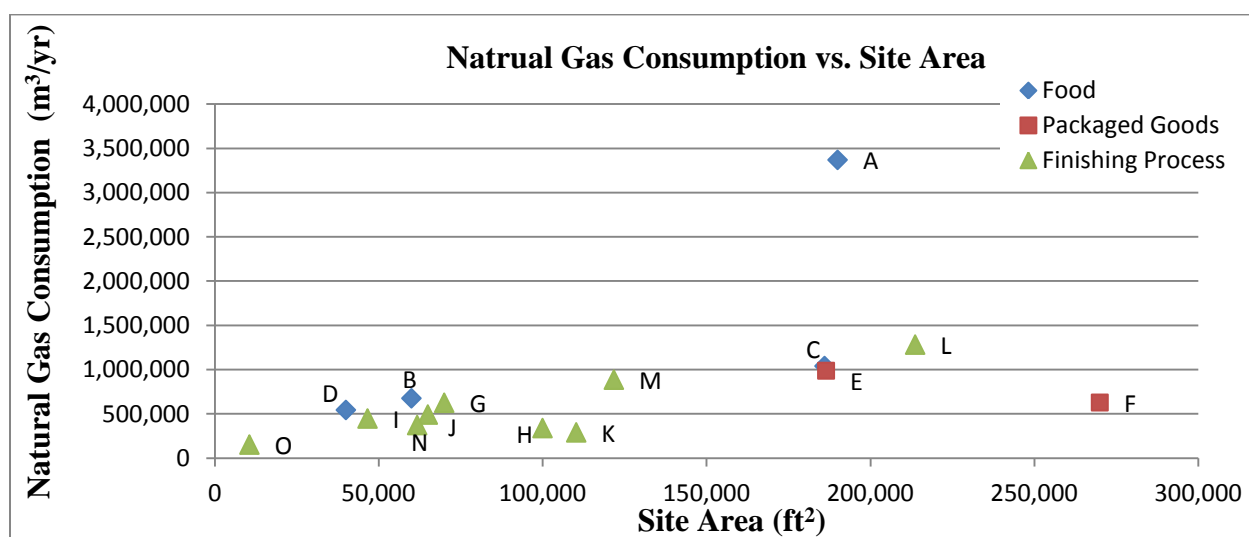


Figure 5.2 Annual natural gas consumption vs. site area

Table 5.2 Energy intensities for the audited sites

Site	Type of Industry	Average Annual Natural Gas Consumption (m ³ / yr)	Site Area (ft ²)	Energy Intensity (m ³ / ft ²)
A	Food	3,369,563	190,008	17.73
B	Food	676,090	60,000	11.27
C	Food	1,040,399	186,026	5.59
D	Food	544,200	40,000	13.61
E	Packaged Goods	987,794	186,500	5.30
F	Packaged Goods	628,339	270,000	2.33
G	Finishing Process	625,765	70,000	8.94
H	Finishing Process	340,017	100,000	3.40
I	Finishing Process	447,889	46,609	9.61
J	Finishing Process	492,795	65,000	7.58
K	Finishing Process	290,981	110,270	2.64
L	Finishing Process	1,283,047	213,668	6.00
M	Finishing Process	886,747	121,762	7.28
N	Finishing Process	373,955	61,756	6.06
O	Finishing Process	153,529	10,573	14.52

Figure 5.3 shows energy intensity plotted against site area. The food sector generally had energy intensities higher than 10 m³/ft². However, site 'C' was an exception which had an energy intensity of less than 6 m³/ft². The two sites from packages goods sector both had energy intensities below 6 m³/ft². The finishing process industry generally had energy intensities below 10 m³/ft² except site 'O'.

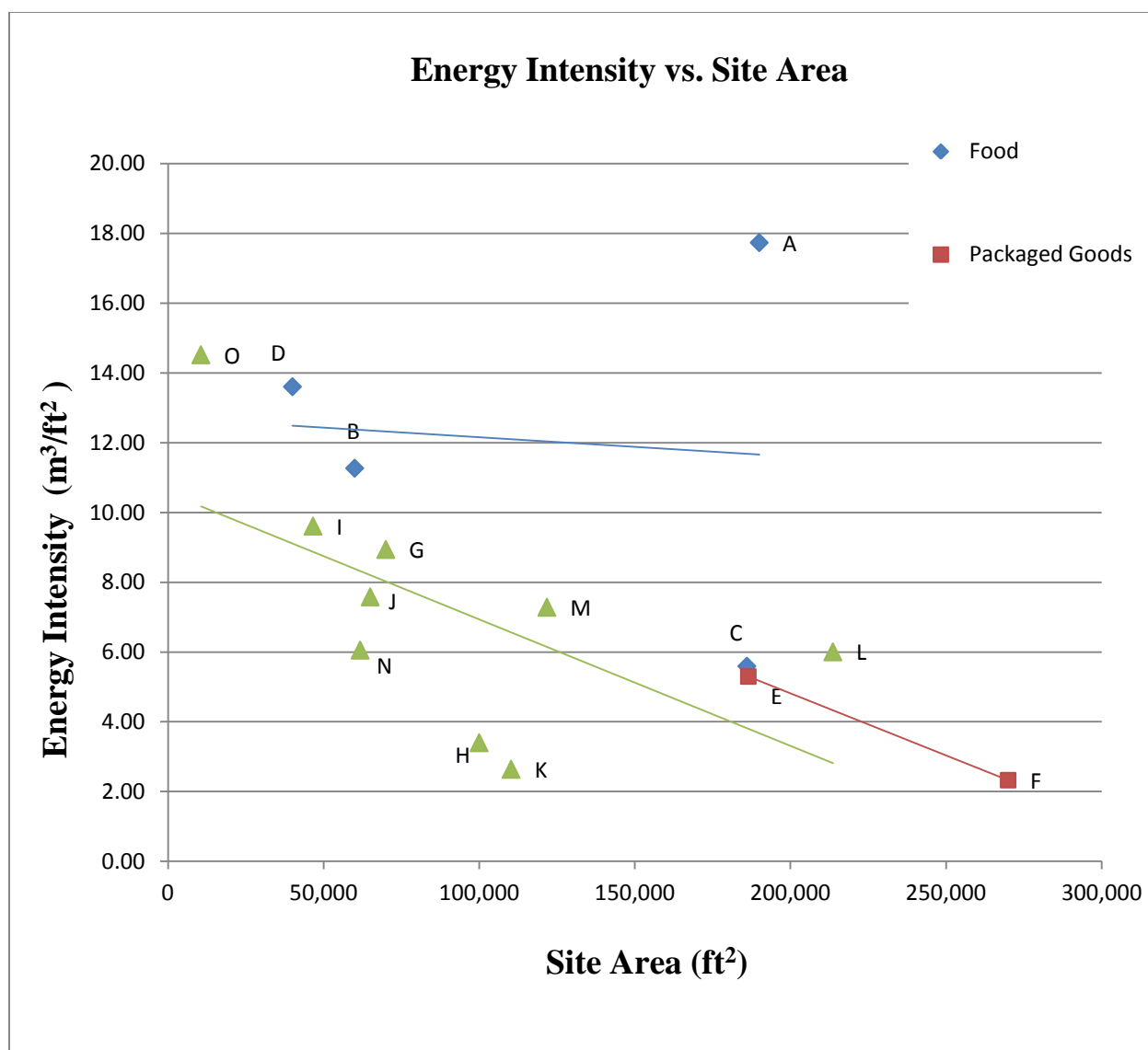


Figure 5.3 Energy intensity vs. site area

5.1.2 Natural Gas Consumption and Hours of Operation

Annual natural gas consumption is also affected by the number of hours the plant remains in operation. Natural gas consumption per hours of operation of the plant have been presented in Table 5.3. Site 'L' had the highest natural gas consumption per hour of operation at 642 m³/h while site 'O' had the lowest consumption per hour of operation at 49 m³/h. Excluding site 'A' food sector industries ranged between 73 and 167 m³/h. The packaged goods industries had 75 m³/h and 158 m³/h. Finishing process industries ranged from 49 m³/h to 641 m³/h.

Table 5.3 Natural gas consumption per hours of operation for audited sites

Site	Type of Industry	Average Annual Consumption (m ³ / yr)	Annual Hours of Operation (h/yr)	Energy Per Hour of Operation (m ³ / h)
A	Food	3,369,563	6,240	540
B	Food	676,090	5,616	120
C	Food	1,040,399	6,240	167
D	Food	544,200	7,488	73
E	Packaged Goods	987,794	6,240	158
F	Packaged Goods	628,339	8,400	75
G	Finishing Process	625,765	2,500	250
H	Finishing Process	340,017	3,640	93
I	Finishing Process	447,889	2,210	203
J	Finishing Process	492,795	2,080	237
K	Finishing Process	290,981	2,000	145
L	Finishing Process	1,283,047	2,000	642
M	Finishing Process	886,747	8,320	107
N	Finishing Process	373,955	2,600	144
O	Finishing Process	153,529	3,120	49

Figure 5.4 shows the natural gas consumption for the audited sites plotted against hours of operation. It could be observed that the sites operating less than 5,000 hours per year had natural gas consumption less than 650,000 m³ per year. However, site 'L' was an exception to this with 2,000 hours of operation and 1,283,047 m³. For the sites that had more than 5,000 hours per year the lowest natural gas consumption was 544,200 m³ for site 'D' while the highest natural gas consumption was 3,369,563 m³ for site 'A'.

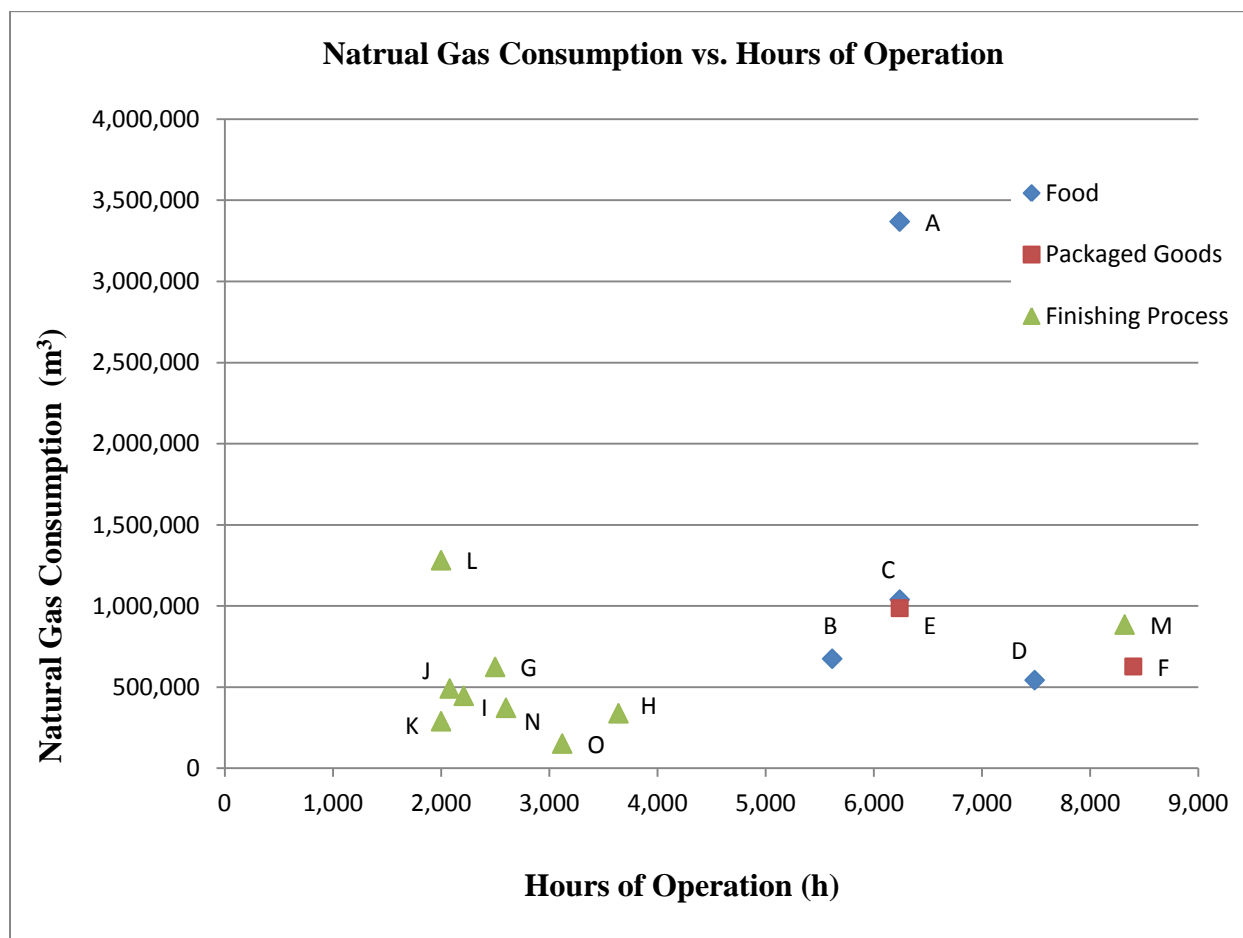


Figure 5.4 Annual natural gas consumption vs. hours of operation

The combined effect of site area and hours of operation was analyzed using energy consumption per unit area per unit operational hour and plotted against site area as shown in Figure 5.5.

Energy intensity per hour of operation for the sites belonging to the food sector were found to increase with the increase in area. Site 'C' was the exception which showed the lowest consumption per unit area per unit hour in the food sector despite having the second largest site area. The trend in packaged goods sector showed a decrease in energy intensity per unit hour of operation with the increase in site area. In the finishing process industry energy intensity per unit hour of operation decreased with increase in area for site areas less than 150,000 ft². However, site 'L' which had a site area greater than 200,000 showed a high energy intensity per unit hour of operation.

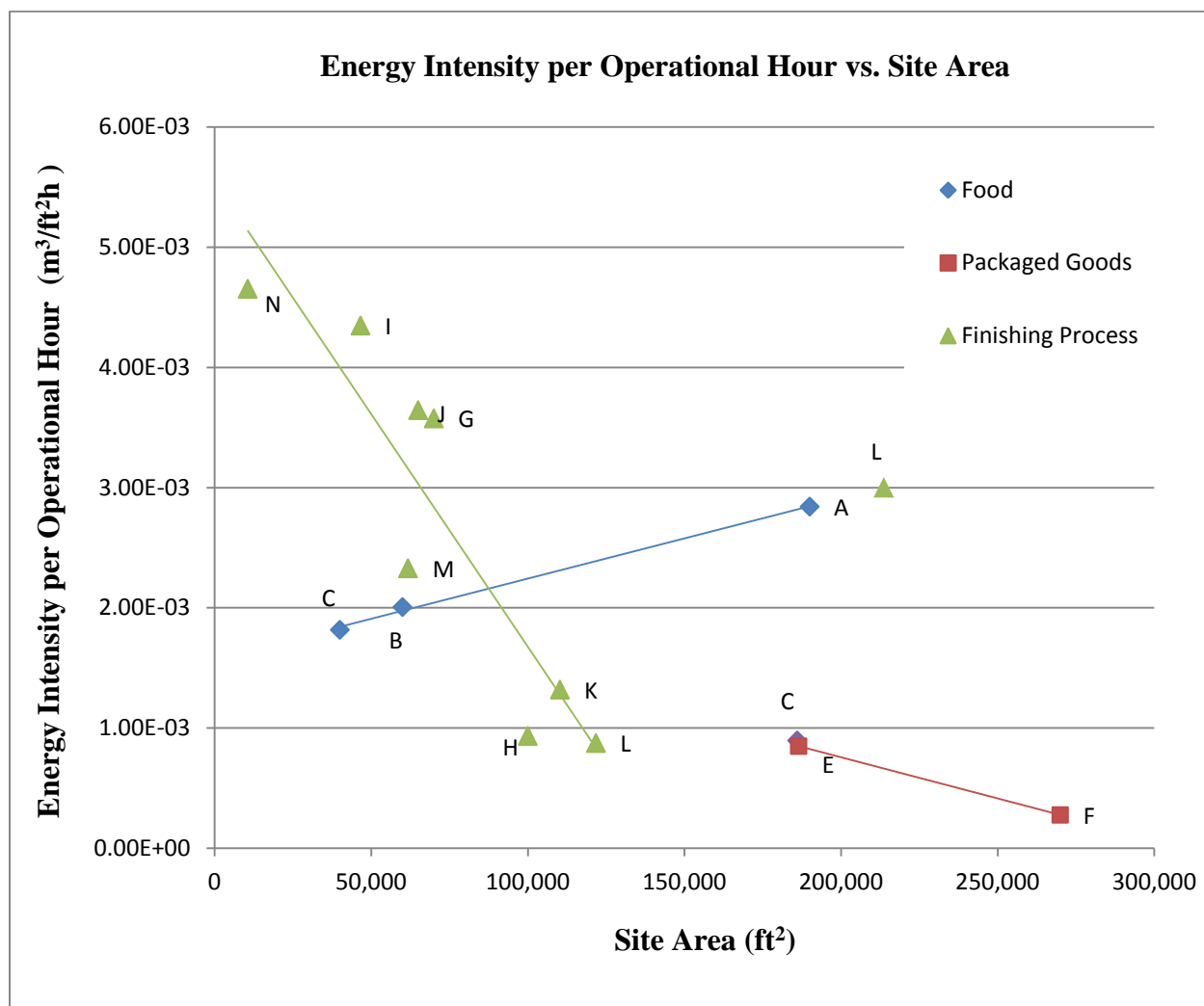


Figure 5.5 Energy intensity per unit hour of operation vs. site area

5.1.3 Productive and Non-Productive Natural Gas Consumption

There were ten sites for which either daily or hourly consumption data was available. The data together with the operating schedule of the plant were used to determine the consumption on days when the industrial plants were not in operation such as weekends, statutory holidays, etc. The consumption on such days was classified as non-productive consumption. The average annual non-productive natural gas consumption is presented in Figure 5.6. Non-productive natural consumption for site 'A' was the highest i.e., close to 700,000 m³. The only other sites to have a non-productive natural gas consumption higher than 100,000 m³ were sites 'J' and 'L'.

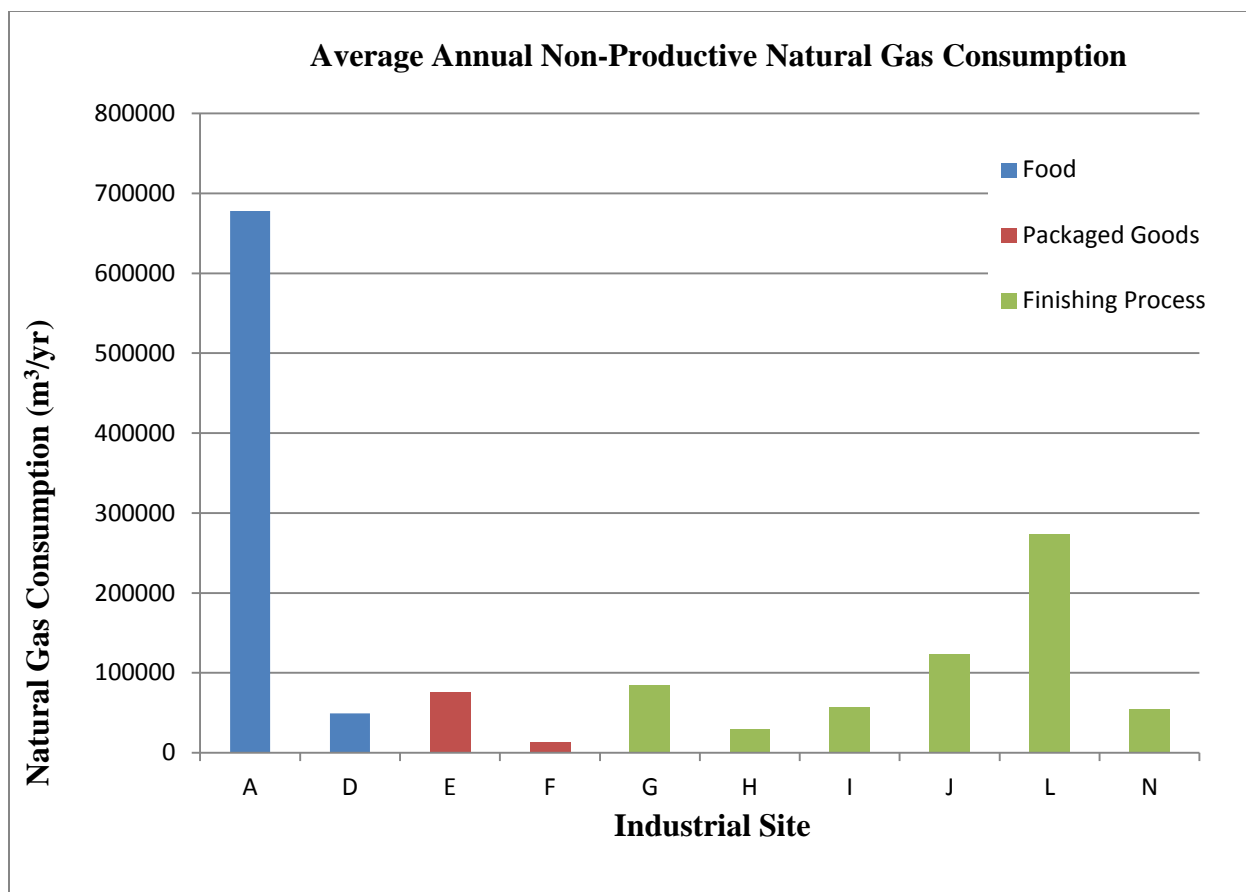


Figure 5.6 Annual non-productive natural gas consumption

The annual non-productive consumption of audited sites is presented in Table 5.4. It could be seen that site 'A' had the highest non-productive consumption at 677,810 m³ (20% of the annual consumption) for 2,520 of non-productive time hours (i.e., 29 % of the hours in a year). This implied that 20% of the annual natural gas consumption and fuel cost was incurred during the 29% of the time of year when the site was not making any product or income. Sites 'J' and 'L' had an even higher percentage non-productive consumption at 25% and 21% of the annual natural gas consumption respectively. However, the non-productive consumptions at sites 'J' and 'L' were spread over a longer period of time throughout the year i.e. 6,680 hours (76% of the year) and 6,760 hours (77% of the year) respectively. On the other hand site 'F' had the lowest non-productive consumption at 12,798 m³ for 360 hours of operation. The natural gas consumption for site 'F' was just 2% of the annual natural gas consumption for the site. Such a low consumption could be attributed to the fact that site 'F' operated on a 24 hours daily schedule with the only shut down on statutory holidays or for scheduled maintenance.

Table 5.4 Average annual non-productive natural gas consumption

Site	Average Annual Non Productive Consumption (m³/ yr)	Percentage of Annual Consumption (%)	Average Annual Non-Productive Time (h/yr)	Percentage of Total Hours in a Year (%)
A	677,810	20%	2,520	29
D	49,166	9%	1,272	15
E	75,710	8%	2,520	29
F	12,798	2%	360	4
G	844,18	13%	6,260	71
H	28,719	8%	5,120	58
I	56,490	13%	6,550	75
J	123,000	25%	6,680	76
L	273,395	21%	6,760	77
N	53,885	14%	6,160	64

The relationship between percentage non-productive time and percentage non-productive consumption was plotted as Figure 5.7. Generally with the increase in percentage non-productive time the percentage non-productive consumption also increased. Percentage non-productive time for the sites belonging to food sector and packaged goods sector remained below 30% of the time in a year. The percentage non-productive consumption for sites in the food and packaged goods sector remained below 20% of the annual natural gas consumption. For the sites in the finishing process sector the non-productive times were more than 55% of the year while the non-productive consumptions ranged from 8% to 25% of the annual natural gas consumption.

The increasing trend of percentage non-productive consumption with the increase in non-productive time implied that even when the industrial plants were not in operation some of the gas-fired equipment was kept running. Therefore, there is an opportunity to achieve considerable natural gas savings by reducing the non-productive natural gas consumption through better management and housekeeping practices.

