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Auditing and Analysis of Natural Gas Consumptions in Small- and Medium-Sized Industrial Facilities in the Greater Toronto Area for Energy Conservation Opportunities

Altamash Ahmad Baig, Alan S. Fung * and Rakesh Kumar

Mechanical, Industrial and Mechatronics Engineering Department, Toronto Metropolitan University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada
* Correspondence: alanfung@torontomu.ca

Abstract: This paper presents the findings of fifteen energy audits conducted on industrial sites in Canada's Greater Toronto Area (GTA). The audits covered a range of industries including food processing, packaged goods, and finishing processes (powder-coating). The primary focus of the audits was to analyze the natural gas consumption and the performance of major-gas-consuming equipment. The audits identified natural-gas-consuming equipment that could be optimized to yield energy and operational cost savings and greenhouse gas (GHG) reduction opportunities. Food production plants' energy intensity ranges from 5.59 m^3/ft^2 to 17.73 m^3/ft^2. Therefore, there is a significant opportunity to improve energy consumption through better technology integration. The results of the audits indicate a trend of an increase in the percentage of non-productive consumption with non-productive time. The proposed energy-saving measures include reducing non-productive natural gas consumption, gas-fired equipment tune-up, optimizing boiler loads, and reducing oven exhaust by using variable frequency drives (VFDs). The findings of this study could be used to develop a demand-side management program specifically for small- and medium-sized industrial facilities in the Greater Toronto Area and other parts of Canada.

Keywords: energy consumption; energy efficiency; energy audit; greenhouse gases; PRISM analysis; small- and medium-sized enterprises (SMEs)

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1. Introduction

In the past few decades, industries have encountered several challenges in their efforts to remain competitive, including globalization, cost-cutting measures, and regulations to address climate change. Achieving a low-carbon economy requires an understanding of energy utilization in industrial plant operations and the incorporation of technological advancements. Energy conservation and efficiency have undeniably received substantial attention in recent decades. Advancements in technology have created opportunities to reduce wasteful energy consumption in all sectors of the economy [1]. In Canada, provinces and municipalities have implemented policies and programs to promote energy conservation, cut operational costs, and decrease industrial carbon footprint. Conducting an energy audit analysis is crucial for effective energy management in industrial facilities. The process involves data collection, analysis, and improvements in equipment and operational procedures [2].

Despite the potential benefits of energy conservation, it needs to be more widely adopted in small- and medium-sized enterprises (SMEs) to significantly benefit the overall economy and the environment. SMEs are responsible for a significant portion of the global workforce [3] and many businesses [4]. According to Calogirou et al. [5], SMEs are responsible for up to 64% of the environmental impact made in the European Union and up to 70% of industrial pollution globally [6]. In 1973, the Canadian Industry Program for Energy Conservation (CIPEC) was established to create sector task forces that could identify energy efficiency opportunities, address barriers associated with industrial energy conservation, and develop strategies for saving measures [7]. Between 1973 and 1990, the program achieved incremental energy savings of 26.1% per unit of production and reduced emissions by 30.4% among Canadian industries.

Globally, there is increasing concern about improving SMEs' environmental and social performance [8,9]. SMEs may be reluctant to invest in energy efficiency due to perceived barriers, including a lack of capital, knowledge, and time and competing priorities such as short-term benefits over long-term goals. Overcoming these barriers often requires targeted support and policy initiatives tailored to SMEs' specific demands and constraints [7,10]. SMEs need more information on the benefits of energy conservation to adopt technological advancements. SMEs are small and usually do not have in-house expertise and/or cannot afford to hire external consultants to conduct detailed and costly energy audits that may or may not result in any benefits [11]. One of the objectives of this study was to create user-friendly Excel tools that SMEs can use to conduct energy analyses of their plants before seeking external support.

The authors have identified a few notable studies from the extensive literature that align with this paper's objectives. The Industrial Assessment Centre (IAC), part of the US Department of Energy, has conducted energy audits of 9034 manufacturing plants for SMEs. As a result of these audits, 38,920 energy management projects have been recommended, with an average implementation cost of $7400. The savings from these projects were estimated to be $5600 per year, with a payback period of only 1.29 years [12]. According to Barbose et al., the spending on electricity and natural gas efficiency measures is expected to rise to $6.5 billion in the low-spending scenario, $9.5 billion in the medium-spending scenario, and $15.6 billion in the high-spending scenario by the year 2025 [13]. Thollander et al. conducted a study to emphasize the significance of characterizing process energy to reduce costs, improve efficiency, and minimize the carbon footprint. They identified obstacles that impede SMEs from implementing energy-saving measures, including time constraints, priority given to non-energy-related tasks, organizational structure, and lack of internal expert competencies [14]. Ahmed et al. conducted audit analyses of several Greater Toronto Area (GTA) SMEs to review the energy used and saving opportunities thoroughly [15]. The results showed that the facilities performing inefficiently could reduce their total natural gas consumption by an average of 9% from mechanical ventilation, 25% from transmission heat loss, and 10% from infiltration loss, compared to the top-performing facility. Boyd et al. have introduced the concept of an "Energy Performance Indicator" for manufacturing plants based on a statistical technique that provides a clear idea of industrial energy consumption, inefficiency, and saving opportunities [16]. The Canadian government has reported that the electricity in the province of Ontario is relatively clean, with an average emission of around 30 g of CO_2 per kilowatt-hour. In comparison, the emission of natural gas is 1.921 kg of CO_2 per cubic meter of natural gas (or equivalent of 185 g of CO_2 per kilowatt-hour) [17]. This means that more conservation efforts are needed to reduce the demand for natural gas in the provinces in order to achieve a significant reduction in greenhouse gas emissions.

Industrial plant energy audits are conducted at various levels of complexity, with the costs increasing based on the depth of analysis [18,19]. There are four energy audit levels: Level 0, which involves benchmarking based on historical data; Level 1, which is a walkthrough audit; Level 2, which is a detailed energy audit; and Level 3, which is an investment-grade audit. Benchmarking is the simplest approach to improving a plant's efficiency, while an investment-grade audit is much more complex and requires significant capital investment. It involves a comprehensive analysis of energy conservation measures, including a rigorous engineering study, simulation analysis, additional measurements, and tests. As a part of Enbridge's demand-side management program, this Level 2 study focused on conducting energy audits for SMEs located in the Greater Toronto Area (GTA), Canada [20]. The objective of the study was to identify opportunities for natural gas savings and consolidate the data gathered from the energy audits. In addition, the study aimed to develop and provide simple and easy-to-use Excel-based tools for SMEs to conduct their own energy analyses using the available high-level information without requiring external consultants.

2. Methodology

The methodology comprises several crucial steps that aim to evaluate energy consumption, identify areas for improvement in inefficiencies, and suggest measures for improvement. The process involves defining the objective and scope of analysis, selecting the site and collecting data, analyzing the consumption of natural gas, segregating productive and non-productive gas consumption, conducting weather normalization analyses to differentiate between weather-dependent consumption, estimating the marginal cost for potential savings, and selecting an appropriate greenhouse gas emission factor. The procedure is illustrated in Figure 1.