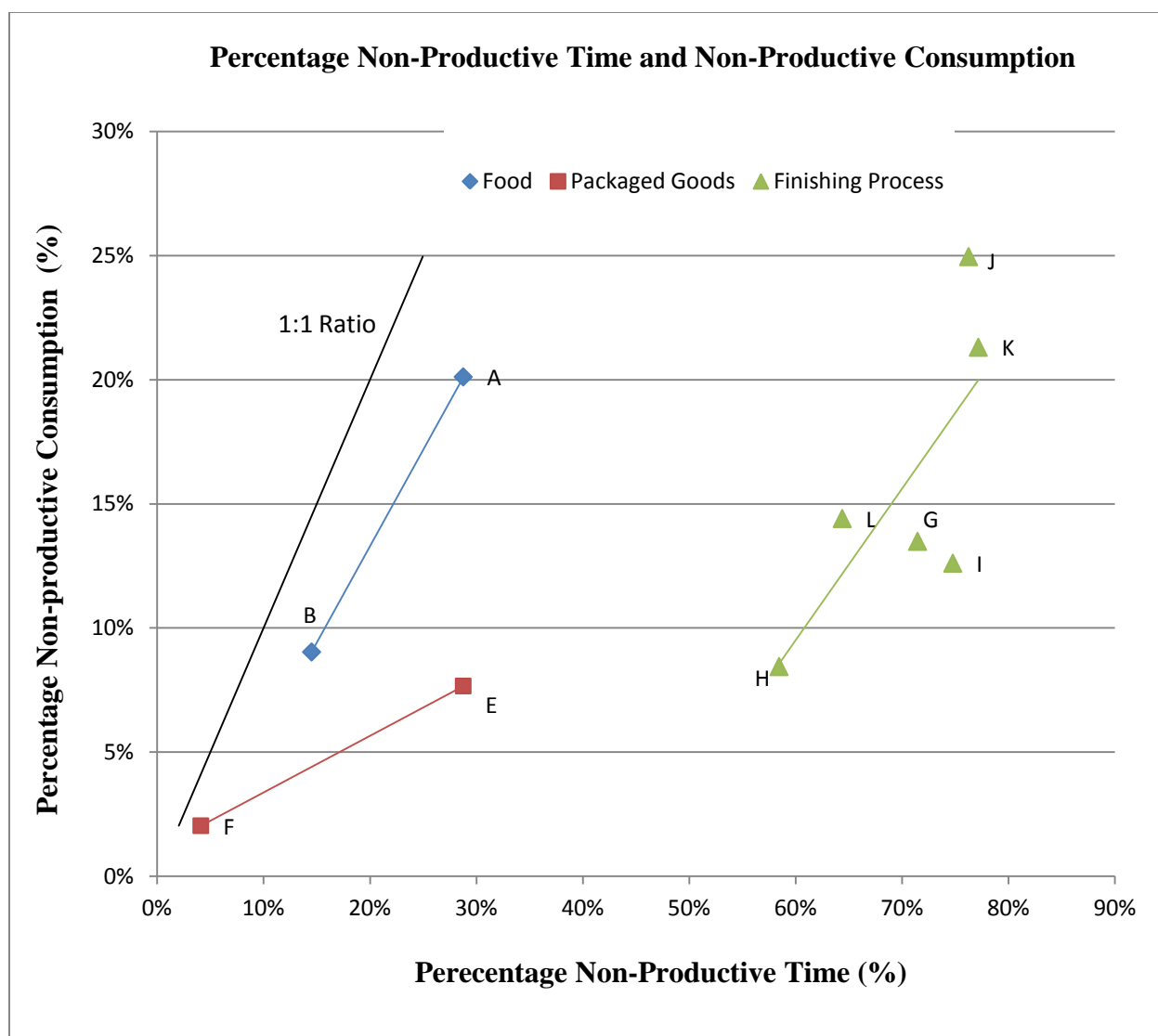


Figure 5.7 Percentage non-productive and percentage non-productive consumption

Average daily non-productive consumption was calculated and compared to average productive consumption for each of the audited sites. Non-productive consumption has been presented as a percentage of productive consumption in Table 5.5.

The percentage of non-productive consumption ranged from 29% to 72% of the productive consumption. This implied that even when the industrial plants were not in operation they were still consuming considerable amount of natural gas. This implied that the audited sites were incurring a considerable cost for the consumption of natural gas even when there was no production.

Table 5.5 Average daily non-productive natural gas consumption as a percentage of productive consumption

Site	Average Productive Time Consumption (m ³ /day)	Average Non-Productive Time Consumption (m ³ /day)	Non-Productive Consumption as a Percentage of Productive Consumption (%)
A	10,753	6,368	59
D	1,630	806	49
E	2,250	670	30
F	1,768	1,422	72
H	1,239	365	29
I	1,537	620	40
J	1,715	683	40
L	11,837	7,139	60
N	1,385	922	70

5.1.4 Normalized Natural Gas Consumption

Energy consumption in any facility is influenced by not only the processes and activities going on inside the facility but also the outside weather conditions especially the weather. As the weather drops the energy consumption for heating increases and vice versa. In order to determine the effect of outside temperature on natural gas consumption, linear regression analysis using PRISM was conducted. Heating degree days calculated from historical weather data from January 1, 1978 to May 31, 2013 was taken as the independent variable and natural gas consumption obtained from utility bills was taken as the dependent variable for each site. The linear regression analysis provided a base level consumption and a weather dependent consumption for each audited site. The base level consumption was termed as process consumption while the weather dependent consumption was termed as seasonal consumption. In addition selecting the Robust model determined the reference temperature (τ) for heating for each site. "The reference temperature for heating for an industrial site is the temperature at which no heating is required" [43]. However, if the outside temperature drops below the reference temperature

then heating would be required to maintain the indoor temperature. The results of the PRISM analysis are presented in Table 5.6.

Table 5.6 Results of linear regression analysis from PRISM

Site	Normalized Annual Consumption (NAC)	Process Consumption	Seasonal Consumption	Coefficient of Correlation
	(m ³ /yr)	(m ³ /yr)	(m ³ /yr)	(R ²)
A	3,413,970	2,674,165	739,805	0.696
B	676,108	445,394	230,714	0.482
C	1,044,810	875,345	169,465	0.525
D	536,523	482,606	53,917	0.654
E	1,040,758	577,809	462,949	0.907
F	656,815	424,035	232,780	0.676
G	591,037	448,844	142,193	0.737
H	366,655	258,624	108,032	0.944
I	458,033	444,432	13,601	0.097
J	485,668	310,243	175,426	0.861
K	302,332	184,472	117,861	0.670
L	1,187,717	192,107	995,610	0.928
M	999,810	191,412	808,398	0.898
N	412,363	60,978	351,385	0.761
O	150,061	100,369	49,693	0.309

Linear regression analysis conducted using PRISM allowed the natural gas consumption to be classified into two distinctly identifiable categories i.e. process and seasonal consumption which are presented in Figure 5.8. In addition it also provided the normalized annual consumption based on historical weather data of the past 35 years.

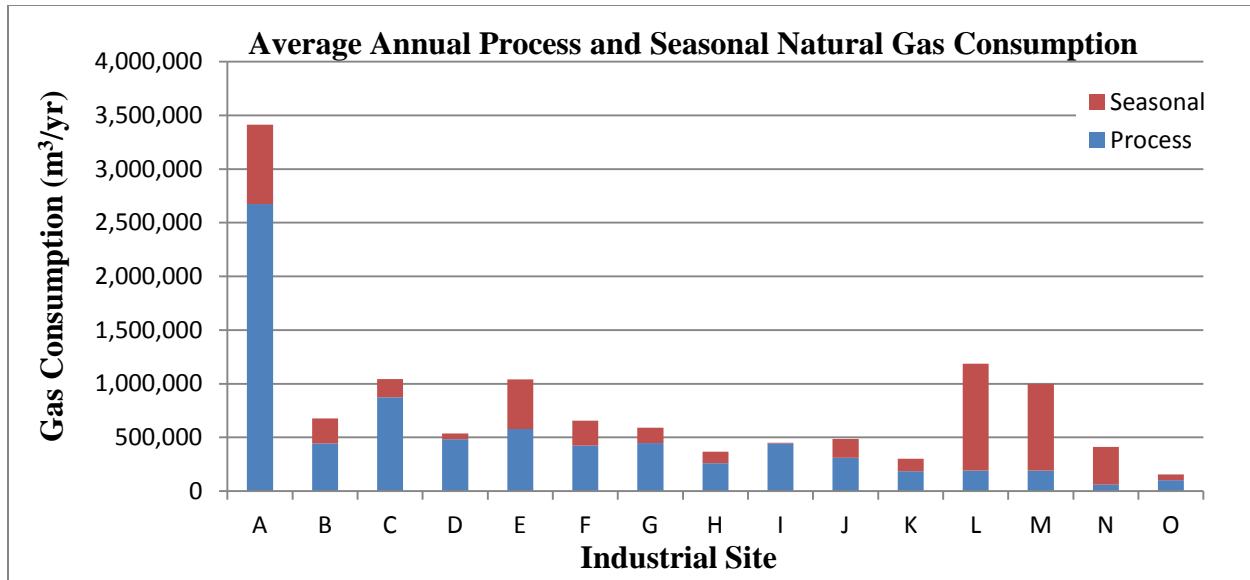


Figure 5.8 Process and seasonal natural gas consumption

It is evident from Figure 5.8 that a major portion of natural gas consumption is for process end-use. Only sites 'L', 'M' and 'N' which had a lot of drying and curing activity in the ovens had a greater seasonal consumption than process consumption.

In order to remove any bias because of the size of the plant, natural gas consumption was normalized using site area and volume and the results were plotted in Figure 5.9 and Figure 5.10.

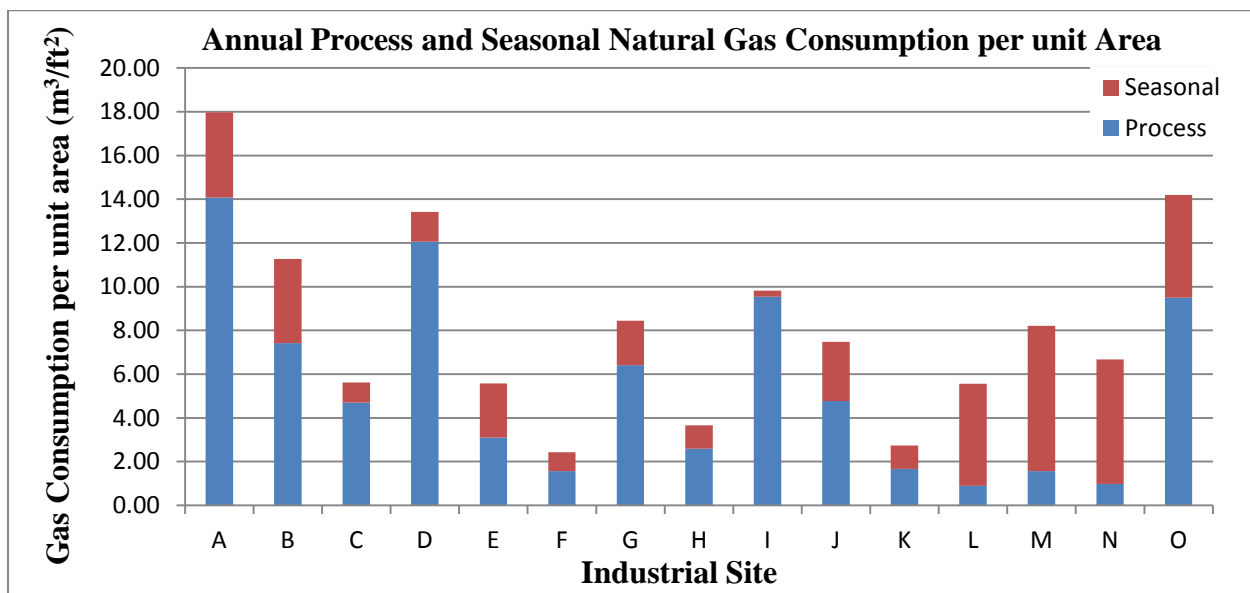


Figure 5.9 Process and seasonal natural gas consumption per unit area

The process consumption normalized with respect to area for the industries from food sector was from 5 to 14 m³/ft² while the normalized seasonal consumption was between 1 to 4 m³/ft². For the industries belonging to the packaged food industries the normalized process consumption was between 1.5 to 3 m³/ft² while the normalized seasonal consumption was between 1 to 2.5 m³/ft².

In the finishing process sector the process consumption per unit of sites was between 1 to 9.5 m³/ft². The seasonal consumption per unit area varied from 0.3 to 7 m³/ft². Sites 'L', 'M' and 'N' 'O' had the higher normalized seasonal consumption compared other industries in the group. Site 'O' which was among the lowest consumer on the basis of annual seasonal natural gas consumption emerged as one of the highest consumers on the basis of seasonal consumption per unit area.

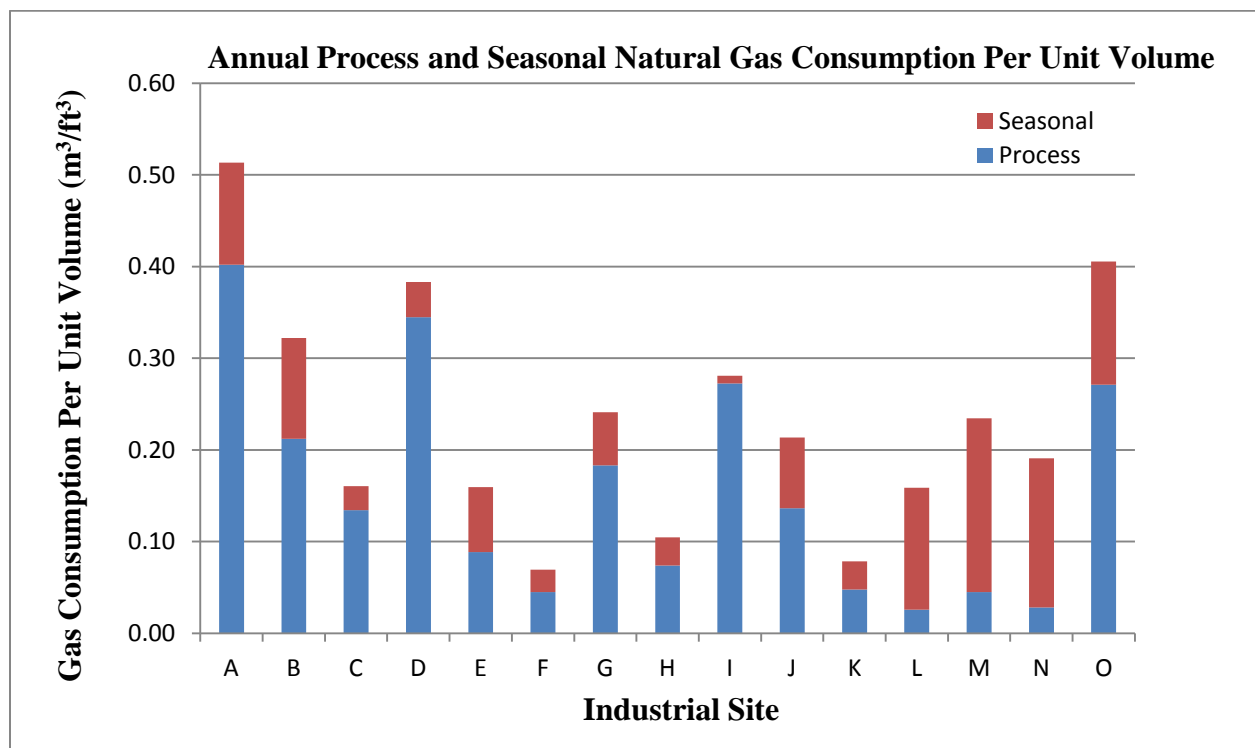


Figure 5.10 Process and seasonal natural gas consumption per unit volume

The process consumption normalized with respect to volume for the industries from food sector was from 0.1 to 0.4 m³/ft³ while the normalized consumption was between 0.03 to 0.11 m³/ft³. For the industries belonging to the packaged food industries the normalized process consumption

was between 0.09 to 0.34 m³/ft³ while the normalized seasonal consumption was between 0.02 to 0.07 m³/ft³. In the finishing process sector the normalized process consumption of sites was between 0.03 to 0.3 m³/ft³. Site 'O' emerged as one of the highest consumer in terms of seasonal consumption when normalized with respect to area and volume.

In addition to statistical results PRISM also returned three important physical parameters for each audited sites. These parameters were daily base level consumption (α_h), daily weather dependent consumption (β_h) and reference temperature "(at which neither heating nor cooling is required)" [43]. These are shown in Table 5.7.

Table 5.7 Physical parameters obtained from PRISM analysis

Site	Daily Base Level Consumption (α_h) (m ³ /day)	Consumption per heating degree day (β_h) (m ³ /°F day)	Reference Temperature (τ) (°F)
A	7321.5	95.4	67.0
B	1219.4	14.6	90.0
C	2396.6	21.9	67.0
D	1321.3	21.3	43.1
E	1582	89.4	57.4
F	1160.9	49.3	55.4
G	1228.9	17.7	68.0
H	708.1	27.7	51.6
I	1216.8	14.3	32.0
J	849.4	29.4	60.5
K	505.1	26.0	54.6
L	526.0	189.4	57.7
M	524.1	225.7	50.1
N	166.9	39.0	71.0
O	274.8	350.4	87.0

The overall annual consumption (which is the sum of process and seasonal consumption), process consumption and seasonal consumption per unit area were plotted against the reference temperature for each of the audited sites as shown in Figure 5.11, Figure 5.12 and Figure 5.13.

Figure 5.11 shows annual consumption per unit area for each site plotted against the reference temperature for each site. Site 'F' had the lowest overall consumption per unit area at $2.43 \text{ m}^3/\text{ft}^2$ while site 'A' had the highest overall consumption per unit area at approximately $18 \text{ m}^3/\text{ft}^2$. Site 'T' had the lowest reference temperature at 32°F and had an overall gas consumption per unit area of approximately $10 \text{ m}^3/\text{ft}^2$. Site 'B' had the highest reference temperature at 90°F and gas consumption per unit area of approximately $11.3 \text{ m}^3/\text{ft}^2$.

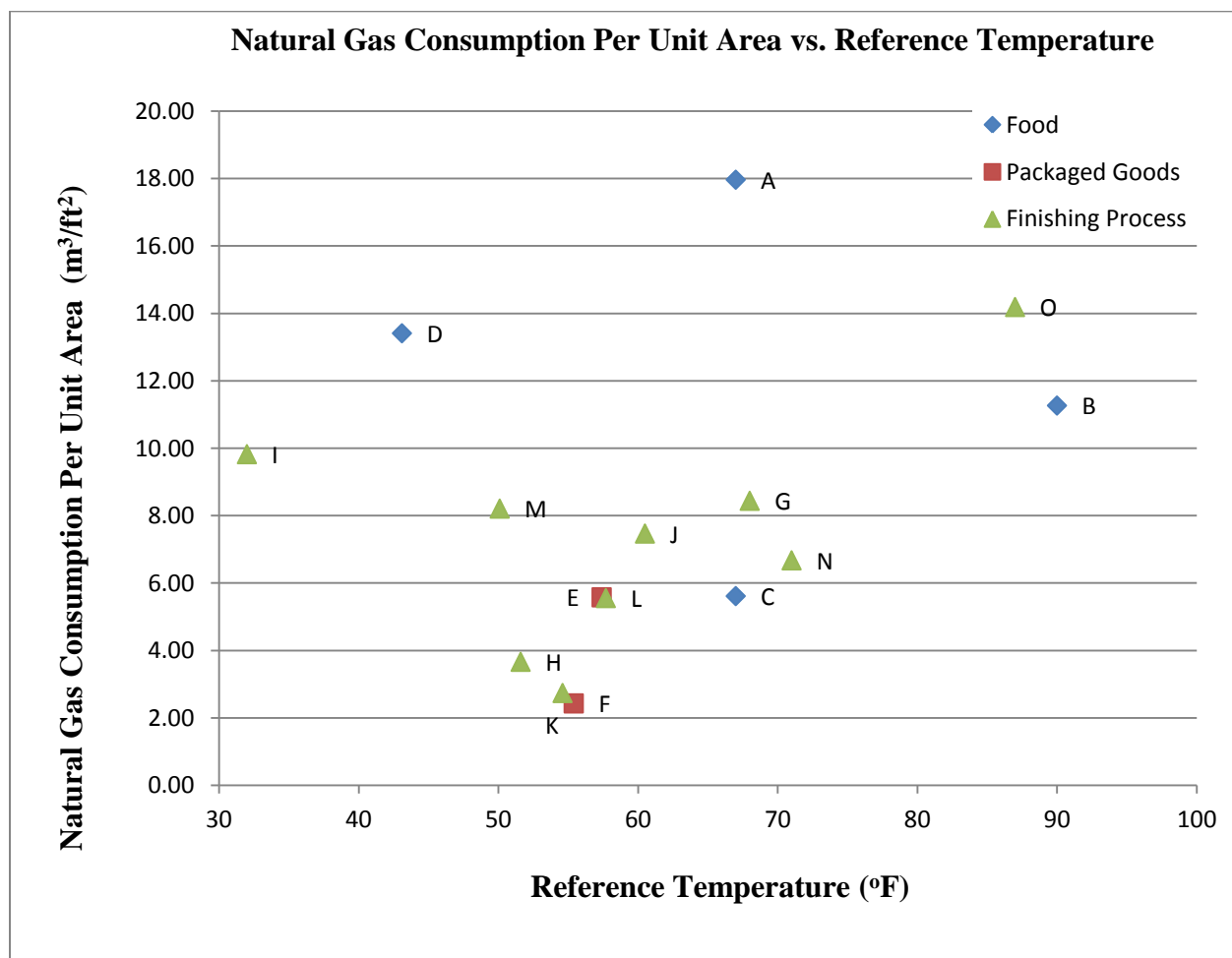


Figure 5.11 Overall consumption per unit area vs. reference temperature

Figure 5.12 shows process consumption per unit area for each site plotted against the reference temperature for each site. Site 'L' had the lowest process consumption per unit area at $0.9 \text{ m}^3/\text{ft}^2$ while site 'A' had the highest overall consumption per unit area at approximately $14 \text{ m}^3/\text{ft}^2$. Site 'T' which had an overall consumption per unit area of approximately $10 \text{ m}^3/\text{ft}^2$ exhibited a process consumption per unit area of approximately $9.5 \text{ m}^3/\text{ft}^2$ which implied that approximately 95% of the consumption at site 'T' was used for process consumption.

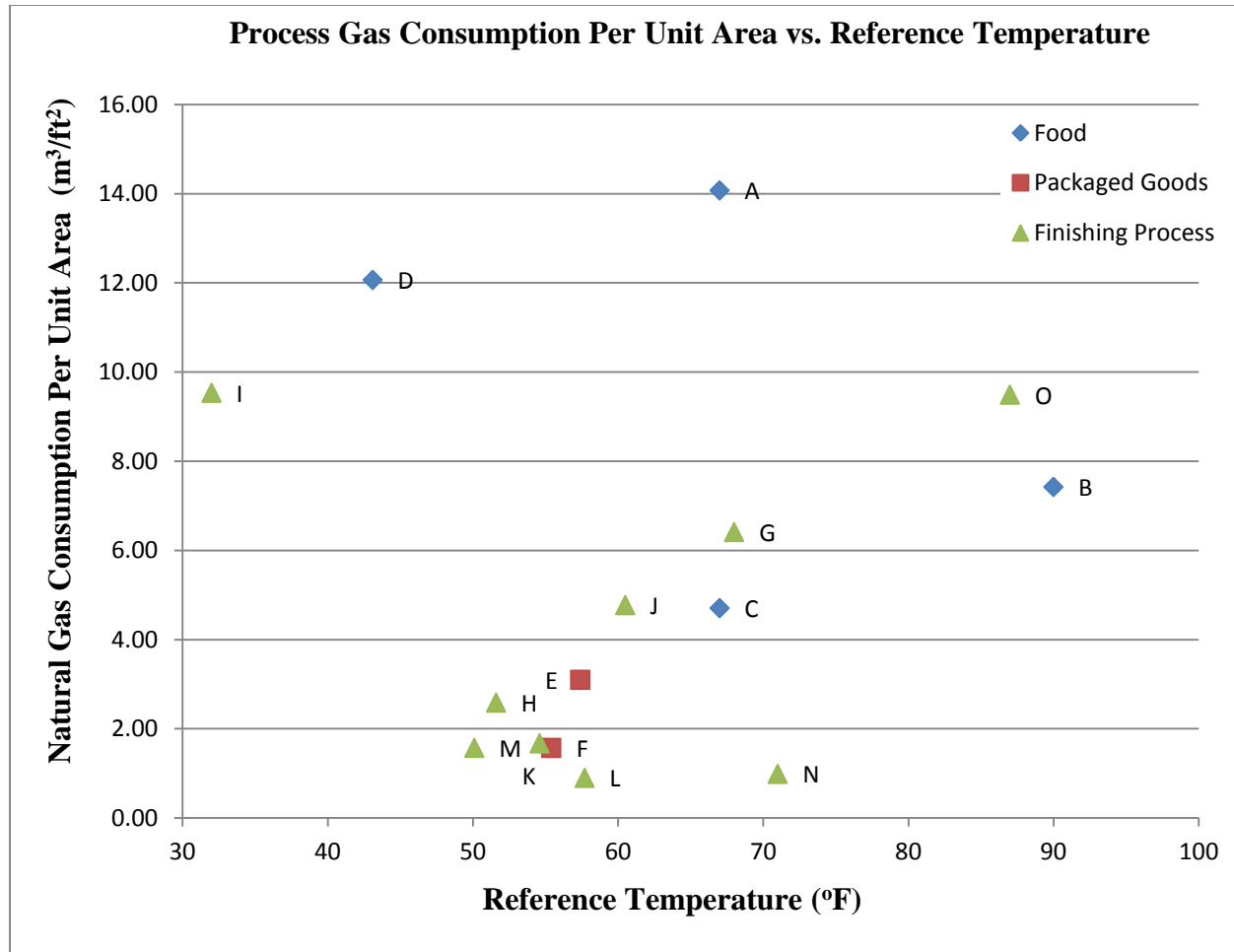


Figure 5.12 Process consumption per unit area vs. reference temperature

Figure 5.13 shows seasonal consumption per unit area plotted against the reference temperature for each site. Site 'M' had the highest seasonal consumption per unit area at approximately $6.6 \text{ m}^3/\text{ft}^2$ followed by site 'N', 'L' and 'O'. Site 'T' that had the lowest reference temperature at 32°F also had the lowest seasonal consumption per unit area at $0.29 \text{ m}^3/\text{ft}^2$. Apart from site 'T' all other sites from finishing process industry had seasonal consumption above $1 \text{ m}^3/\text{ft}^2$. Sites from the

food sector had seasonal consumption higher than 1 m³/ft² except site 'C'. Sites 'E' and 'F' from the packaged goods sector had seasonal consumption per unit area of 2.5 m³/ft² and 0.9 m³/ft² respectively.

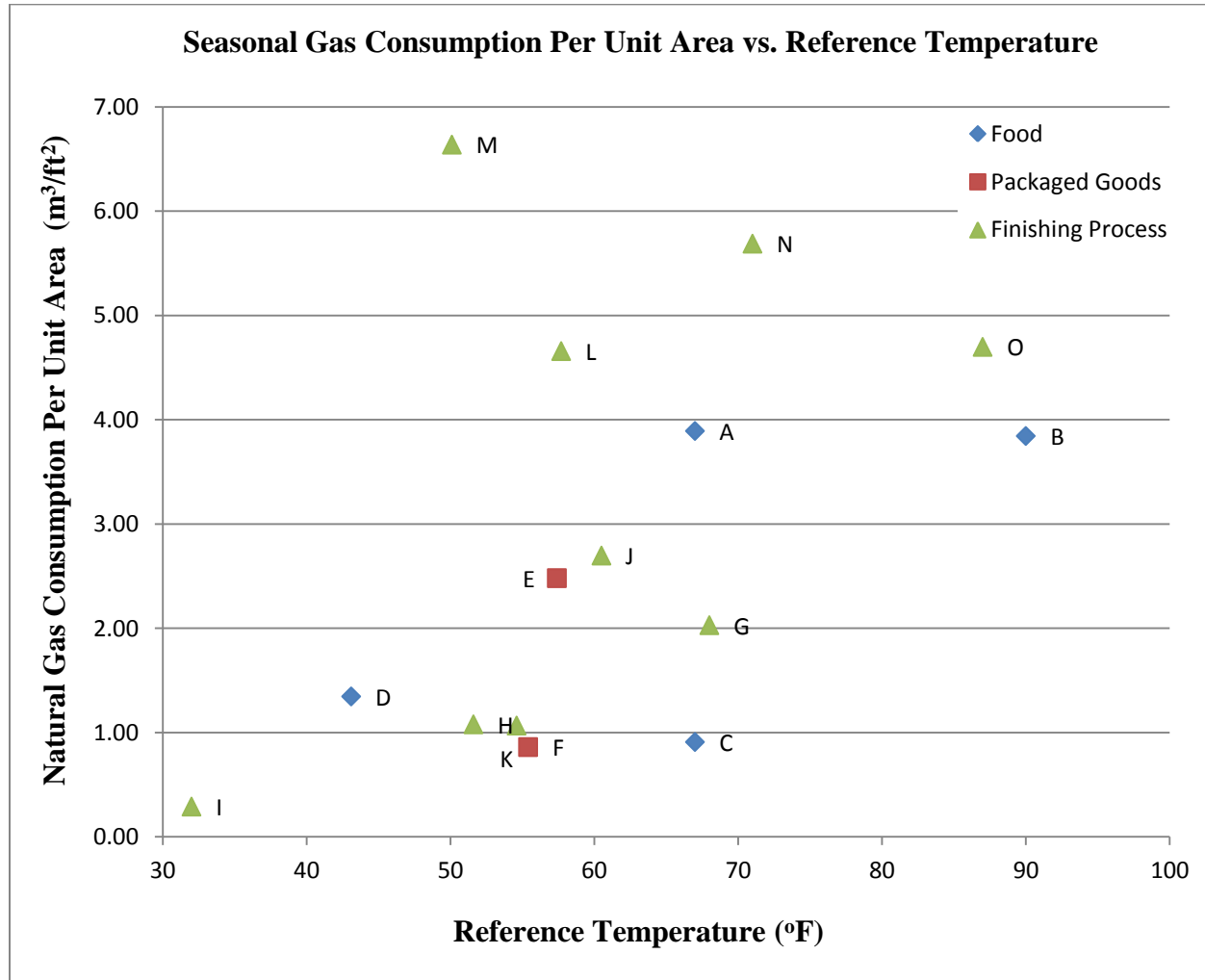


Figure 5.13 Seasonal consumption per unit area and reference temperature

The daily weather dependent consumption (β_h) is an important parameter obtained as a result of PRISM analysis. This parameter is important as it allows comparison between sites irrespective of the industry sector, size and type of industry. The parameter β_h is dependent on the building envelope. It represents the weather dependent natural gas consumption required to maintain the inside temperature of the building. Hence, building envelope of different sites can be compared by comparing β_h for different buildings. The daily weather dependent consumption β_h was plotted against the reference temperature for each of the audited sites as shown in Figure 5.14.

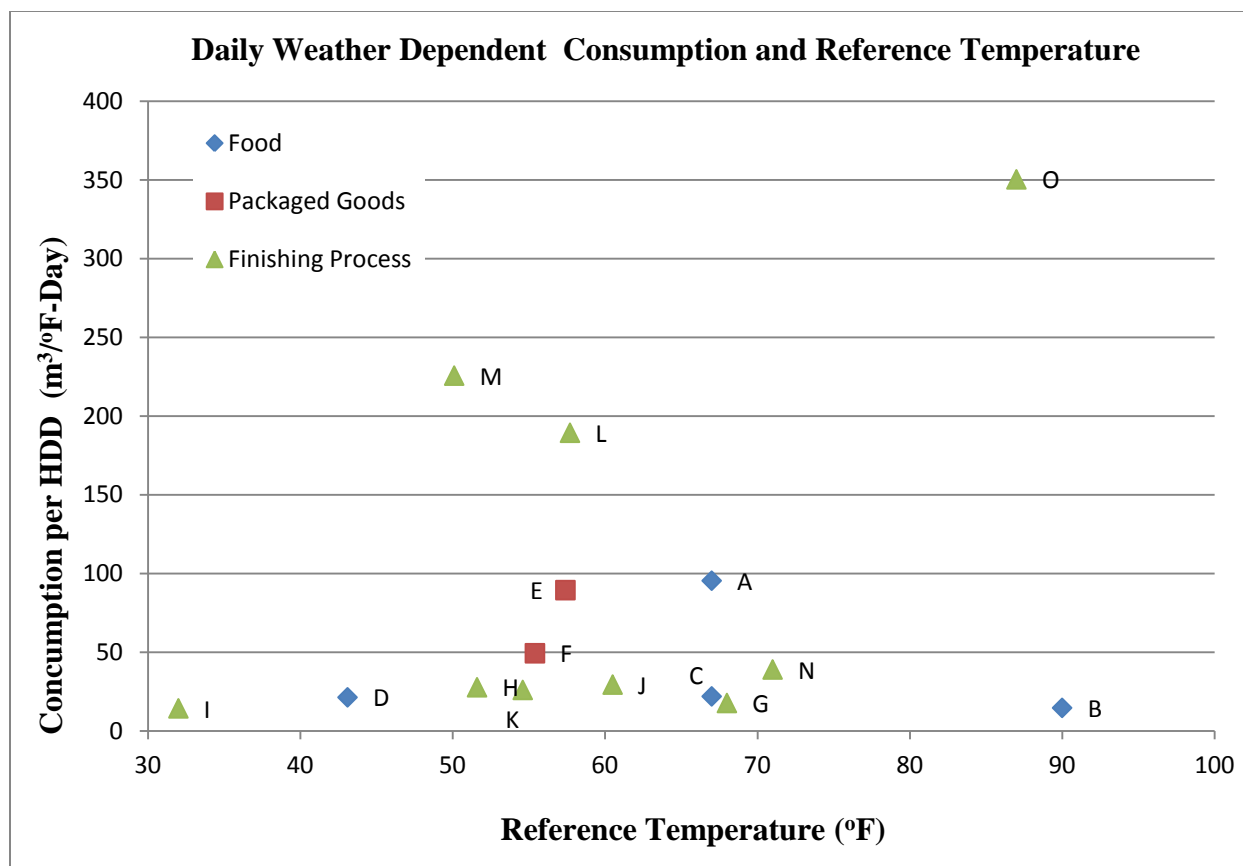


Figure 5.14 Weather dependent consumption of audited sites

Daily weather dependent consumption for sites from the food sector as well as from the finishing process industry remained below 50 m³/°F Day and showed little fluctuation with the increase in reference temperature. Site 'A' from the food sector and sites 'L', 'M' and 'O' had daily weather dependent consumption higher than 100 m³/°F Day. Sites 'E' and 'F' from the packaged goods sector showed an increase in daily weather dependent consumption with increase in reference temperature. Site 'O' had the highest natural gas consumption per degree day at 350 m³/°F Day while site 'I' had the lowest natural gas consumption per degree day at 14.3 m³/°F Day. This implied that whenever outside temperature would be colder than normal site 'O' would require the greatest amount of natural gas per degree day, while 'I' would require the least amount of natural gas per degree day.

Seasonal consumption was further classified into consumption for ventilation and consumption for space heating. These were plotted against site area as shown in Figure 5.15 and Figure 5.16.

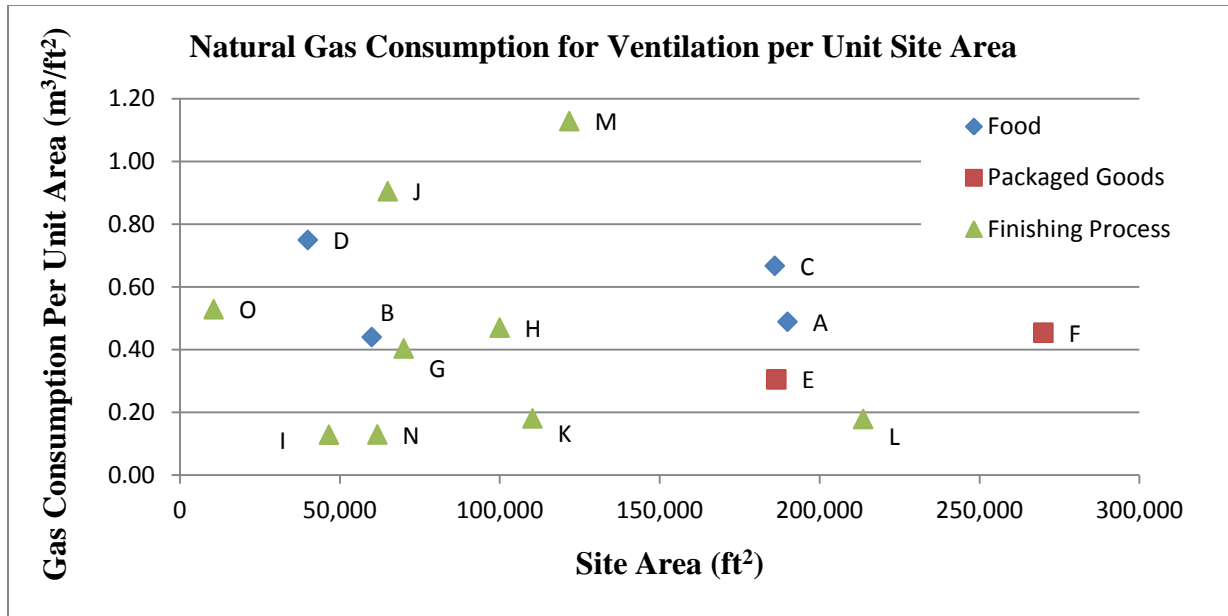


Figure 5.15 Natural gas consumption for ventilation per unit area vs. site area

Natural gas consumption for ventilation per unit area for food sector was found to be between $0.40 \text{ m}^3/\text{ft}^2\text{yr}$ and $0.80 \text{ m}^3/\text{ft}^2\text{yr}$. Industries from packaged goods sector ranged between 0.3 and $1.20 \text{ m}^3/\text{ft}^2\text{yr}$ and 0.45 $1.20 \text{ m}^3/\text{ft}^2\text{yr}$. The finishing process sector was found to be between $0.13 \text{ m}^3/\text{ft}^2\text{yr}$ and $1.20 \text{ m}^3/\text{ft}^2\text{yr}$.

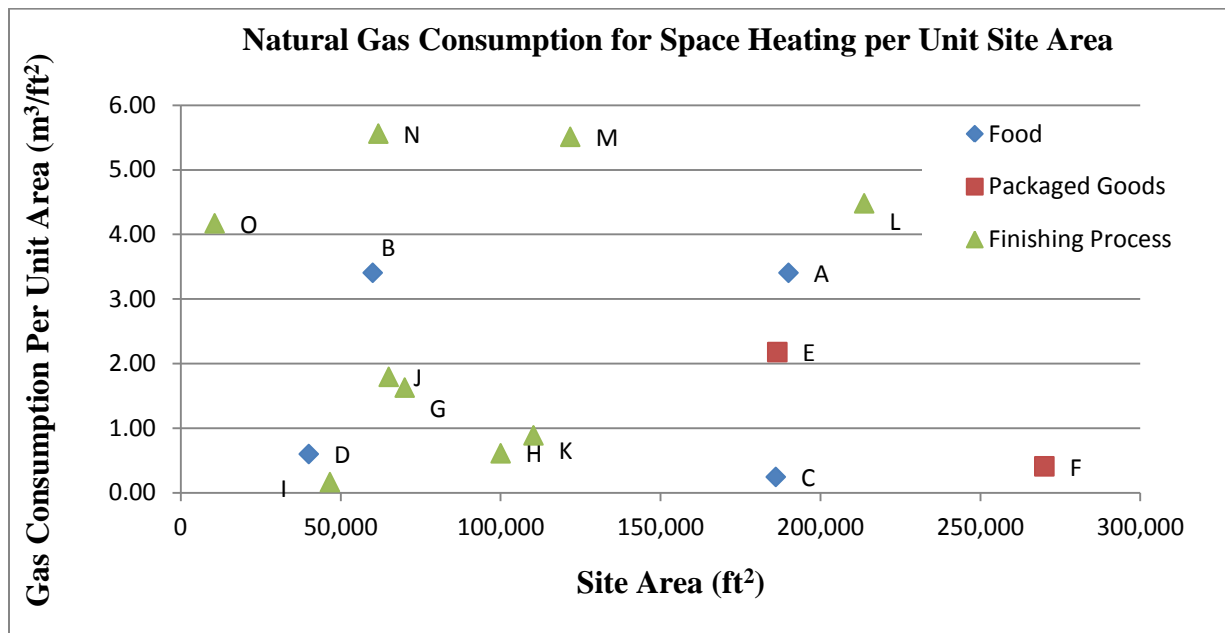


Figure 5.16 Natural gas consumption for space heating per unit area vs. site area

Natural gas consumption for space heating per unit area for food sector was found to be between 0.24 m³/ft²yr and 3.40 m³/ft²yr. Industries from packaged goods sector showed decreasing trend with the increase in site area. In the finishing process sector was found to be between 0.1 m³/ft²yr and 5.50 m³/ft²yr.

PRISM analysis also determined the coefficient of correlation (R^2). This coefficient was used to gauge the extent to which the natural gas consumption was related to the heating degree days. The coefficients of correlation for the audited sites were plotted against the reference temperature of each site as shown in Figure 5.17.

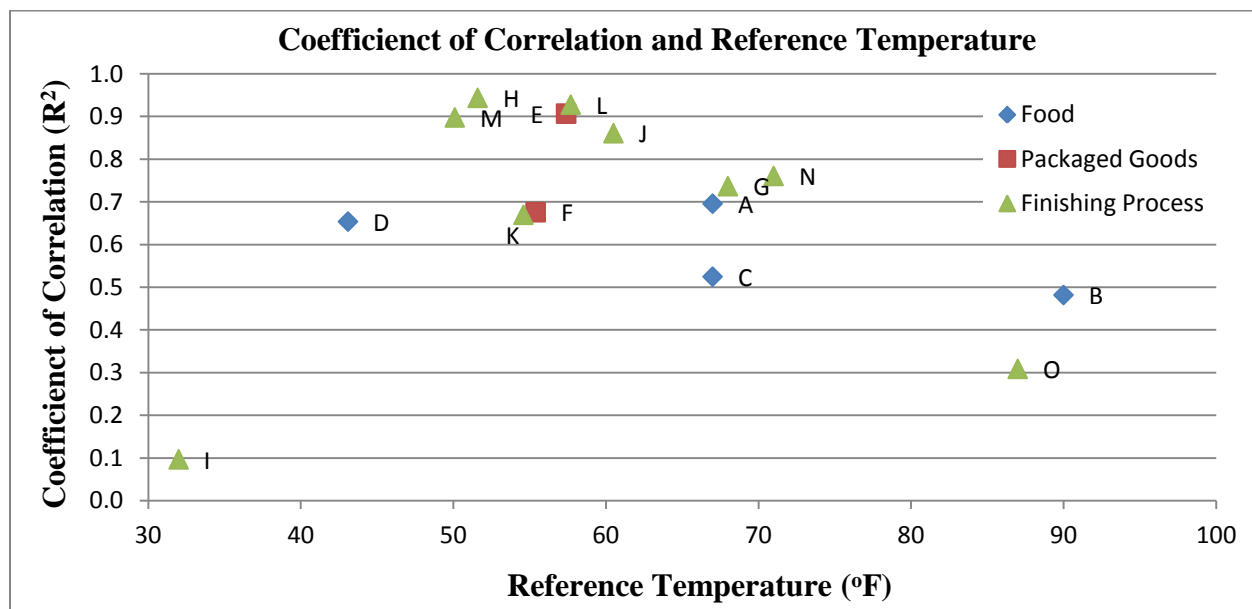


Figure 5.17 Coefficient of correlation and reference temperature

For the PRISM model to have good correlation, it is necessary that coefficient of correlation to be higher than 0.7. Eight out of the 15 audited sites had an R^2 value higher than 0.7 which implied good correlation between heating degree days and natural gas consumption. However, there were seven sites that had a value lower than 0.7. It could be concluded that the assumption of constant average base level consumption throughout the year did not apply to these seven sites. These seven sites had busy seasons in summer when the number of heating degree days is low. Instead of having high natural gas consumption in winter those seven industrial sites had high natural gas consumption in summer. The fact that the production of those seven sites varied

throughout the year resulted in lower coefficients of correlation for those sites. This discrepancy could be remedied by conducting a multivariable regression analysis using heating degree days and production output of the plant as the variables. Production data for the audited sites were not available and hence, the multivariable regression analysis could not be conducted.

5.2 Major Gas-Fired Equipment

Major gas-fired equipment observed during site audits were boilers and ovens. The performance of these equipment were analyzed to identify energy saving opportunities.

5.2.1 Boiler Performance

There were six sites that had at least one boiler. The combustion and fuel to steam efficiency of the each of the boilers tested at those sites are presented in Table 5.8.

Table 5.8 Combustion and fuel to steam efficiencies of boilers at audited sites

Site	Boiler Number	Combustion Efficiency (%)	Fuel to Steam Efficiency (%)
A	1	75.9	68.4
	2	73.4	66.1
	3	77.8	71.0
B	1	83.9	81.2
C	1	82.2	80.5
	2	82.3	80.6
	3	81.2	79.5
D	1	82.4	78.3
E	1	84.0	82.7
	2	82.5	80.8
F	1	82.8	79.8

The efficiencies of boiler were plotted along with their ages in a quadrant chart shown in Figure 5.18 and Figure 5.19. Each point on the chart was labeled by the letter that represents the

industrial site at which the boiler was located. Furthermore, wherever there were more than one boiler at one site the boiler number was added to the label after the site name e.g. a label C, B1 represents boiler number '1' at site 'C'. The charts were plotted using age on the horizontal axes while the efficiencies were taken along the vertical axes.

The first (upper right) quadrant represented boilers that were more than 25 years old but still had high efficiency. The threshold for combustion efficiency was chosen as 80% while that for fuel to steam efficiency was 75%. This quadrant represented the boilers that had been well maintained to have high efficiencies. The second (upper left) quadrant had the boilers that had high efficiencies but were less than 25 years old. Hence, those were the boilers whose high efficiency can be attributed to them being new. The second quadrant is the one where newly installed boilers are expected to be. The third (lower left) quadrant had the boilers that were less than 25 years old but also had lower efficiencies most likely due to malfunction. The fourth quadrant had the boilers that were more than 25 years old and lower efficiencies. The boilers that are near the end of their life were expected to be in this quadrant.

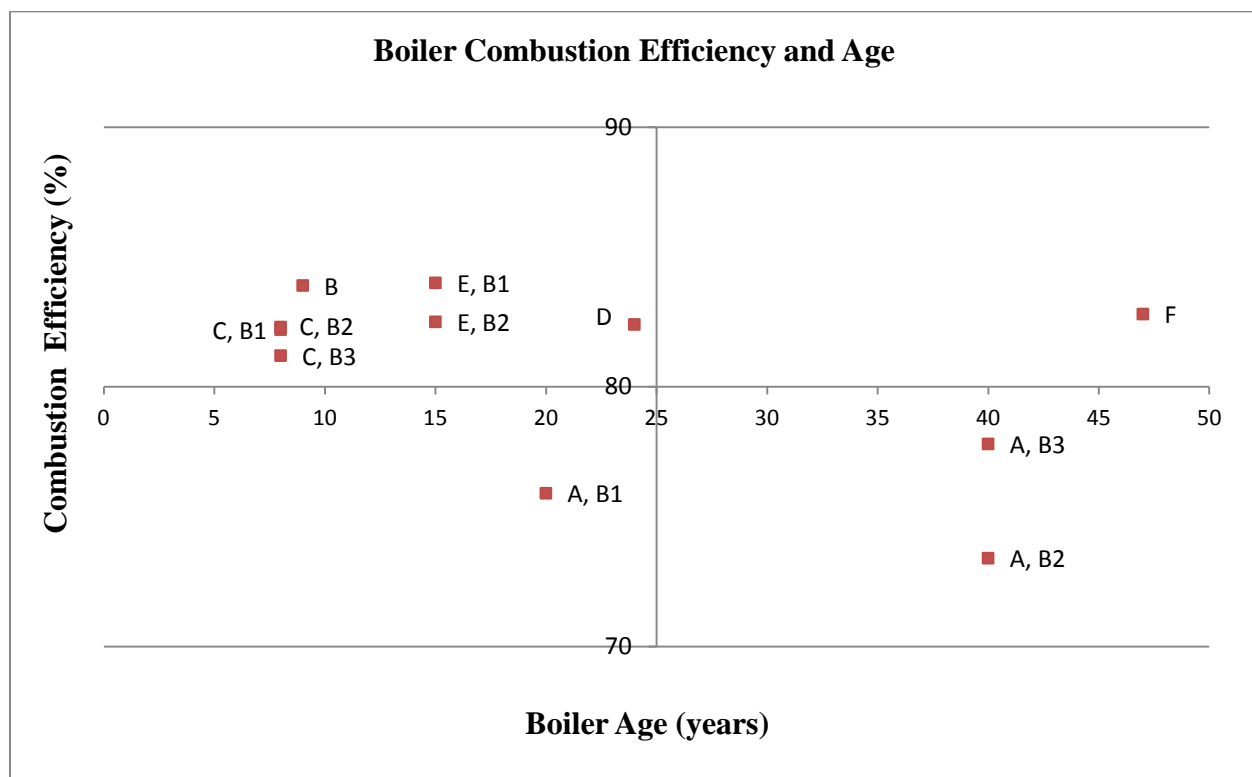


Figure 5.18 Boiler combustion efficiency vs. age

It is evident from Figure 5.18 that most of the boilers tested had more than 80% combustion efficiency. The boilers from site 'A' were the exception and had lower than 80% combustion efficiency. Boilers '2' and '3' from site 'A' were both 40 years old and were expected to have become less efficient over the years but boiler '1' from site 'A' was 20 years old. Low efficiency for that boiler was indicative of malfunction. The only boiler at site 'F' had a higher than 80% efficiency despite being 47 years old. This implied that the boiler was properly maintained and was still capable of operating with high efficiency.

The quadrant chart for fuel to steam efficiency and age in Figure 5.19 followed the same pattern as that of the combustion efficiency in Figure 5.18 except that the threshold of efficiency was 75% instead of 80%. This was chosen because fuel to steam efficiency is generally less than combustion efficiency on account of other losses, in addition to the stack losses.

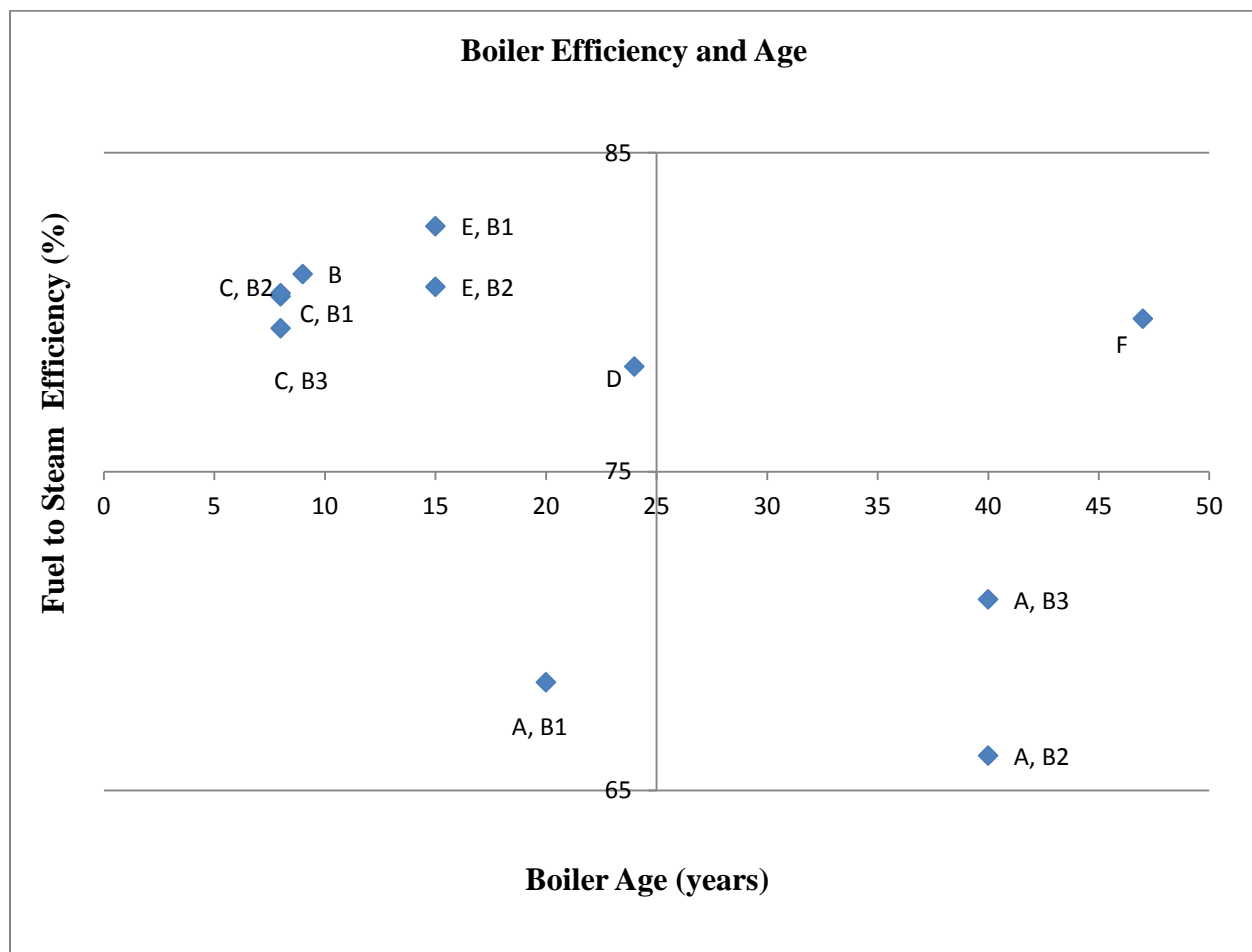


Figure 5.19 Boiler efficiency vs. age

Combustion efficiencies of boilers were also plotted against flue gas temperature as shown in Figure 5.20. Combustion efficiencies showed a decreasing trend with increase in flue gas temperature. All the boilers that had flue gas temperature lower than 450 °F had combustion efficiencies above 80%. When the flue gas temperature is high a lot of energy released from combustion of fuel is used to heat the products of combustion which are then exhausted and therefore, the efficiency is lowered.

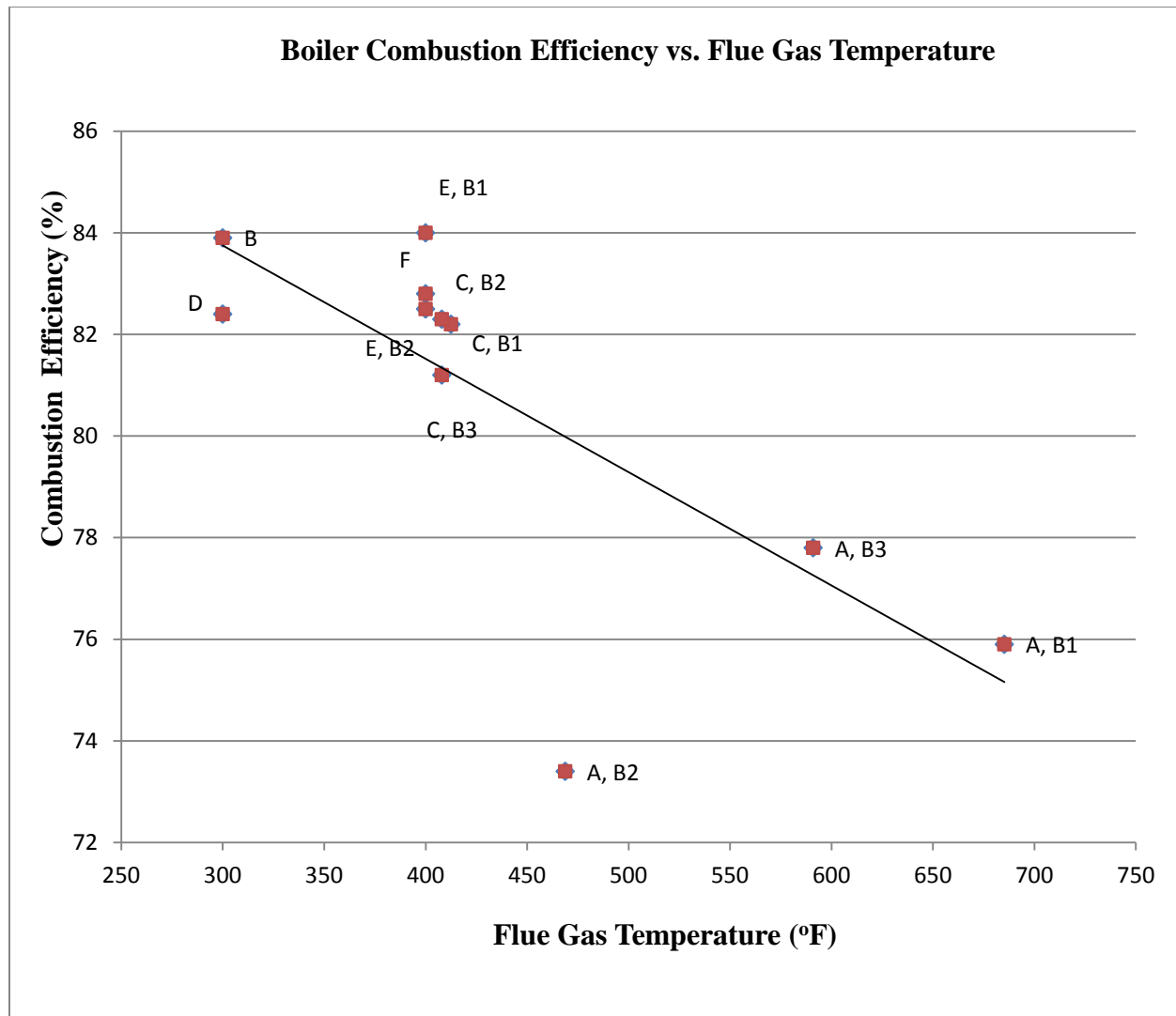


Figure 5.20 Boiler efficiencies and flue gas temperature

Combustion efficiencies of boilers were plotted against rated capacities of boilers as shown in Figure 5.21. Apart from the boilers from site 'A' combustion efficiencies did not appear to vary greatly with boiler rating.

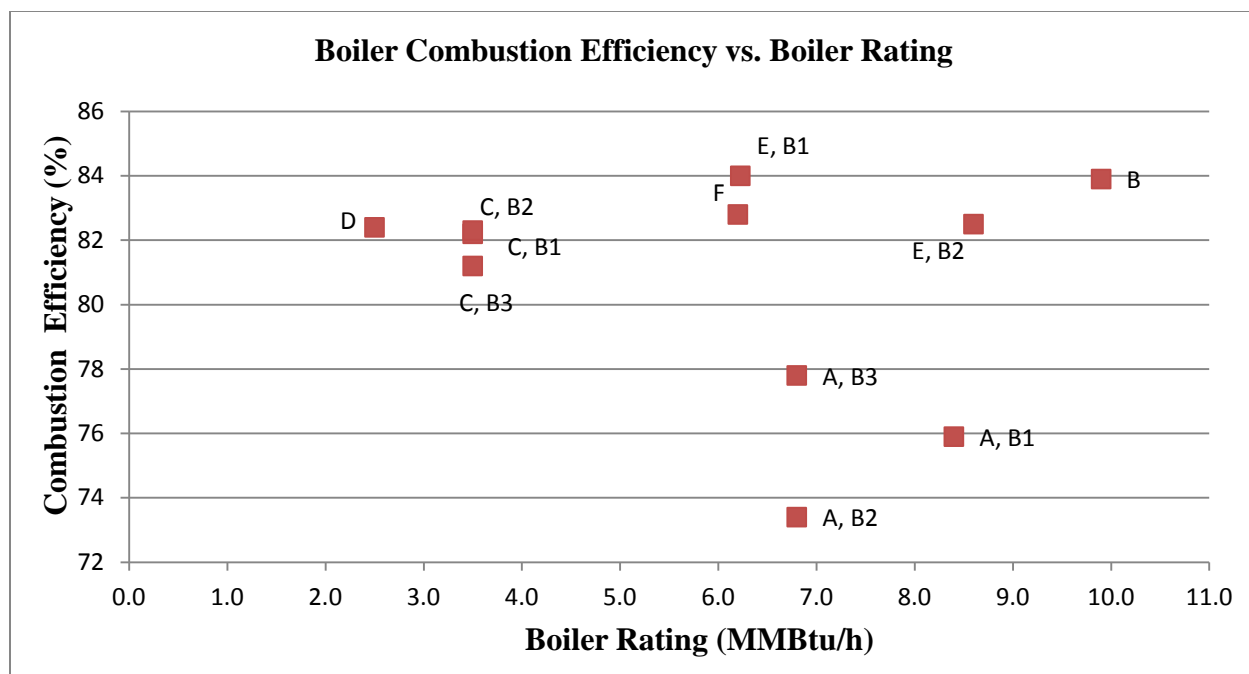


Figure 5.21 Boiler efficiencies and boiler rating

Natural gas consumptions of the boilers were estimated using the information such as firing rates and hours of operation from the boiler logs. Gas consumptions of boilers were compared against the annual consumption of the audited sites and tabulated as Table 5.9.

Table 5.9 Estimated boiler consumption as a percentage of total annual consumption of the site

Site	Consumption (m ³ /yr)	Cost (\$/yr)	Percentage of Annual Consumption (%)
A	1,288,334	290,777	38
B	344,917	77,848	51
C	616,255	139,089	59
D	152,500	344,19	28
E	553,165	124,849	56
F	293,835	66,319	47

The boiler consumptions at the audited sites ranged from 28% such as site 'D' to 59% for site 'C'. Therefore, it was justifiable to focus on the boilers to identify energy saving opportunities.

5.2.2 Ovens

Eleven sites out of the fifteen audited sites were found to have ovens. The ovens seen at sites belonging to food sector were bake ovens while the ones found at finishing process industry were dry-off ovens and cure ovens.

There was no provision in the stack to insert the flue gas analyzer. Hence, the combustion efficiencies could not be determined. However, the heat input to the oven could be estimated and compared with the annual consumption of audited sites as shown in Table 5.10.

Table 5.10 Estimated oven consumptions as a percentage of annual consumption of audited sites

Site	Type	Consumption	Cost	Oven Consumption as a Percentage of Annual Consumption	Combined Oven Consumption of Oven as a Percentage of Annual Consumption
		(m ³ /yr)	(\$/yr)	(%)	(%)
A	bake oven	848,676	191,546	25	25
D	bake oven	366,000	82,606	54	54
G	dry off	121,134	27,340	19	42
	cure	140,804	31,780	23	
H	dry off	119,317	26,930	35	71
	cure	121,134	27,340	36	
I	dry off	90,000	10,157	20	42
	cure	100,000	11,285	22	
J	dry off	90,596	20,448	18	42
	cure	119,509	26,973	24	
K	dry off	68,143	15,380	23	58
	cure	100,394	22,659	35	
L	dry off	313,444	70,744	24	46
	cure	288,369	65,085	22	
M	dry off	221,687	50,035	25	60
	cure	310,361	70,049	35	
N	dry off	183,365	41,385	49	73
	cure	88,015	19,865	24	
O	dry off	32,565	7,350	21	55
	cure	52,809	11,919	34	

5.3 Energy Saving Measures

Energy saving measures were analyzed and the natural gas savings along with the associated fuel cost savings and greenhouse emissions reduction were calculated.

5.3.1 Reduction in Non-Productive Consumption

The magnitude of non-productive consumption was calculated and estimates of savings achieved by reducing non-production consumptions were made. For this purpose energy savings achieved by reducing the non-productive time energy consumption by 25%, 50%, 75% and 100% were calculated along with the accompanying cost savings and reduction in greenhouse gas emissions. The natural gas savings achieved by reducing non-productive consumption are presented in Table 5.11.

Table 5.11 Natural gas savings achieved by reducing non-productive consumption

Site	Base Case (0 % Reduction) (m ³ /yr)	25% Reduction (m ³ /yr)	50% Reduction (m ³ /yr)	75% Reduction (m ³ /yr)	100 % Reduction (m ³ /yr)
A	677,810	169,453	338,905	508,358	677,810
D	49,166	12,292	24,583	36,875	49,166
E	75,710	18,928	37,855	56,783	75,710
F	12,798	3,200	6,399	9,599	12,798
G	84,418	21,105	42,209	63,314	84,418
H	28,719	7,180	14,360	21,539	28,719
I	56,490	14,123	28,245	42,368	56,490
J	123,000	30,750	61,500	92,250	123,000
L	273,395	68,349	136,698	205,046	273,395
N	53,885	13,471	26,943	40,414	53,885

The annual fuel cost savings would reduce proportionately as a result of reducing natural gas consumption. The fuel cost savings achieved by reducing non-productive consumption are shown in Table 5.12.

Table 5.12 Fuel cost savings achieved by reducing non-productive consumption

Site	Base Case 0 % Reduction (\$/yr)	25% Reduction (\$/yr)	50% Reduction (\$/yr)	75% Reduction (\$/yr)	100 % Reduction (\$/yr)
A	152,982	38,245	76,491	114,736	152,982
D	11,097	2,774	5,548	8,323	11,097
E	17,088	4,272	8,544	12,816	17,088
F	2,889	722	1,444	2,166	2,889
G	19,053	4,763	9,527	14,290	19,053
H	6,482	1,620	3,241	4,861	6,482
I	12,750	3,187	6,375	9,562	12,750
J	27,761	6,940	13,881	20,821	27,761
L	61,705	15,426	30,853	46,279	61,705
N	12,162	3,040	6,081	9,121	12,162

In addition to fuel and cost savings a reduction in non-productive consumption would also benefit the environment in the form of reduced greenhouse gas emissions as shown in Table 5.13.

Table 5.13 Reduction in greenhouse gas emissions achieved by reducing non-productive consumption

Site	Base Case 0 % Reduction (tonnes CO ₂ /yr)	25% Reduction (tonnes CO ₂ /yr)	50% Reduction (tonnes CO ₂ /yr)	75% Reduction (tonnes CO ₂ /yr)	100 % Reduction (tonnes CO ₂ /yr)
A	1,274	318	637	955	1,274
D	92	23	46	69	92
E	142	36	71	107	142
F	24	6	12	18	24
G	159	40	79	119	159
H	54	13	27	40	54
I	106	27	53	80	106
J	231	58	116	173	231
L	514	128	257	385	514
N	101	25	51	76	101

5.3.2 Tune Up of Gas Fired Equipment

Combustion efficiencies for boilers as well as the potential energy savings for tune-up of the boilers were calculated. Figure 5.22 shows combustion efficiencies estimated for the boilers tuned to have optimal excess air for combustion. Combustion efficiencies after tune up were calculated using the method described in Chapter 3.

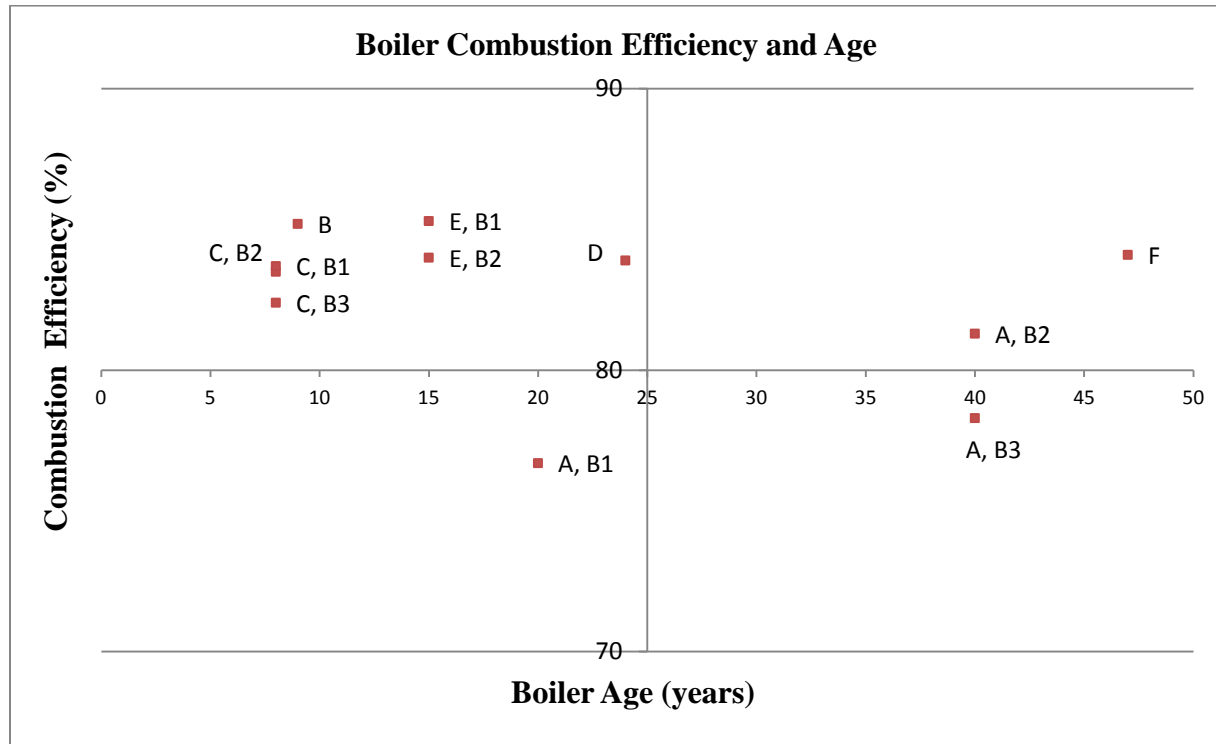


Figure 5.22 Boiler combustion efficiencies and ages after tune-up

By comparing of Figure 5.22 with Figure 5.18 it is evident that the improvement in combustion efficiencies as a result of tune-up could be easily seen. Considerable improvement can be seen in the combustion efficiency of boiler '2' at site 'A' which in Figure 5.18 was in the fourth (bottom right) quadrant with the boilers that were old and had relatively lower efficiencies, moved to the first (top right) quadrant in Figure 5.22 with the boilers that had relatively high efficiency despite being more than 25 years old.

Natural gas savings along with percentage reduction in stack loss and boiler consumption were calculated and are shown in Table 5.14.

Table 5.14 Natural gas savings achieved by boiler tune up

Site	Boiler Number	Natural Gas Savings (m ³ /yr)	Savings as a Percentage of Stack Loss (%)	Savings as Percentage of Boiler Consumption (%)
A	1	6,361	1	0.9
	2	31,333	11	4.3
	3	3,382	1	2.5
B	1	3,457	2	0.5
C	1	2,052	2	0.3
	2	2,052	2	0.3
	3	2,096	1	0.3
D	1	5,342	2	0.7
E	1	5,433	2	0.7
	2	6,170	2	0.8
F	1	2,961	2	0.4

Fuel cost savings and the reduction in greenhouse gas emissions were calculated and are presented in Table 5.15.

Table 5.15 Natural gas savings, fuel cost savings and reduction in greenhouse gas emissions achieved by boiler tune up

Site	Boiler Number	Fuel Cost Savings	Reduction in Greenhouse Gas Emissions
		(\$/yr)	(tonnes CO ₂ /yr)
A	1	1,436	12.0
	2	7,072	58.9
	3	763	6.4
B	1	780	6.5
C	1	463	3.9
	2	463	3.9
	3	473	3.9
D	1	1,206	10.0
E	1	1,226	10.2
	2	1,393	11.6
F	1	668	5.6

5.3.3 Optimized Load Management of Boilers

There were only two sites where at least two boilers were running simultaneously. Natural gas consumption was plotted against steam production load as shown in Figure 5.23 and Figure 5.24. The boilers were found to have quadratic relationship between the amount of steam produced and natural gas consumption in the form of the following equation.

$$Z = aX^2 + bX + c \quad (5.1)$$

where

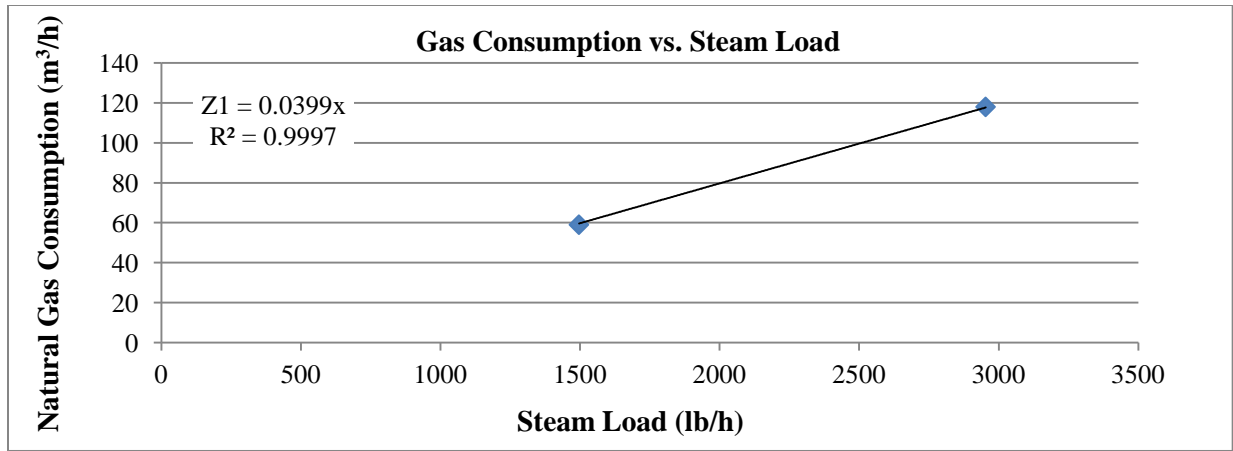
X is the steam load on the boiler

Z is the natural gas consumption of the boiler

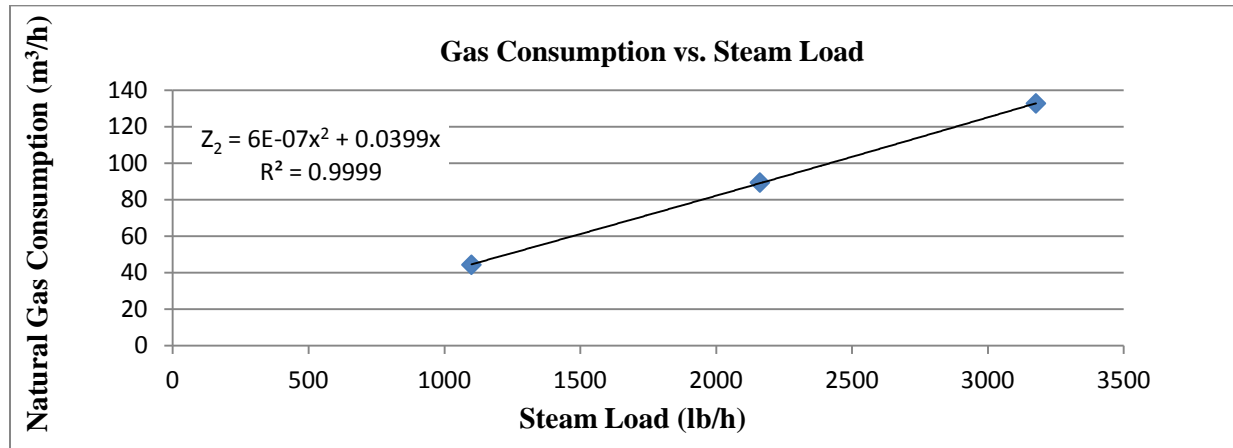
The coefficients 'a' and 'b' for the boilers along with the coefficient of correlation are shown in Table 5.16. The high R^2 value emphasize the strong correlation between steam load and natural gas consumption.

Table 5.16 Coefficients of quadratic equation representing the relationship between amount of steam produced and natural gas consumption

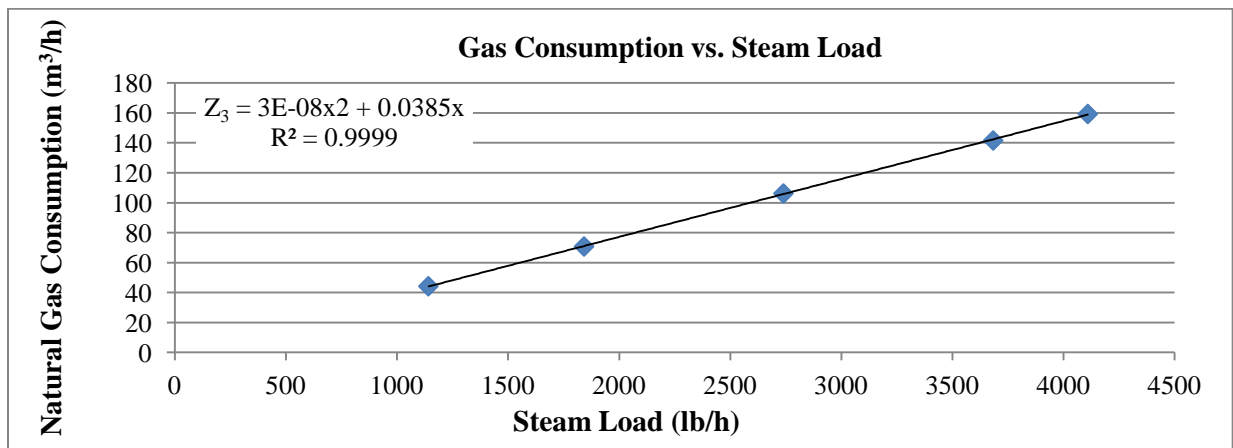
Site	Boiler Number	coefficients		Coefficient of Correlation
		a	b	R^2
A	1	-	0.0399	0.9997
	2	6.00E-07	0.0399	0.9999
	3	3.00E-08	0.0385	0.9999
C	1	6.00E-07	0.0395	0.9984
	2	1.00E-07	0.0379	0.9999
	3	5.00E-07	0.0375	0.9998



(a) Boiler # 1

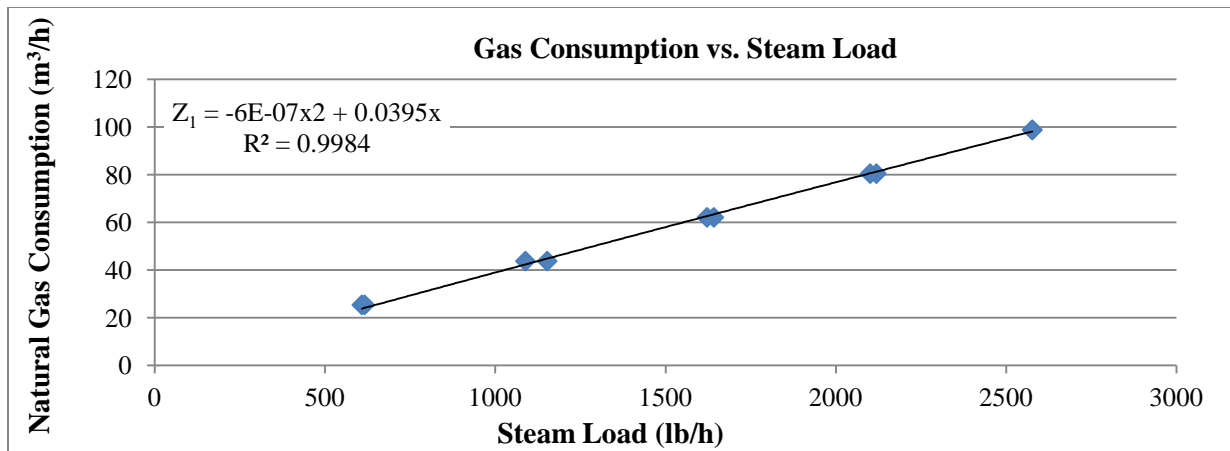


(b) Boiler # 2

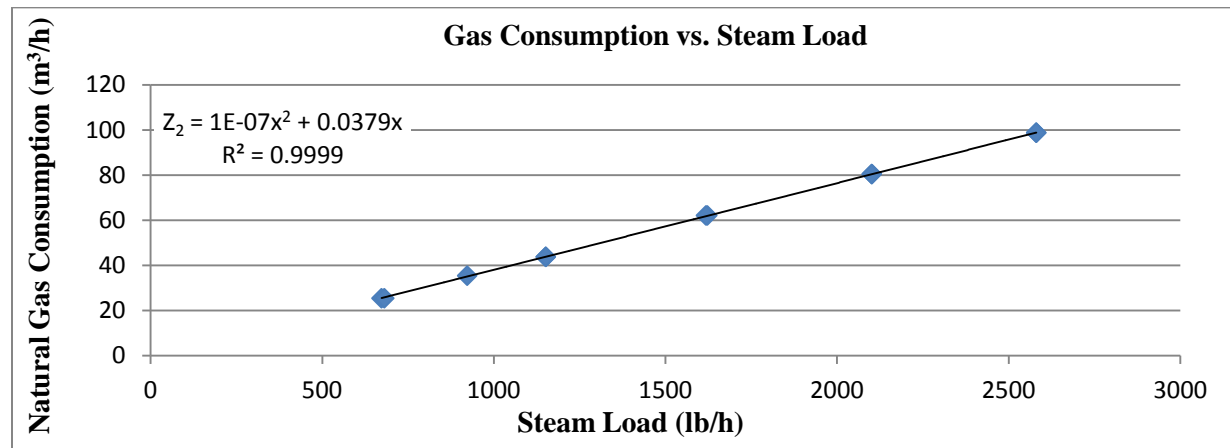


(c) Boiler # 3

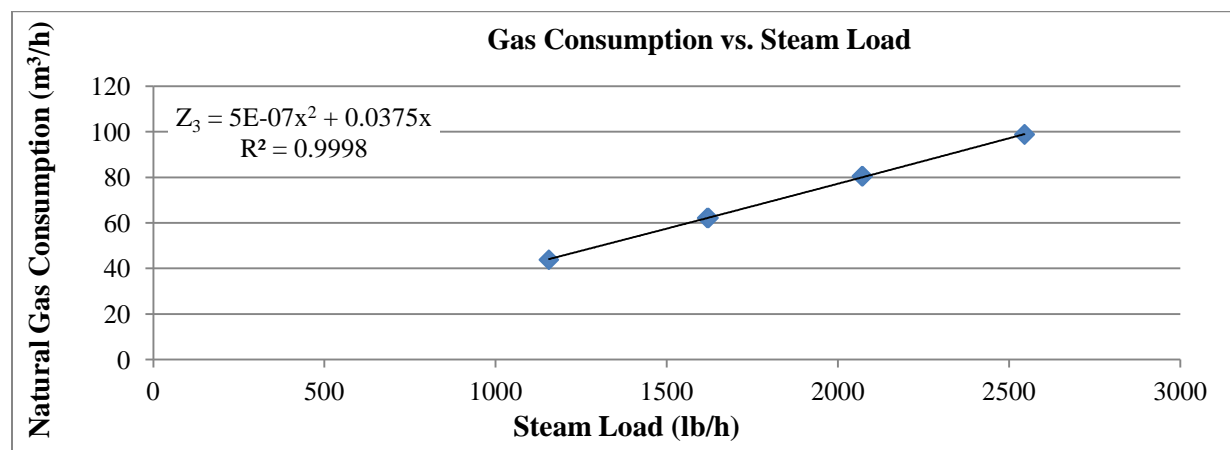
Figure 5.23 Natural gas consumption vs. steam load for boilers at site 'A' (a) boiler #1 (b) boiler #2 (c) boiler #3



(a) Boiler # 1



(b) Boiler # 2



(c) Boiler # 3

Figure 5.24 Natural gas consumption vs. steam load for boilers at site 'C' (a) boiler #1 (b) boiler #2 (c) boiler #3

Natural gas and fuel cost savings along with the reduction in greenhouse gas emissions achieved by optimized load management of boilers were calculated and are shown in Table 5.17.

Table 5.17 Natural gas savings, achieved by optimized load management

Site	Base Case Natural Gas Consumption of Boiler Room	Natural Gas Savings	Savings as Percentage of Base Case
	(m ³ /yr)	(m ³ /yr)	(%)
A	1,294,176	33,945	2.6
C	837,009	3,594	0.4

Fuel cost savings and reduction in greenhouse gas emissions for the above mentioned energy saving measure are shown in Table 5.18.

Table 5.18 Fuel cost savings and reduction in greenhouse gas emissions achieved by optimized load management

Site	Fuel Cost Savings	Reduction in Greenhouse Gas Emissions
	(\$/yr)	(tonnes CO ₂ /yr)
A	7,661	63.8
C	811	6.8

Boiler at site 'A', which had considerable differences in ages and efficiencies showed greater potential as compared to site 'C' which had boilers of the same age, which were installed at the same time and had very similar efficiencies. Site 'A' had three boilers having ages of 20 years, 40 years and 40 years while the boilers at site 'C' were relatively new and less than 10 years old. The boilers at site 'C' also had combustion efficiency values very close to each other. Therefore, the energy saving potential at site 'C' was considerably lower than at site 'A'. Therefore, it can be concluded that this energy saving measure would be best suited to sites where there are considerable differences in the efficiencies and ages of the boilers in the boiler room

5.3.4 Heat Recovery using Feedwater Economizer

Natural gas saving achieved by recovering heat from flue gas and using it to heat incoming feedwater, was calculated. The gas savings are shown in Table 5.19.

Table 5.19 Natural gas savings achieved by recovering heat from flue gas to heat feedwater

Site	Boiler Number	Natural Gas Savings	Savings as a Percentage of Boiler Consumption	Savings as a Percentage of Total Site Consumption
		(m ³ /yr)	(%)	(%)
A	1	93,205	12.7	2.8
	2	102,490	18.4	3.0
	3	79,962	15.6	2.4
B	1	11,845	3.4	1.8
C	1	27,021	9.1	2.6
	2	27,020	8.4	2.6
	3	31,175	7.8	3.0
D	1	8,364	3.9	1.5
E	1	10,866	6.7	1.1
	2	12,340	6.3	1.2
F	1	5,922	6.0	0.9

Natural gas savings were plotted against flue gas temperature for the boilers at audited sites as shown in Figure 5.25.

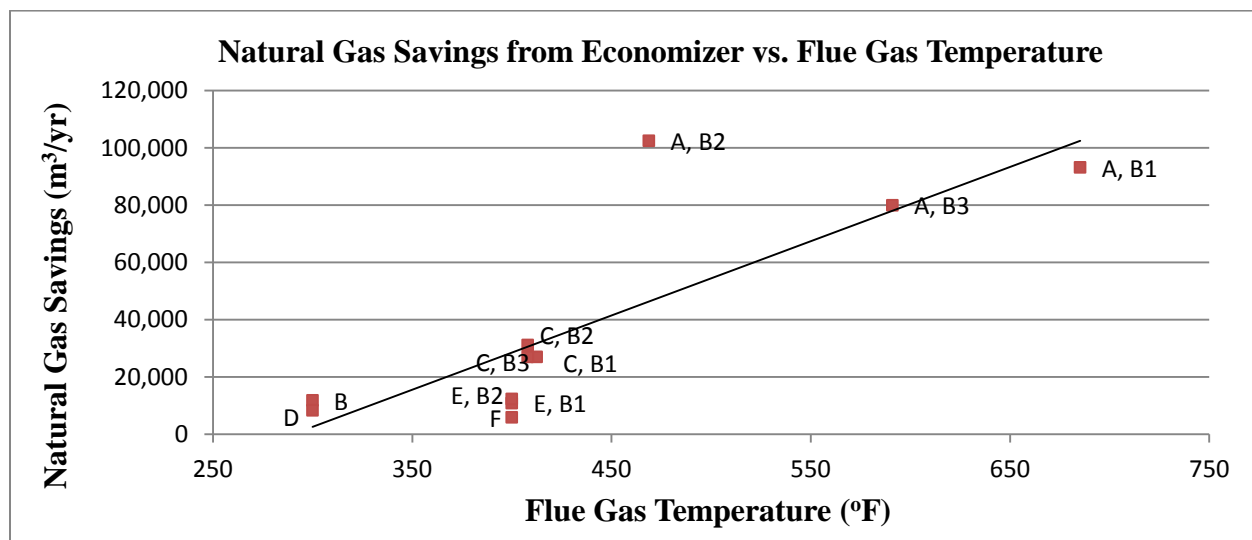


Figure 5.25 Savings achieved by installing feedwater economizer vs. flue gas temperature

The boilers where the flue gas temperature was higher exhibited a greater potential for natural gas savings achieved by recovering flue gas heat through feedwater economizer.

Fuel cost savings and reduction in greenhouse gas emission achieved by installing feedwater economizer are shown in Table 5.20.

Table 5.20 Fuel cost savings and reduction in greenhouse gas emissions achieved by recovering heat from flue gas to heat feedwater

Site	Boiler Number	Fuel Cost Savings	Reduction in Greenhouse Gas Emissions
		(\$/yr)	(tonnes CO ₂ /yr)
A	1	21,036	175.1
	2	23,132	192.6
	3	18,047	150.2
B	1	2,673	22.3
C	1	6,099	50.8
	2	6,098	50.8
	3	7,036	58.6
D	1	1,888	15.7
E	1	2,452	20.4
	2	2,785	23.2
F	1	1,337	11.1

It was observed that the boilers with relatively lower combustion efficiencies signifying considerable stack loss would result in greater natural gas savings by employing feedwater economizer to recover heat from exhaust flue gases, compared to the boilers that had relatively higher combustion efficiencies.

5.3.5 Oven Exhaust Reduction by using Variable Frequency Drive

This energy saving measure is applicable to ovens. The savings achieved by reducing the exhaust flow rate of ovens by using variable frequency drive was calculated as shown in Table 5.21. The natural gas savings achieved were highest for the bake oven at site 'D' at 183,027 m³/yr while the lowest savings were for the dry-off oven at site 'O' at 22,727 m³/yr.

Table 5.21 Natural gas savings achieved by reducing oven exhaust

Site	Type of oven	Natural Gas Savings	Savings as Percentage of Oven Consumption	Savings as Percentage of Site consumption
		(m ³ /yr)	(%)	(%)
A	bake oven	112,478	13	3%
D	bake oven	183,027	50	34%
G	dry off	54,570	45	9%
	cure	68,220	48	11%
H	dry off	60,000	50	18%
	cure	59,450	49	17%
I	dry off	28,643	32	6%
	cure	31,918	32	7%
J	dry off	41,279	46	8%
	cure	50,117	42	10%
K	dry off	22,727	33	8%
	cure	39,550	39	14%
L	dry off	70,093	22	5%
	cure	70,093	24	5%
M	dry off	44,548	20	5%
	cure	50,225	16	6%
N	dry off	41,458	23	11%
	cure	48,380	55	13%
O	dry off	11,005	34	7%
	cure	25,837	49	17%

Fuel cost savings and reduction in greenhouse gas emissions achieved by reducing oven exhaust are shown in Table 5.22.

Table 5.22 Natural gas savings, fuel cost savings and reduction in greenhouse gas emissions achieved by reducing oven exhaust by using variable frequency drive

Site	Type of oven	Fuel Cost Savings	Reduction in Greenhouse Gas Emissions
		(\$/yr)	(tonnes CO ₂ /yr)
A	bake oven	25,386	211,346
D	bake oven	41,309	343,908
G	dry off	12,316	102,537
	cure	15,397	128,185
H	dry off	13,542	112,740
	cure	13,418	111,707
I	dry off	6,465	53,819
	cure	7,204	59,973
J	dry off	9,317	77,563
	cure	11,311	94,170
K	dry off	5,129	42,704
	cure	8,926	74,314
L	dry off	15,820	131,705
	cure	15,820	131,705
M	dry off	10,055	83,706
	cure	11,336	94,374
N	dry off	9,357	77,900
	cure	10,919	90,907
O	dry off	2,484	20,679
	cure	5,831	48,547

Table 5.23 shows the summary of total savings for applicable energy saving measures for each of the audited sites. The savings shown in Table 5.23 were calculated considering each opportunity

independently. However, not all the measures were applicable to all the sites. Blank spaces have been left for such cases.

Table 5.23 Summary of total estimated savings applicable to the audited sites

Site	Maximum Energy Savings for Reduced Non-Productive Consumption	Energy Savings for Boiler Tune-up	Energy Savings for Optimized Boiler Load Management	Energy Savings for Heat Recovery from Flue Gas using Feedwater Economizer	Energy Savings for Reduced Oven Exhaust by using VFDs
	(m ³ /yr)	(m ³ /yr)	(m ³ /yr)	(m ³ /yr)	(m ³ /yr)
A	677,810	41,076	33,945	275,657	112,478
B	–	3,457		11,845	–
C	–	6,200	3,594	85,216	–
D	49,166	5,342	–	8,364	183,027
E	75,710	11,603	–	23,206	–
F	12,798	2,961	–	–	–
G	84,418	–	–	–	261,938
H	28,719	–	–	–	240,451
I	56,490	–	–	–	60,560
J	123,000	–	–	–	91,396
K	–	–	–	–	62,277
L	273,395	–	–	–	140,186
M		–	–	–	94,774
N	53,885	–	–	–	89,838
O	–	–	–	–	36,842

Table 5.24 shows the summary of total savings for applicable energy saving measures as a percentage of total natural gas consumption of the site

Table 5.24 Summary of total estimated savings as a percentage of total consumption of the site

Site	Percentage Savings for Reduced Non-Productive Consumption	Percentage Savings for Boiler Tune-up	Percentage Savings for Optimized Boiler Load Management	Percentage Savings for Heat Recovery from Flue Gas using Feedwater Economizer	Percentage Savings for Reduced Oven Exhaust by using VFDs
	(%)	(%)	(%)	(%)	(%)
A	2.2	1.2	1.0	8.2	3.3
B	–	0.5	–	1.8	–
C	–	0.6	0.3	8.2	–
D	2.4	1.0	–	1.5	33.6
E	8.5	1.2	–	2.3	–
F	4.6	0.5	–	–	–
G	13.5	–	–	–	41.9
H	8.4	–	–	–	70.7
I	12.6	–	–	–	13.5
J	25.0	–	–	–	18.5
K	–	–	–	–	21.4
L	21.3	–	–	–	10.9
M	–	–	–	–	10.7
N	14.4	–	–	–	24.0
O	–	–	–	–	24.0

6 Software Tool

While conducting audits, it was observed that many industrial sites had similar gas-fired equipment. The performance analyses for such equipment followed a similar methodology. In order to expedite the process of analyzing the performance and to perform lengthy calculations quickly for boilers which are widely present in residential, commercial and industrial buildings, the boiler efficiency tool was created using MATLAB. The partnership between Ryerson University and Enbridge Gas Distribution is still continuing. Therefore, there is a possibility of additional tools being created.

6.1 Boiler Efficiency Tool

The boiler efficiency tool uses the readings from combustion analysis tests and boiler operational parameters as inputs and returns combustion efficiency and overall boiler efficiency along with the visual presentation of input, output and percentage losses in the form of a Sankey diagram [77, 78].

The inputs for this tool are:

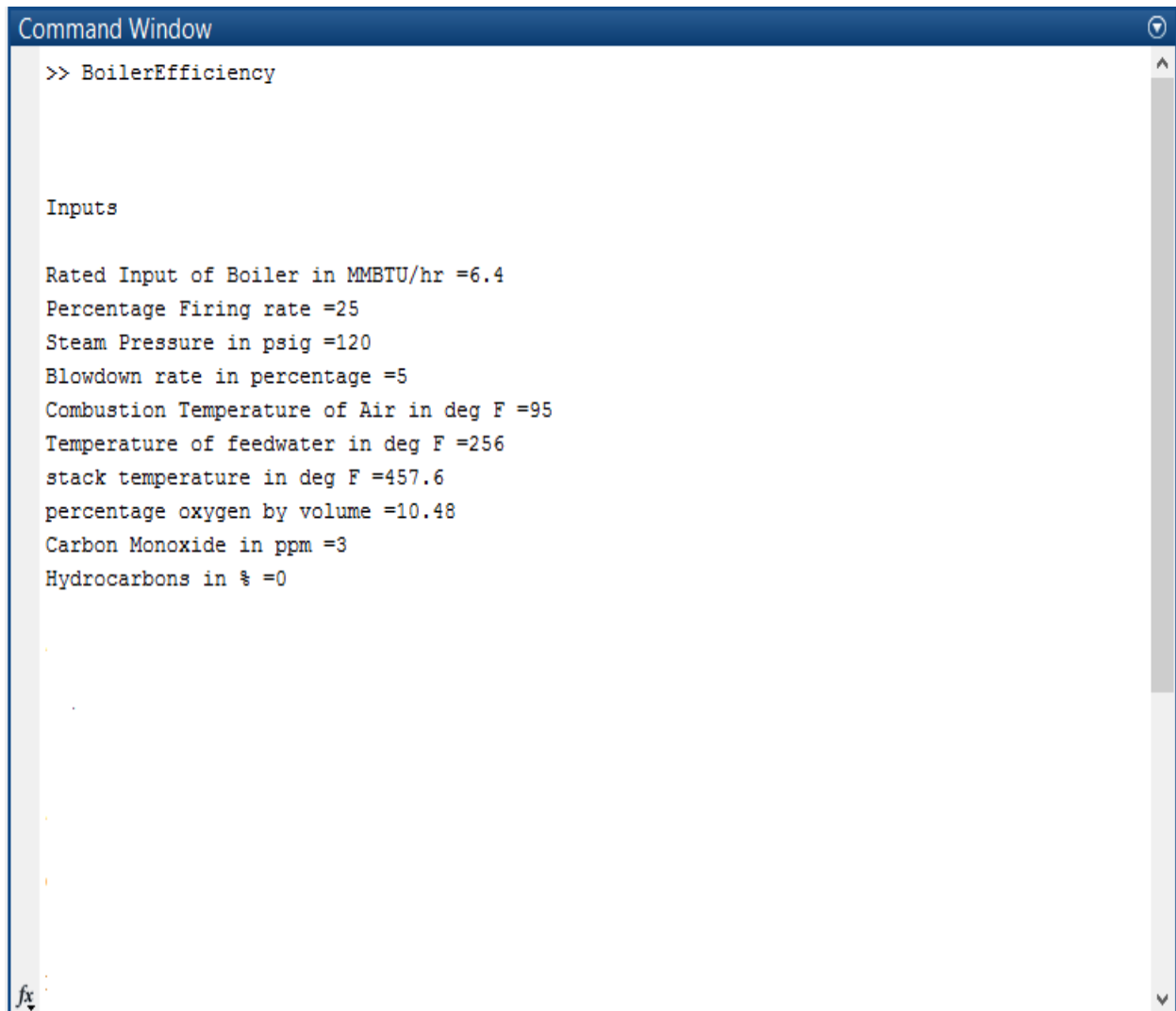
1. Combustion analysis

- Temperature of combustion air (°F)
- Temperature of flue gas (°F)
- Concentration of oxygen in dry flue gas (%)
- Concentration of carbon monoxide in dry flue gas (ppm)
- Concentration of unburned hydrocarbons in dry flue gas (%)

2. Boiler parameters

- Rated input of boiler (MMBtu/h)
- Percentage firing rate (%)
- Steam pressure (psi)
- Blowdown rate as a percentage of steam produced(%)
- Temperature of feedwater (°F)

Figure 6.1 shows a screenshot of the inputs as they were entered in MATLAB.

A screenshot of the MATLAB Command Window. The title bar is blue with the text 'Command Window' and a close button. The window contains the following text: '>> BoilerEfficiency' followed by a blank line, then 'Inputs' followed by a blank line. Below this, a list of inputs is displayed: 'Rated Input of Boiler in MMBTU/hr =6.4', 'Percentage Firing rate =25', 'Steam Pressure in psig =120', 'Blowdown rate in percentage =5', 'Combustion Temperature of Air in deg F =95', 'Temperature of feedwater in deg F =256', 'stack temperature in deg F =457.6', 'percentage oxygen by volume =10.48', 'Carbon Monoxide in ppm =3', and 'Hydrocarbons in % =0'. The window has a vertical scrollbar on the right and a small icon in the bottom left corner.

```
>> BoilerEfficiency

Inputs

Rated Input of Boiler in MMBTU/hr =6.4
Percentage Firing rate =25
Steam Pressure in psig =120
Blowdown rate in percentage =5
Combustion Temperature of Air in deg F =95
Temperature of feedwater in deg F =256
stack temperature in deg F =457.6
percentage oxygen by volume =10.48
Carbon Monoxide in ppm =3
Hydrocarbons in % =0
```

Figure 6.1 Screenshot of the inputs entered in boiler efficiency tool

The outputs of the tools are:

1. Combustion Efficiency
2. Overall Boiler Efficiency
3. Sankey diagram

The outputs of the boiler efficiency tool are shown in Figure 6.2.

```
Command Window

.

Outputs

ans =

Combustion Efficiency

Eff_comb =

    77.3071

ans =

Boiler Efficiency

Eff_Boiler =

    73.2081

fx >>
```

Figure 6.2 Screenshot of the outputs obtained from boiler efficiency tool

The Sankey diagram shows the energy input, energy output and the percentage losses. The tool has been programmed to use Imperial Units. Sankey diagram obtained by running this tool is shown in Figure 6.3.

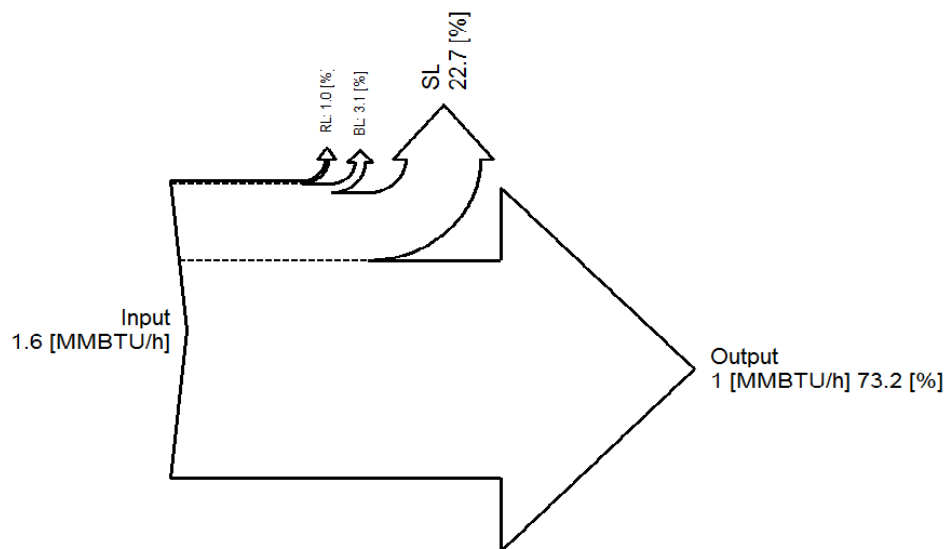


Figure 6.3 Sankey diagram for boiler efficiency tool

The diagram shows the input energy and the output energy along with the percentage losses i.e., stack losses (SL), blowdown losses (BL) and radiation, convection and other unaccountable losses (RL). MATLAB code for boiler efficiency tool is presented in Appendix B.

6.2 Accuracy of Software Tool and Uncertainty Analysis

Uncertainty analysis was performed on the combustion and boiler efficiencies analyzed in Chapter 3. Generally, the uncertainty of a result is expressed in terms of a standard uncertainty, ' σ ', which has the same units as the quantity. Uncertainty can also be expressed in terms of a fractional (relative uncertainty), shown as ' ϵ '. For the uncertainty of ' x ', the relationship between ' σ ' and ' ϵ ' can be defined in Equation 6.1 [79, 80].

$$\epsilon_x = \frac{\sigma_x}{x} \quad (6.1)$$

Table 6.1 shows the common formulas used for propagating uncertainty. When calculating the uncertainty for mixed operations the propagation of uncertainty can be easily calculated by treating each operation separately and using equations listed in the Table 6.1.

Table 6.1 Mathematical operation of propagating uncertainty [79, 80]

Operation	Calculation	Formula	Uncertainty Formula
1	Sum or difference	$f = px + qy,$ $f = px - qy$	$\sigma_f = \sqrt{(p\sigma_x)^2 + (q\sigma_y)^2}$
2	Multiplication or division	$f = xy,$ $f = x/y$	$\epsilon_f = \sqrt{(\epsilon_x)^2 + (\epsilon_y)^2}$

Since, the software tool calculated combustion and overall boiler efficiencies by performing mathematical operations on values of quantities measured by the flue gas analyzer, it was necessary to perform propagation of error analysis for the boiler efficiency tool. "The propagation of errors is defined as the method of computing the uncertainty in a result which depends on the uncertainties from multiple variables" [79]. It is simply arithmetic calculations performed with measured quantities that contain uncertainties.

The source of error for the software tool was assumed to be the accuracy limitation of the sensors of the flue gas or combustion analyzer. The sensors could only measure readings with a certain level of accuracy. The errors or uncertainties of the sensors of the combustion analyzer are presented in Table 6.2.

Table 6.2 Uncertainty values for the sensors of combustion analyzer [81].

Measurement Parameter	Uncertainty
Concentration of Oxygen by Volume of Dry Flue Gas	$\pm 0.2 \%$
Concentration of Carbon Monoxide in ppm of Dry Flue Gas	± 2 ppm (0 – 40 ppm) ± 10 ppm (rest of the range)
Concentration of Hydrocarbons in ppm of Dry Flue Gas	± 400 ppm (0 – 4000 ppm)
Temperature of Air and Flue Gas	± 0.72 °F (-148 °C – 392 °F) ± 1.8 °F (rest of the range)

Using the mathematical operation for propagation from of uncertainty along with the uncertainty values for the measured quantities, propagation of error analysis was conducted. Uncertainties for a sample boiler test reading are shown in Appendix C. Standard and relative uncertainties for combustion efficiencies of boilers are shown in Table 6.3.

Table 6.3 Standard and relative uncertainties for combustion efficiencies of boilers

Site	Boiler	Estimated Combustion Efficiency	Standard Uncertainty ' σ '	Relative Uncertainty ' ϵ '
		(%)	(%)	(%)
A	1	75.9	0.5	0.7
	2	73.4	1.3	1.8
	3	77.8	0.6	0.8
B	1	83.9	0.3	0.4
C	1	82.2	0.7	0.8
	2	82.3	0.7	0.9
	3	81.2	0.6	0.7
D	1	82.4	0.3	0.4
E	1	84.0	0.6	0.7
	2	82.5	0.5	0.7
F	1	82.8	0.5	0.6

Standard and relative uncertainties for boiler efficiencies of boilers are shown in Table 6.4.

Table 6.4 Standard and relative uncertainties for combustion efficiencies of boilers

Site	Boiler	Estimated Boiler Efficiency (%)	Standard Uncertainty ' σ ' (%)	Relative Uncertainty ' ϵ ' (%)
A	1	68.4	0.5	0.7
	2	66.1	1.4	2.1
	3	71.0	0.8	1.1
B	1	81.2	0.9	1.1
C	1	80.5	0.9	1.1
	2	80.6	1.0	1.2
	3	79.5	0.9	1.1
D	1	78.3	0.3	0.4
E	1	82.7	0.8	0.9
	2	80.8	0.7	0.9
F	1	79.8	0.7	0.9

7 Summary and Conclusion

7.1 Summary of Thesis

This study was part of Enbridge Gas Distribution Inc's demand side management (DSM) program for small and medium-sized industries. This study focused on the analysis of natural gas consumption in small and medium-sized industries in the Greater Toronto Area (GTA). In addition to analyzing natural gas consumption, measures to reduce wasteful natural gas consumption and improve energy efficiency were also identified. This study had three main parts, i.e., conducting energy audits, consolidating of data, observation and results obtained from the audits and generating software tool to facilitate analysis of energy performance of gas-fired equipment. This study addressed some of barriers hindering the implementation of energy saving measures in small and medium-sized industries. This thesis contributed to reducing barriers such as lack of awareness, limited access to and availability of technical information and expertise. However, in order to address the barrier of short term investment strategy prevalent in industries, detailed economic analysis could be undertaken based on the results of the analysis of energy saving measures.

During the course of this study 15 on-site energy audits were conducted. Analysis and results from those sites have been included in this study. The audited sites belonged to food sector, packaged goods sector and finishing processes (powder coating) sector. Energy audits provided useful information regarding natural gas consumption in small and medium-sized industries in the GTA. The audits allowed the classification of overall natural gas consumption of an industrial plant into consumption for process use and consumption for seasonal use (further classified as consumption for ventilation and space heating). Furthermore, through the energy audits productive and non-productive natural gas consumptions of audited sites were identified. In addition to analysis of natural gas consumption, performances of major gas consuming equipment present at audited sites were analyzed. Furthermore, opportunities for saving natural gas were identified, and measures for saving energy were proposed.

The proposed energy saving measures included reduction in non-productive gas consumption, tune-up of gas fired equipment, optimized load management, heat recovery through feedwater

economizer and reduction in exhaust using variable frequency drives (VFDs). The analysis of these opportunities showed that considerable natural gas savings could be achieved by employing simple energy saving measures or implementing available technologies. In addition to natural gas savings, the accompanying fuel cost savings were also determined. Also the environmental benefits of saving natural gas were quantified in terms of reduction in greenhouse gas emissions.

During the course of this study, a software tool was developed using MATLAB to calculate boiler efficiencies and to visually represent the inputs, outputs and percentage losses in the form of a Sankey diagram.

7.2 Author's Contribution

Enbridge's university partnership program presented the opportunity to study energy (natural gas) efficiency in small and medium-sized industries. In this regard, the author has performed and achieved the following tasks:

- Consolidation of data from 15 energy (natural gas) audits The study is a first of its kind for small and medium-sized industries in the GTA.
- Development of MATLAB-based analysis tool for quick estimation of boiler efficiencies and representation of input, output and result in the form of Sankey diagram.
- Creation of a mixed integer non-linear programming (MINLP) algorithm with branch and bound for optimized load management of boilers
- Calculation of normalized annual natural gas consumption for the audited sites by conducting linear regression analysis using PRISM and estimation of gas consumption for process and seasonal end-uses.
- Identification and estimation of productive time and non-productive time gas consumption using daily gas consumption data for 10 out of the 15 audited sites.
- Analysis of performance of major gas consuming equipment (i.e., boilers and ovens) present at the audited sites and identification of major energy losses (such as stack losses for boilers and exhaust ventilation losses for ovens).
- Estimation of gas savings along with financial and environmental benefits in terms of fuel

cost savings and reduction in greenhouse gas emissions.

- Determination of the errors through uncertainty analysis for results obtained from the MATLAB-based boiler efficiency tool.

7.3 Limitations

This study was part of Enbridge Gas Distribution Inc's demand side management (DSM) program for small and medium-sized industries. In this program energy audits are conducted for industrial customers of Enbridge Gas at no cost to the customer. However, in order to benefit from this program the initiative must be taken by the industrial customer. For this reason, the number of audited sites as well the type of audited industrial sites were limited to only those industrial customers that availed the opportunity to receive a free energy audit. The author did not have much control over this aspect of the project and hence, the type of audited industrial sites was limited to food sector, packaged goods sector and finishing process sector.

The other limitation was on the information that the industrial plants were willing to share. For example, there was no production data available for the industrial sites. In the absence of production data, regression analysis could only be conducted using the utility bills data and weather data for the region. For more than half the audited sites natural gas consumption showed good correlation with weather. The sites for which natural gas consumption showed good correlation with weather data had approximately constant production demand throughout the year. For such industrial sites periods of high consumption corresponded with the time of the year when weather was cold. However, there were sites for which production demand varied throughout the year. For such sites there were periods of natural gas consumption that occurred during the summer season (hot weather). Hence, there was not a good correlation between consumption and weather data for those sites.

7.4 Conclusions

Even with the limitations mentioned in the previous section there were meaningful conclusions that could be drawn from this study.

- Analysis of natural gas consumption along with the area and annual operation hours resulted in identifying sector specific trends for energy intensity per unit operational hour. Sites for food processing sector showed an increase in energy intensity per unit operational hour with the increase in site area. Both the packaged goods and finishing process industries showed a decreasing trend in energy intensity per operational hour with the increase in site area.
- Due to the availability of daily metered data for natural gas consumption, productive and non-productive consumption could be identified. The existence of non-productive consumption is likely to be gas-fired equipment that are not switched off. In some cases the non-productive consumption was found to be as high as 25% of the annual gas consumption of the plant.
- It was determined that natural gas consumption for industrial plants having steady production throughout the year, could be accurately analyzed using statistical methods like linear regression. Using heating degree days obtained from long-term weather data could be used to estimate weather-dependent consumption and process consumption. The coefficient of correlation (R^2 value) was higher than 0.5 for 12 of the audited sites. Eight of the 12 sites had R^2 values of 0.7 or higher. Three sites with R^2 values lower than 0.5 were the ones that had unsteady demand and production throughout the year and therefore, did not show good correlation.
- For most of the boilers in the study, employing energy saving measures such as tuning-up boilers showed potential reduction of 1% to 2% in stack losses and 0.3% to 2.5% savings in annual consumption of individual boilers.
- Potential savings for optimization of boiler load allocation were found to be 2.6% and 0.4% of the annual consumption of the boiler room for the two sites that had two or more boilers running simultaneously.
- Potential savings for heat recovery through feedwater economizer ranged from 3.4% to 18.4% of annual gas consumption of the boilers while the potential savings for installation of VFDs ranged from 13% to 49% of the annual gas consumption of the ovens.

Appendices

Appendix A: PRISM Results

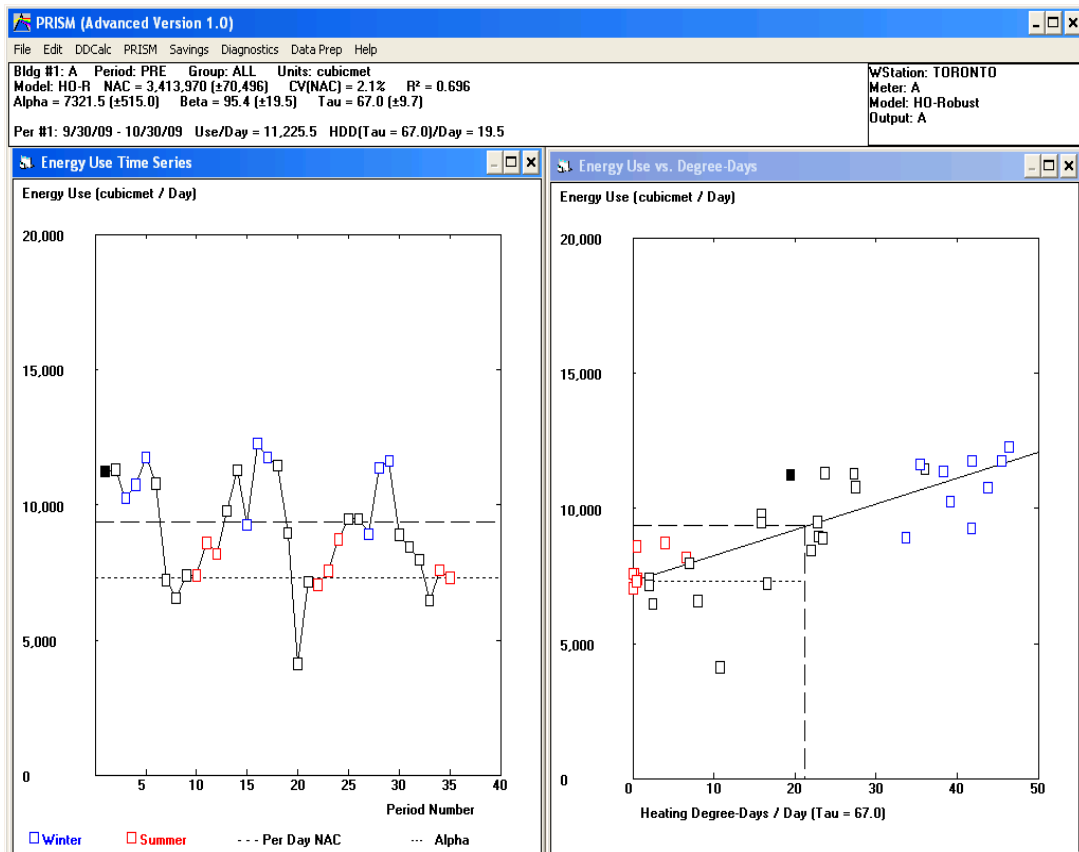


Figure A.0.1 Energy consumption plots for site 'A'

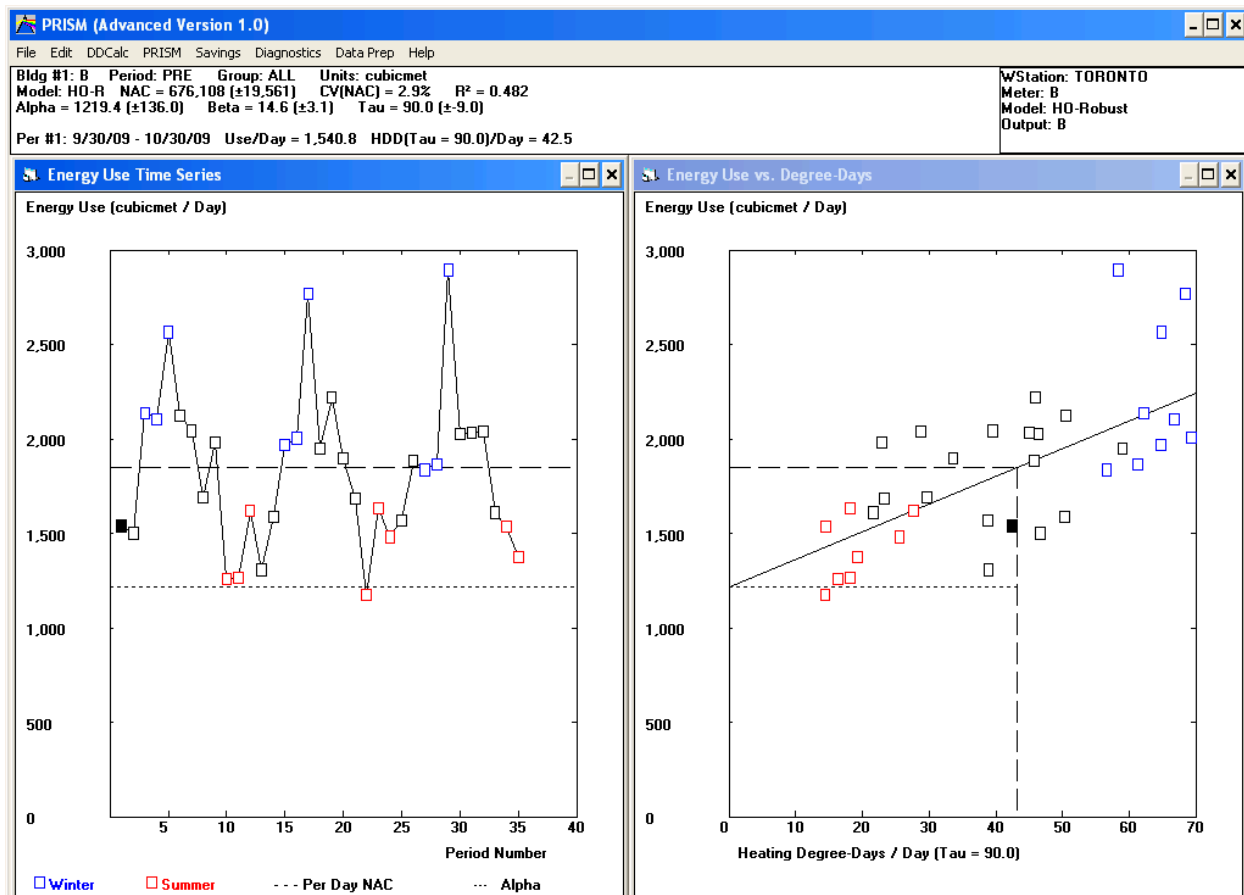


Figure A.0.2 Energy consumption plots for site 'B'

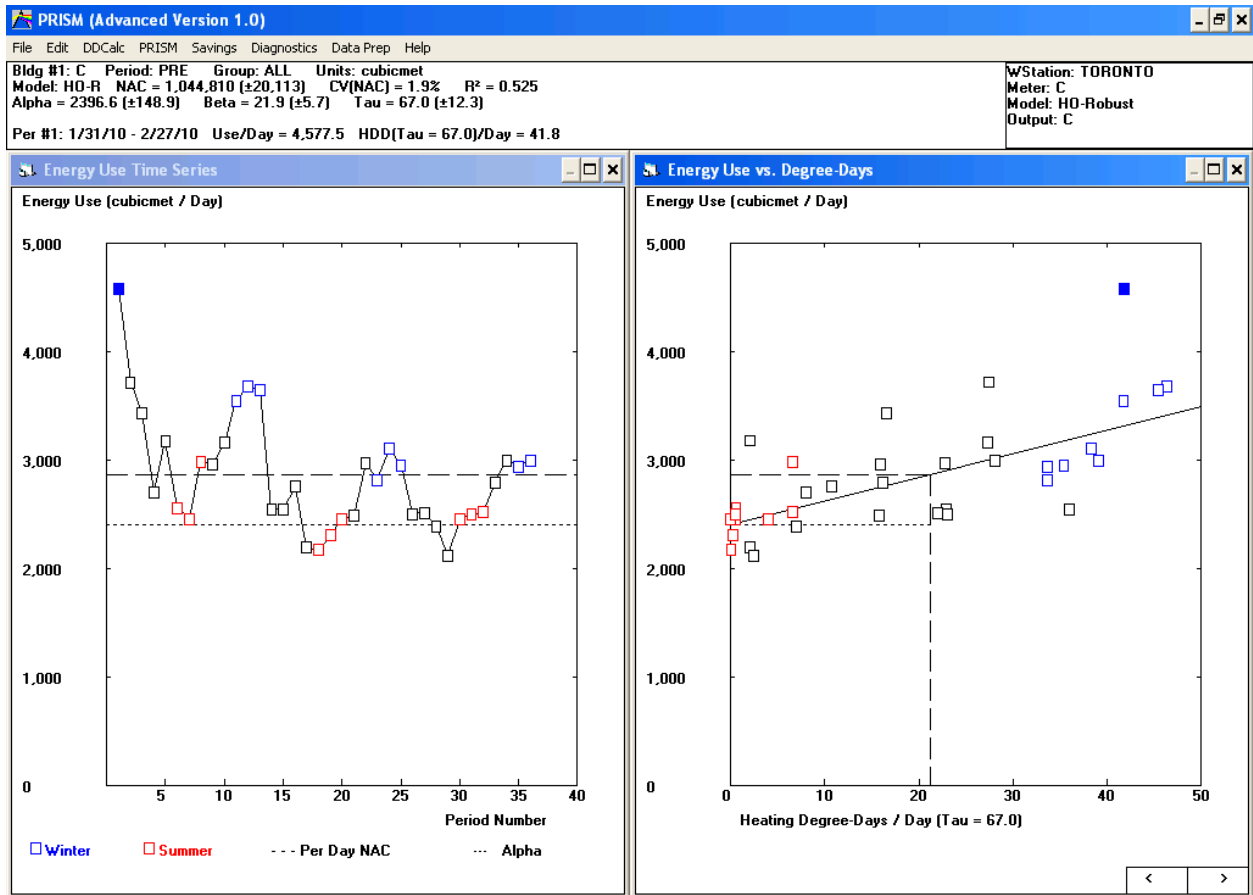


Figure A.0.3 Energy consumption plots for site 'C'

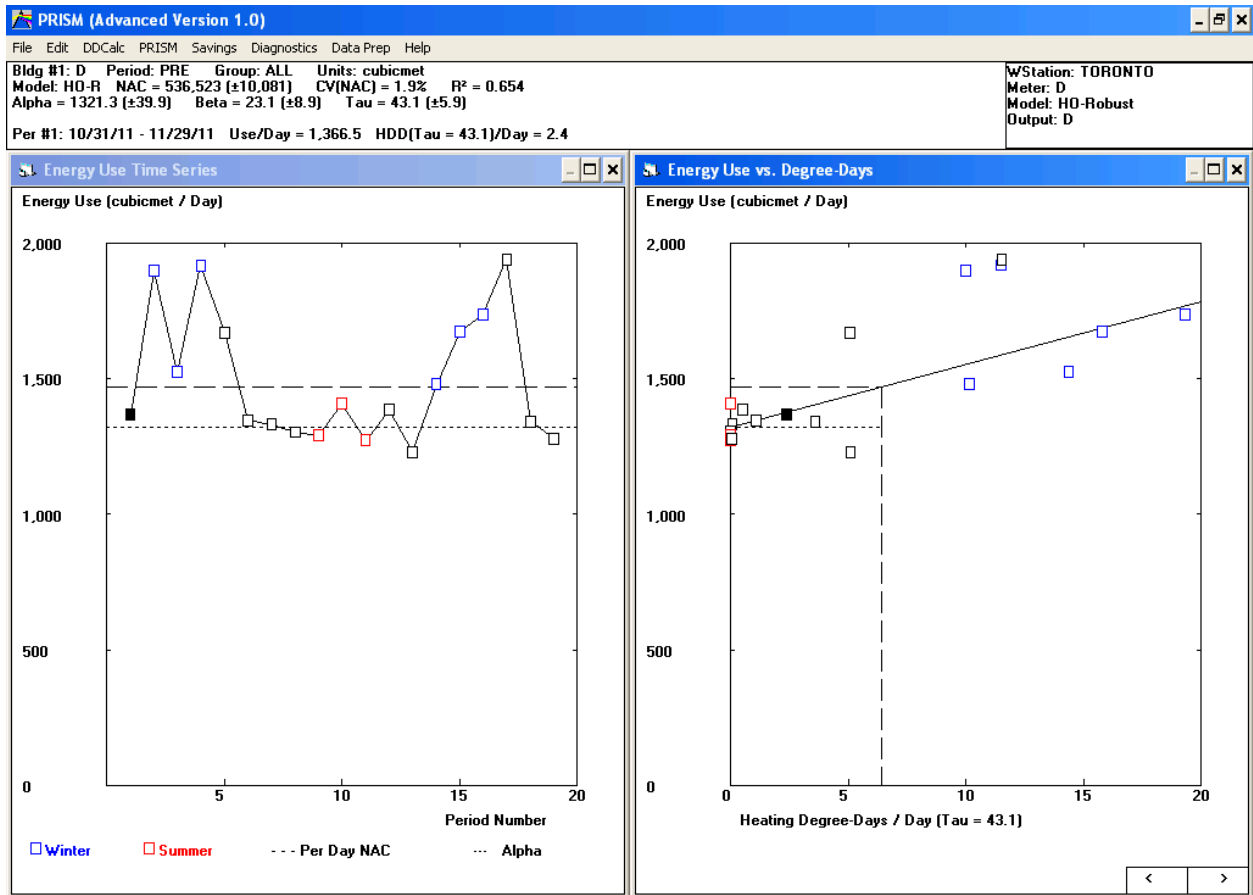


Figure A.0.4 Energy consumption plots for site 'D'

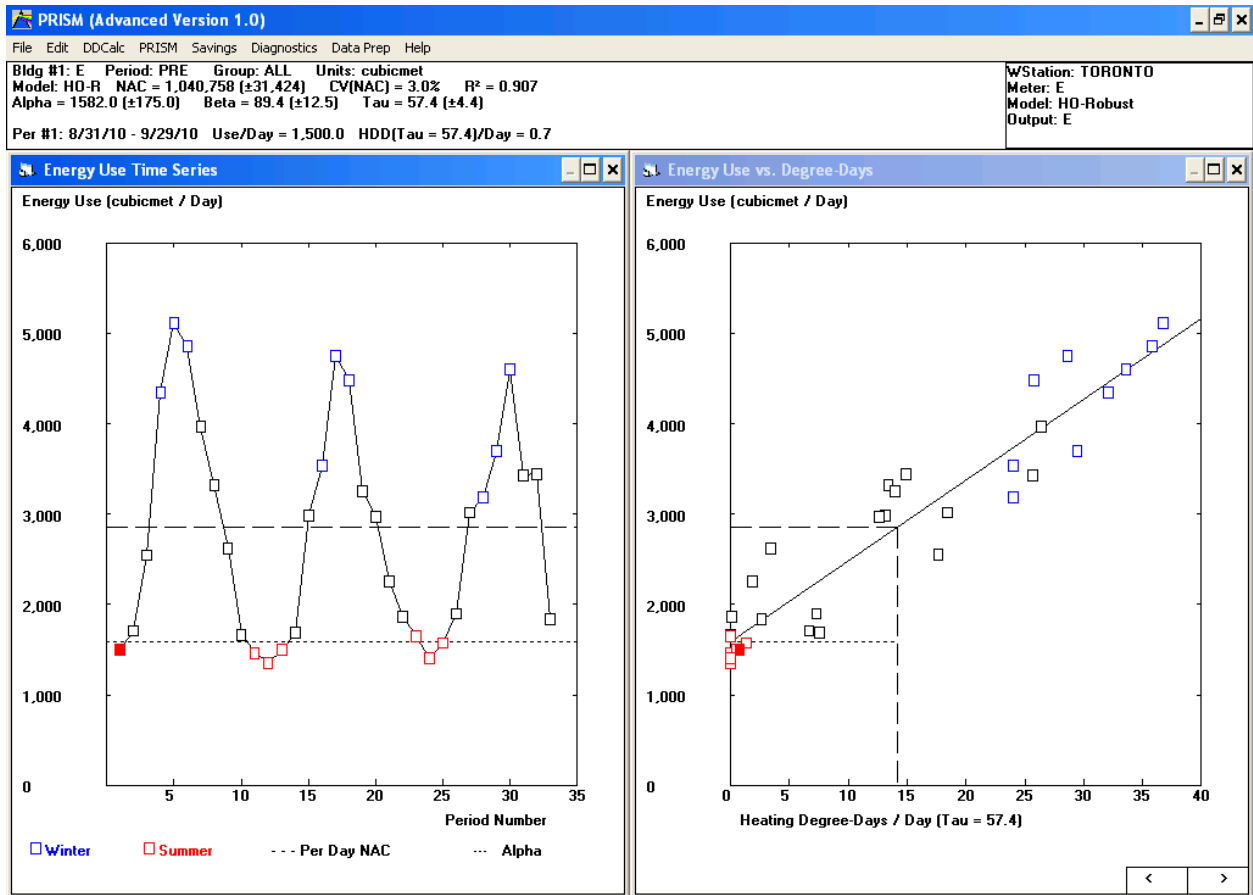


Figure A.0.5 Energy consumption plots for site 'E'

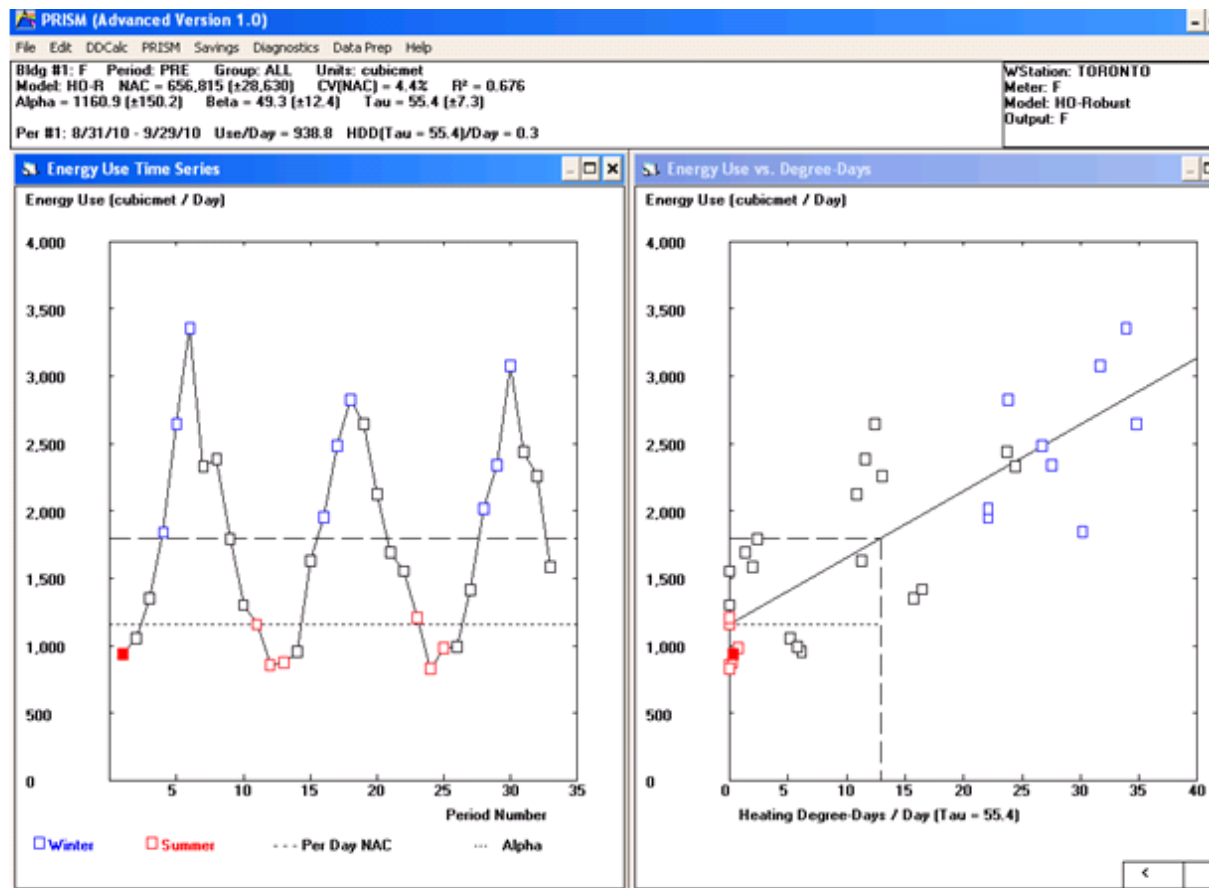


Figure A.0.6 Energy consumption plots for site 'F'

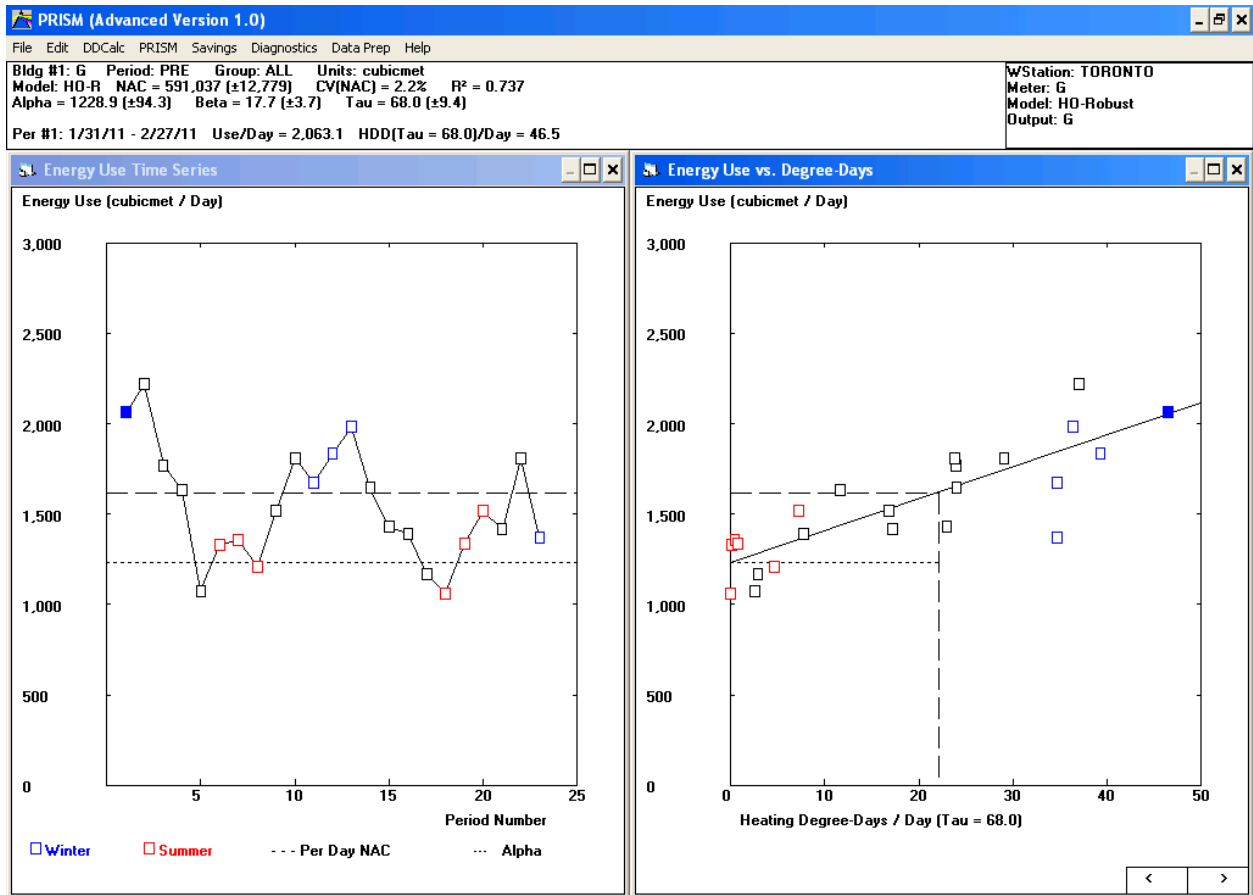


Figure A.0.7 Energy consumption plots for site 'G'

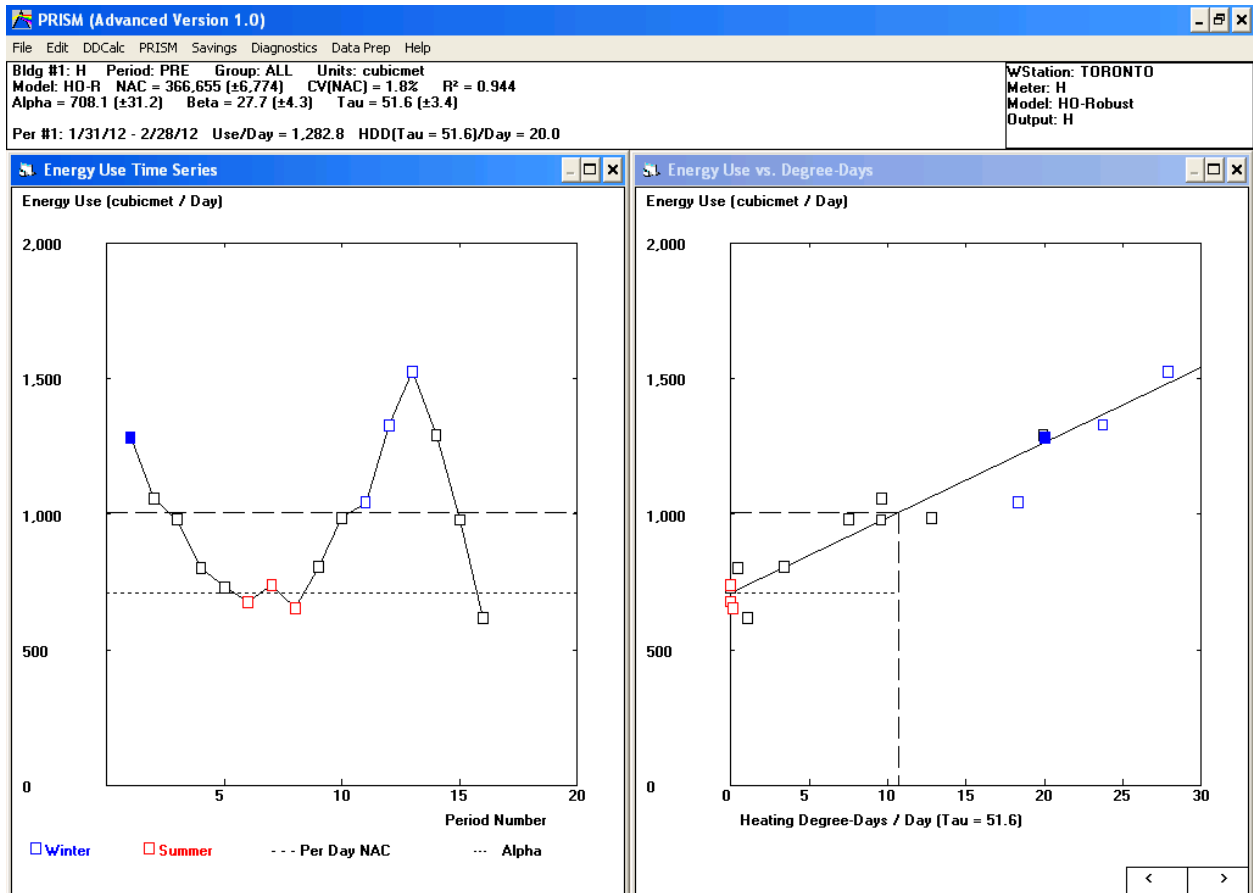


Figure A.0.8 Energy consumption plots for site 'H'

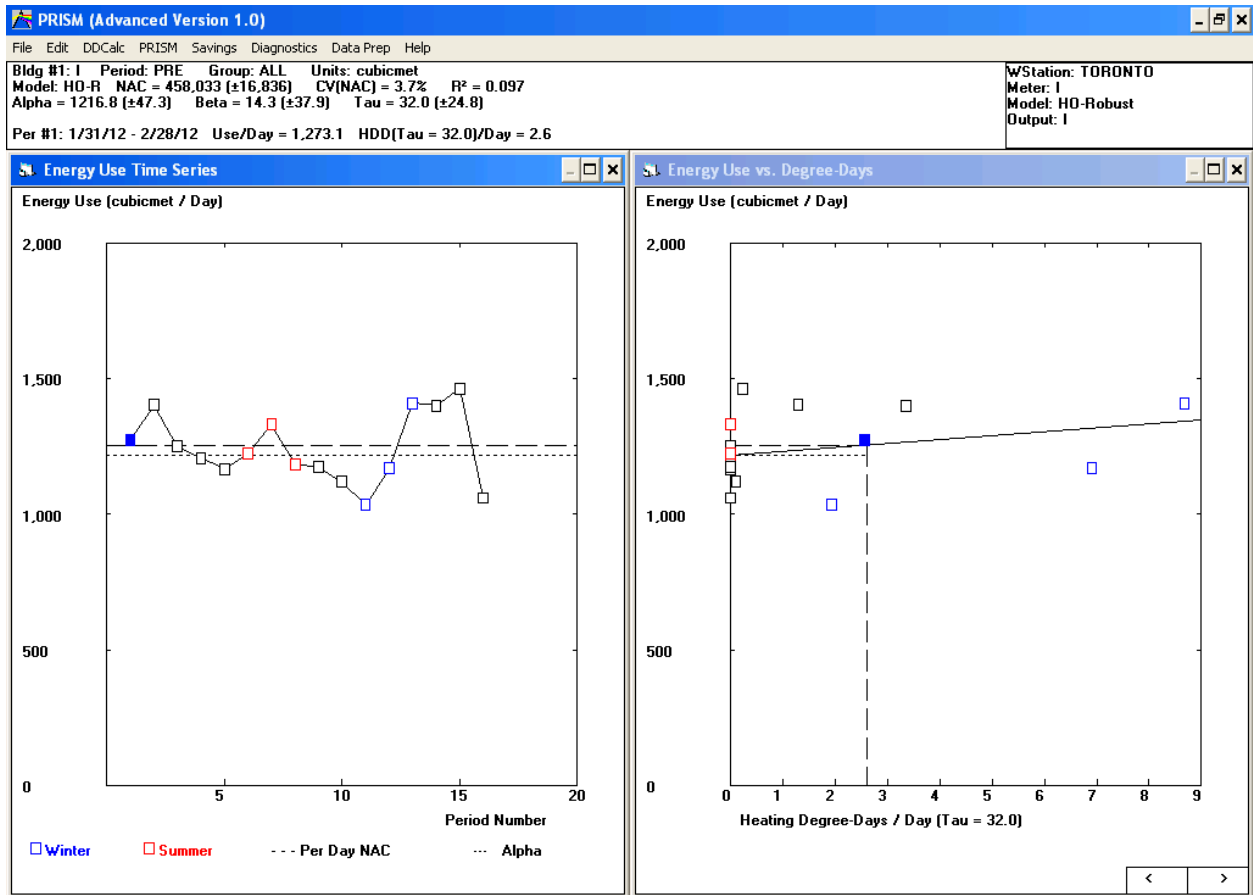


Figure A.0.9 Energy consumption plots for site 'T'

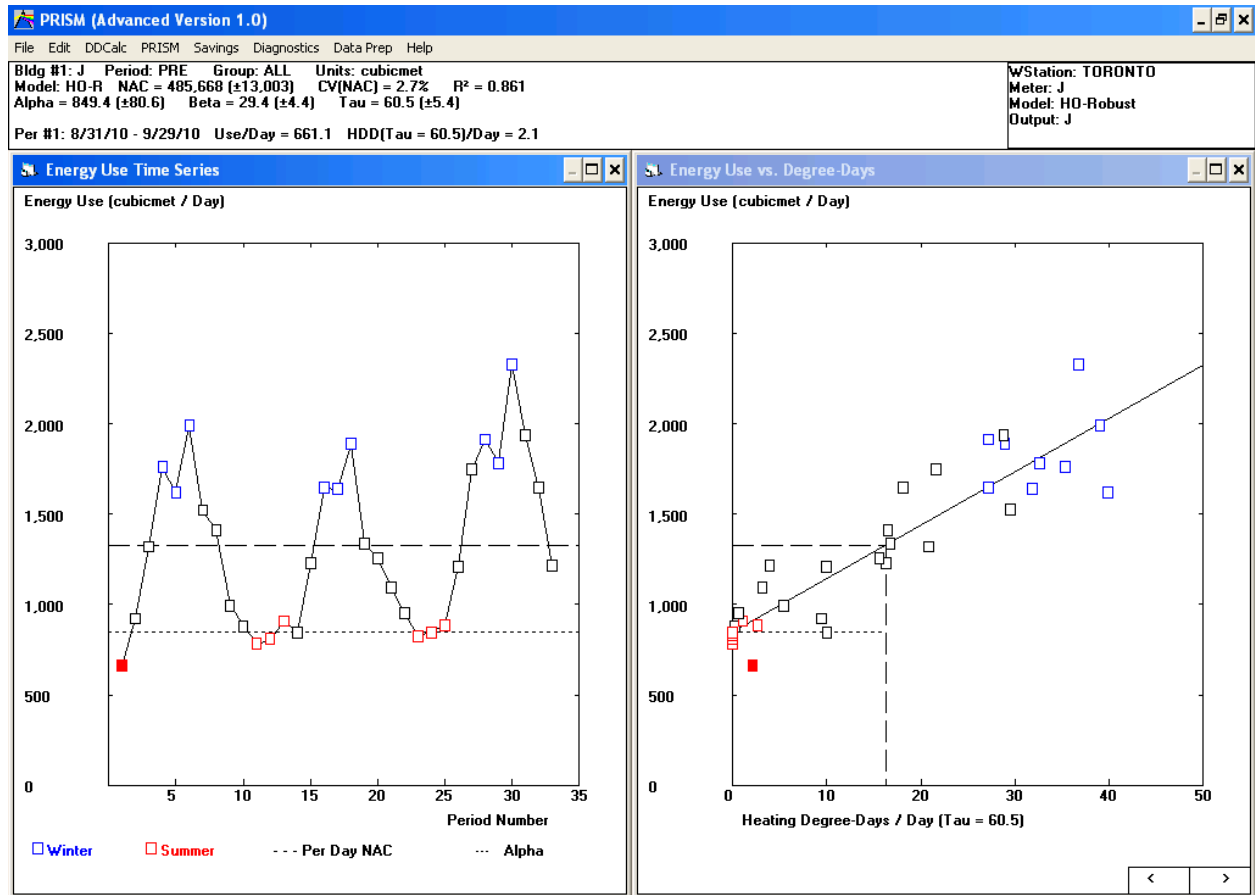


Figure A.0.10 Energy consumption plots for site 'J'

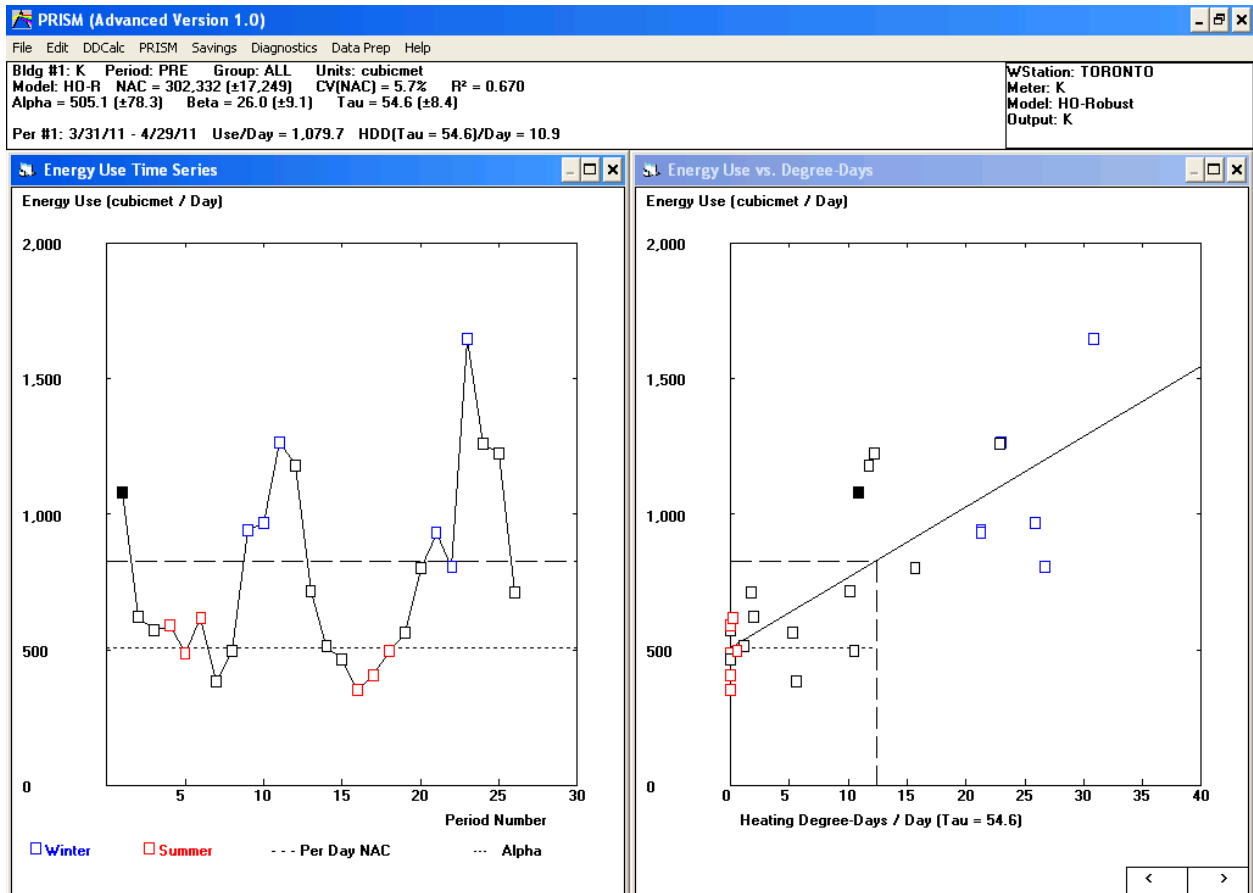


Figure A.0.11 Energy consumption plots for site 'K'

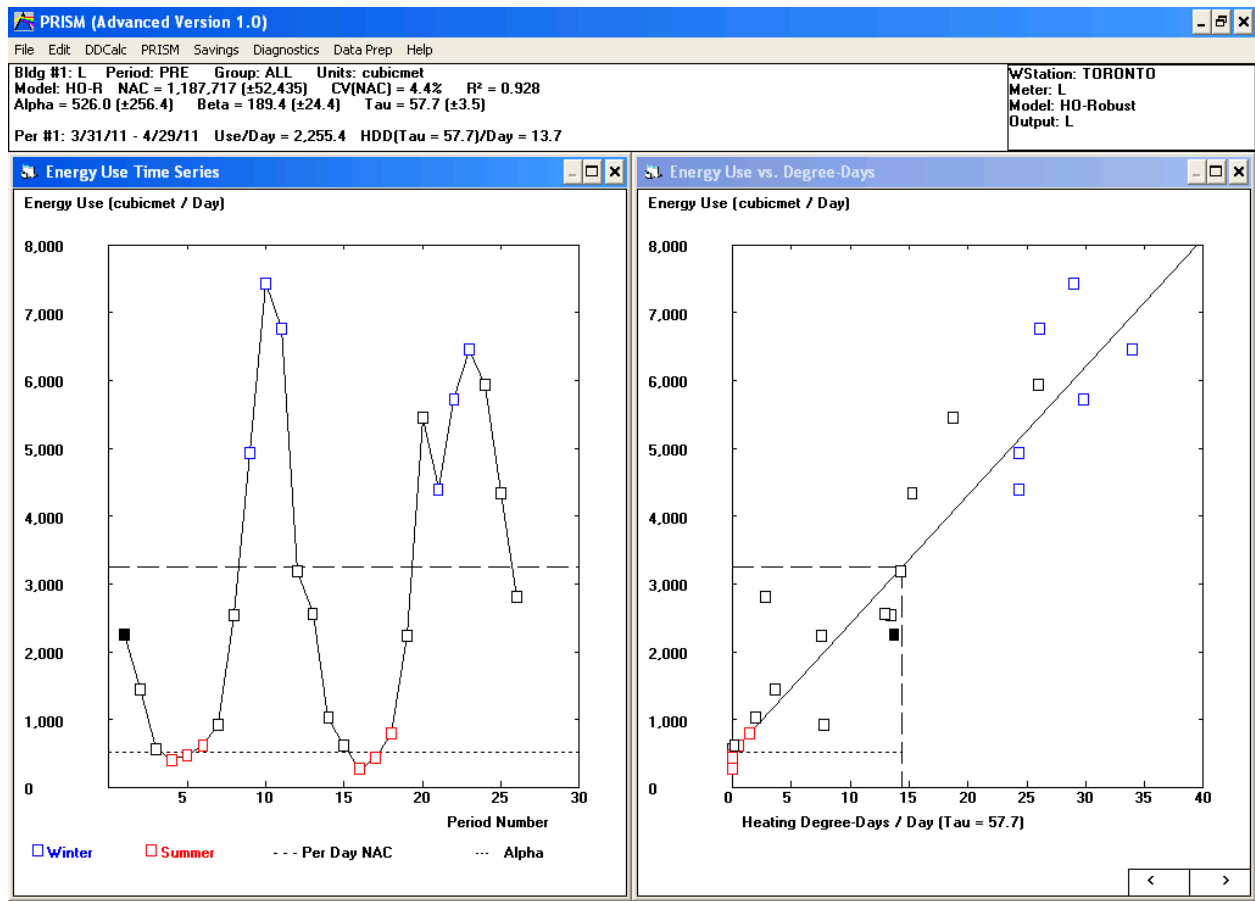


Figure A.0.12 Energy consumption plots for site 'L'

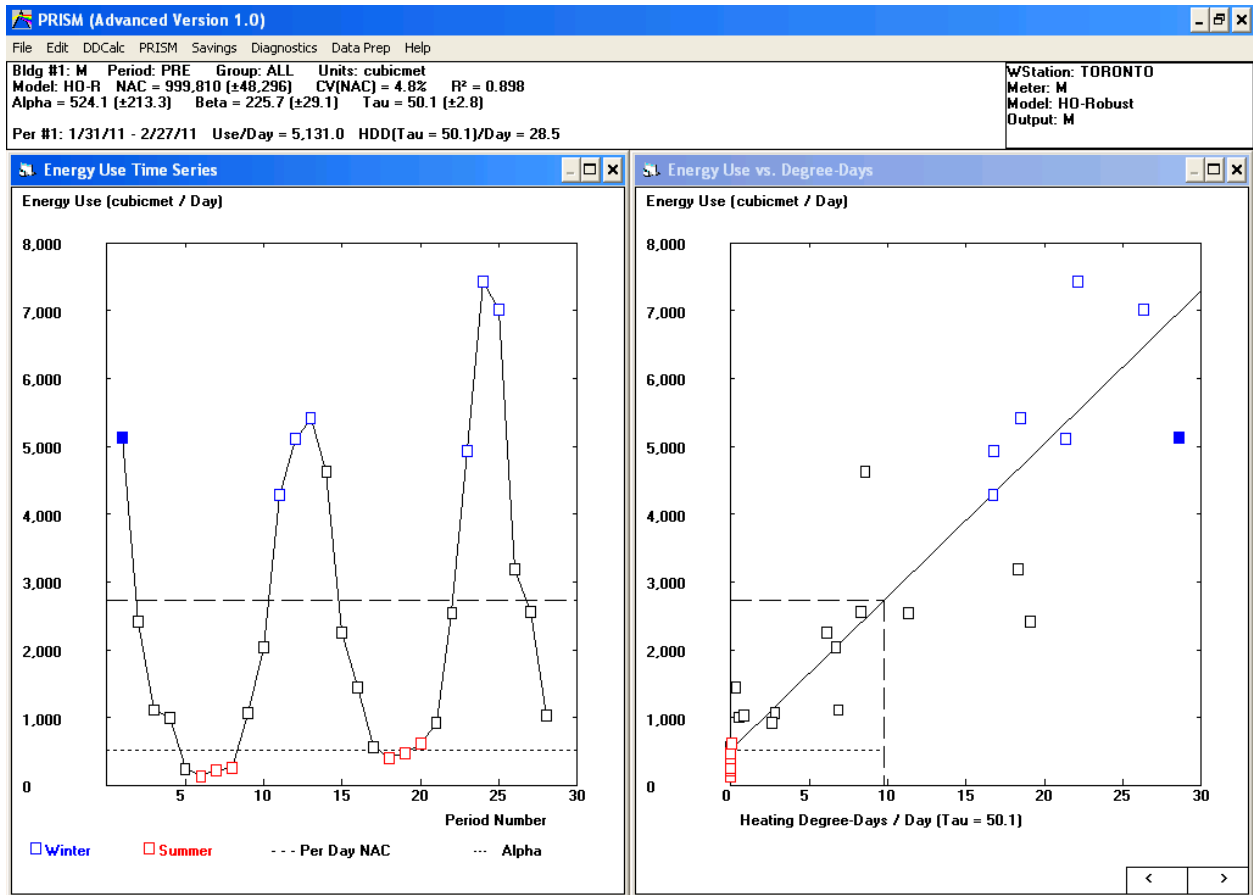


Figure A.0.13 Energy consumption plots for site 'M'

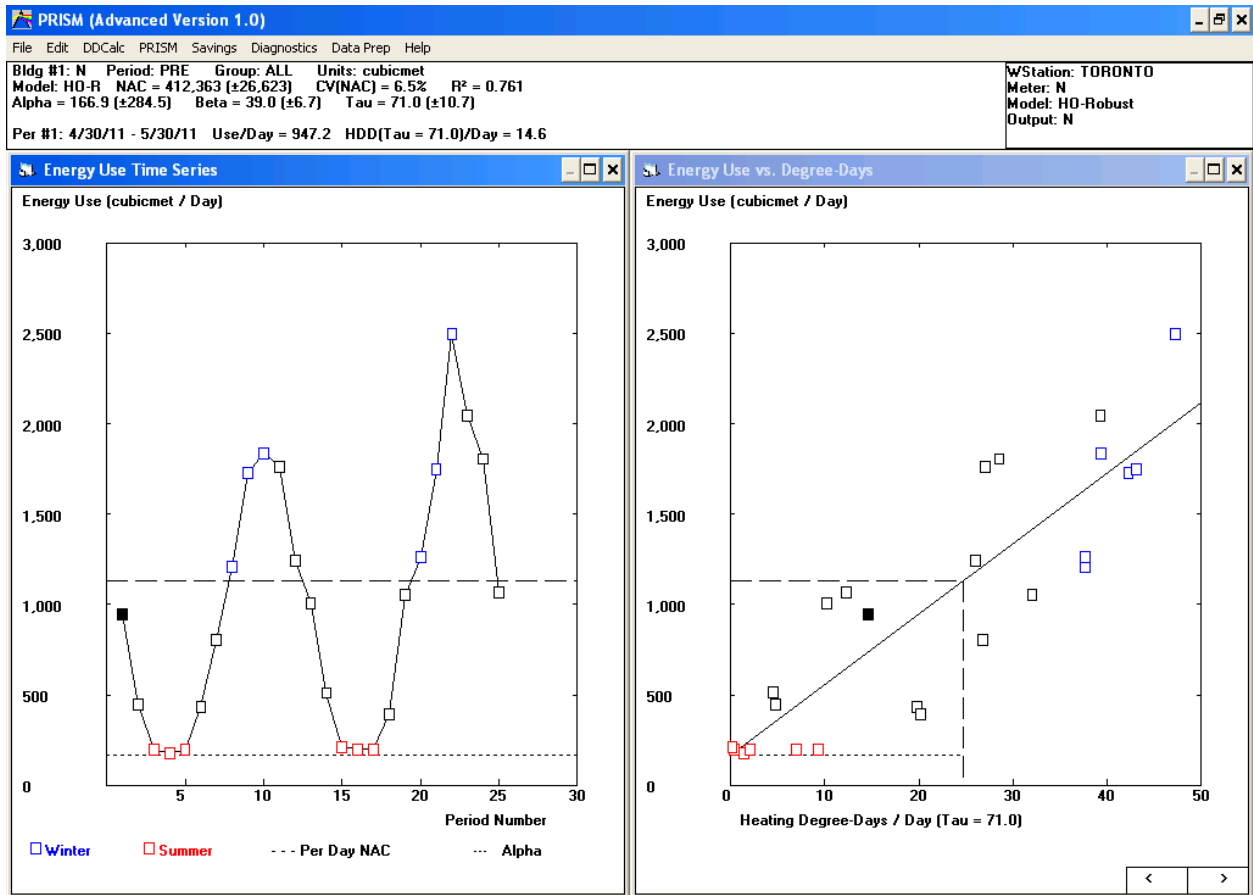


Figure A.0.14 Energy consumption plots for site 'N'

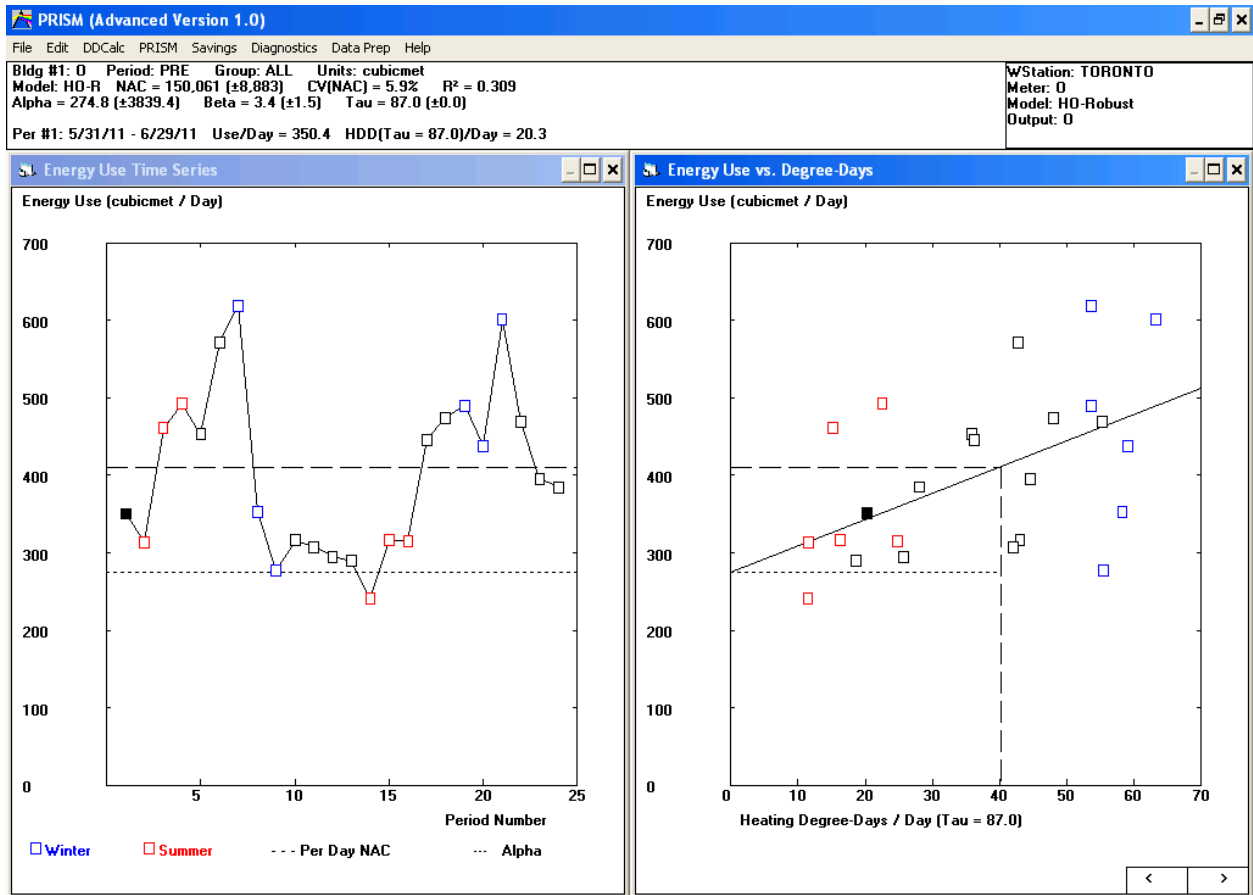


Figure A.0.15 Energy consumption plots for site 'O'

Appendix B: MATLAB Code for Boiler Efficiency

```
% Higher Heating Value of Fuel per BTU/lb
FuelHHVm = 22997;
% Higher Heating Value of Methane in BTU/cubic feet
MethaneHHV = 1015.1;
% Operational Hours
hr = input('Annual Operational Hours of the Boiler =');
% Rated Input in MMBTU/hr
RI = input('Rated Input of Boiler in MMBTU/hr =');
% Minimum Energy Input
Min = input('Minimum Energy Input of the Boiler in MMBTU/hr =');
% Firing Rate as Percentage of RI
FR = input('Percentage Firing rate =');
% Energy Input
E = Min + (RI - Min)*FR/100;
% Steam Pressure of the Boiler in pounds per square inch gauge
P_g = input('Steam Pressure in psig =');
% Steam Conditions
P = (P_g+14.7)*0.0689475729;
h_g = 0.429923 * XSteam('hV_p',P);
% Blowdown Rate
BD = input('Blowdown rate in percentage =');
B = BD/100;
h_bd = 0.429923 * XSteam('hL_p',P);
% Combustion Air Temperature in degrees Fahrenheit
T_a = input('Combustion Air Temperature in deg F =');
% Temperature of Feedwater
T_w = input('Temperature of feedwater in deg F =');
% Enthalpy of feed water in BTU/lb
h_w = T_w-32;
% Stack Temperature before Economizer in degrees Fahrenheit
T_i = input('stack temperature before economizer in deg F =');
% Stack Temperature after Economizer in degrees Fahrenheit
T_f = input('stack temperature after economizer in deg F =');
% Net Stack Temperature
dT = T_i - T_f;
% Percentage Oxygen by volume
O = input('percentage oxygen by volume =');
% Percentage Carbon Monoxide by parts per million
CO_ppm = input('Carbon Monoxide in ppm =');
CO = CO_ppm/10000;
% Percentage Hydrocarbons UHCs in parts per million
UHC = input('Hydrocarbons in % =');
% Excess Air by Volume as a function of Oxygen in Dry Flue Gas (DFG)
EA = (8.52*O/100)/(2-(9.52*O/100))*100;
```

% Theta
Theta = 400;
% Ratio of Volumes of Dry Flue gas to the volume of As Fired Fuel (AFF)
 $DFGAFF_v = 8.58 + (0.0289 * CO) + (EA * 0.0239 * Theta / 100);$
% Ratio of Volumes of Carbon dioxide to the volume of As Fired Fuel (AFF)
 $CO2AFF_v = 1.014 + (0.01 * CO);$
% Ratio of Volumes of Carbon dioxide to the volume of Dry Flue Gas (DFG)
 $CO2DFG_v = CO2AFF_v / DFGAFF_v * 100;$
% Ratio of Volumes of Nitrogen to the volume of As Fired Fuel (AFF)
 $N2AFF_v = ((0.01 * 0.0094) + (1 + EA / 100)) * 0.0189 * Theta;$
% Ratio of Volumes of Nitrogen to the volume of Dry Flue Gas (DFG)
 $N2DFG_v = N2AFF_v / DFGAFF_v * 100;$
% Ratio of Masses of Dry Flue gas to the volume of As Fired Fuel (AFF)
 $DFGAFF_m = ((11 * CO2DFG_v + 8 * O + 7 * (N2DFG_v + CO)) / (3 * (CO2DFG_v + CO))) * 0.7227;$
% Density of Dry Flue Gas (DFG)
 $Rho_DFG = DFGAFF_m * 0.04414 / DFGAFF_v;$
% Energy Loss due to Carbon Monoxide in Dry Flue Gas in BTU/lb of AFF
 $EL_CO = (CO / (CO2DFG_v + CO)) * 10160 * 0.7227;$
% Percentage Energy Loss due to Carbon Monoxide
 $L_CO = EL_CO * 100 / FuelHHV_m;$
% Energy Loss due to Hydrocarbons in Dry Flue Gas in BTU/lb of AFF
 $EL_HC = (UHC * DFGAFF_m * MethaneHHV) / (100 * Rho_DFG);$
% Percentage Loss due to Hydrocarbons
 $L_HC = EL_HC * 100 / FuelHHV_m;$
% Energy Loss due to Dry Flue Gas in BTU/lb of AFF
 $EL_DFG = DFGAFF_m * 0.24 * (T_i - T_a);$
% Percentage Energy Loss due to dry flue gas
 $L_DFG = EL_DFG / FuelHHV_m * 100;$
% Energy Loss due to Water Vapor in BTU/lb of AFF
 $h_wv = T_a - 32;$
 $EL_wv = 9 * 0.2397 * (1106 + 0.476 * (T_i - 102) - h_wv);$
% Percentage Energy Loss due to Water Vapor
 $L_w = EL_wv / FuelHHV_m * 100;$
% Percentage of Total combustion losses
 $L = L_CO + L_DFG + L_HC + L_w;$
% Combustion Efficiency
'Combustion Efficiency'
 $Eff_comb = 100 - L$
% Stack Losses in MMBTU/hr
 $SL = (1 - Eff_comb / 100) * E;$
% Radiation Losses
 $RL = RI / 100;$
% Blowdown Losses in MMBTU/hr
 $BL = (E - RL - SL) * (h_bd - h_w) * B / ((h_g - h_w) * (1 - B) + B * (h_bd - h_w));$
% Total Losses
 $TL = SL + RL + BL;$

```

%Energy in Steam
E_s = E-TL;
% Fuel to Steam Efficiency
'Boiler Efficiency'
Eff_Boiler = E_s* 100/E
% Steam Produced
M_g = E_s/(h_g - h_w);
% Snakey diagram for Energy
inputs = E;
losses = [RL BL SL];
unit = 'MMBTU/h';
labels = {'Input','RL','BL','SL','Output'};
sep = [1,3];
drawSankey(inputs, losses, unit, labels, sep);
% Sankey Diagram for $
cost_i = hr*E*0.25/35.44e-3;
cost_l = hr*losses*0.25/35.44e-3;
cost_unit = '$';
labels = {'Input','RL','BL','SL','Output'};
drawSankey(cost_i, cost_l, cost_unit, labels, sep);

```


Appendix C: Uncertainty Analysis

The uncertainty analysis presented in this section is for the following combustion test readings

- Temperature of air $= (95 \pm 0.72) ^\circ\text{F}$
- Stack Temperature $= (457.6 \pm 1.8) ^\circ\text{F}$
- Concentration of Oxygen in dry flue gas $= (10.5 \pm 0.2) \%$
- Concentration of carbon monoxide in dry flue gas $= (3 \pm 2) \text{ ppm}$
 $= (3 \pm 2) * 10^{-4} \%$
- Hydrocarbons in ppm $= 0 \pm 10\% \text{ of measured value}$

The uncertainty in the measured values were named as follows:

σ_1 is the uncertainty in percentage concentration of oxygen by volume of dry flue gas

σ_2 is the uncertainty in concentration of carbon monoxide by volume of dry flue gas

σ_3 is the uncertainty in concentration of hydrocarbons by volume of dry flue gas

σ_4 is the uncertainty in temperature of combustion air

σ_5 is the uncertainty in temperature of dry flue gas

Uncertainty analysis was performed on all the equations that involved the measured quantities mentioned above.

C.1 Excess Air

The percentage of excess air was calculated using Equation 3.16 while the uncertainty was calculated by applying operation '2' to the Equation 3.16.

$$\text{Percentage Excess Air} = \%XA = 89.1 \%$$

$$\text{Uncertainty in percentage excess air} = \sigma_6 = \pm 2.4\%$$

C.2 Analysis of Dry Flue Gas

Uncertainty in theta ' σ_7 ' was determined by applying operation '1' to Equation 3.18.

$$\theta = 400$$

$$\sigma_7 = \pm 0.2$$

The ratio of volumes of dry flue gas per unit volume of fuel could be determined using the in Equation 3.17. Uncertainty (σ_8) was determined by applying a combination of operation '1' and '2' to Equation 3.17.

$$\frac{\text{Volume of DFG}}{\text{Volume of Fuel}} = 17.1$$

$$\sigma_8 = \pm 0.48$$

Uncertainty in the volume of nitrogen per unit volume of fuel (σ_8) was determined by applying operation '2' on Equation 3.21.

$$\frac{\text{Volume of N}_2}{\text{Volume of Fuel}} = 14.3$$

$$\sigma_9 = \pm 0.18$$

Uncertainty (σ_{10}) in the percentage of nitrogen by volume of dry flue gas was determined applying operation '2' on Equation 3.22.

$$N_{2\text{dry}} = 83.6\%$$

$$\sigma_{10} = \pm 2.6 \%$$

Uncertainty (σ_{11}) in the mass of dry flue gas per unit mass of fuel was determined by using both operation '1' and '2' on Equation 3.23.

$$\frac{\text{Mass of DFG}}{\text{Mass of Fuel}} = 29.8$$

$$\sigma_{11} = \pm 1.03$$

C.3 Stack Losses

Uncertainty (σ_{12}) in the percentage heat loss due to dry flue gas was determined by using both

operation '1' and '2' on Equation 3.27.

$$\% \text{ Heat loss to DFG} = 11.3\%$$

$$\sigma_{12} = \pm 0.4\%$$

Uncertainty (σ_{13}) in the percentage heat loss due to water was calculated using operation '1' on Equation 3.30.

$$\% \text{ Heat loss to Water Vapor} = 11.4 \%$$

$$\sigma_{13} = \pm 1\%$$

Uncertainty (σ_{14}) in the combustion efficiency was determined by applying operation '1' on stack losses.

$$\eta_{\text{comb}} = 77.3 \%$$

$$\sigma_{14} = \pm 0.4 \%$$

Operation '1' was applied to Equation (3.37)

$$SL = 0.3632 \text{ MMBTU/h}$$

$$= 363.2 \text{ BTU/h}$$

$$\sigma_{15} = \pm 6.4 \text{ BTU/h}$$

C.4 Boiler Efficiency

For calculating boiler efficiency blowdown and radiation losses were estimated. Applying operation '1' on the Equation 3.42 to Equation 3.44, boiler efficiency and the uncertainty in the calculation were determined.

$$\eta_{\text{boiler}} = 77.3 \%$$

$$\sigma_{15} = \pm 0.42 \%$$

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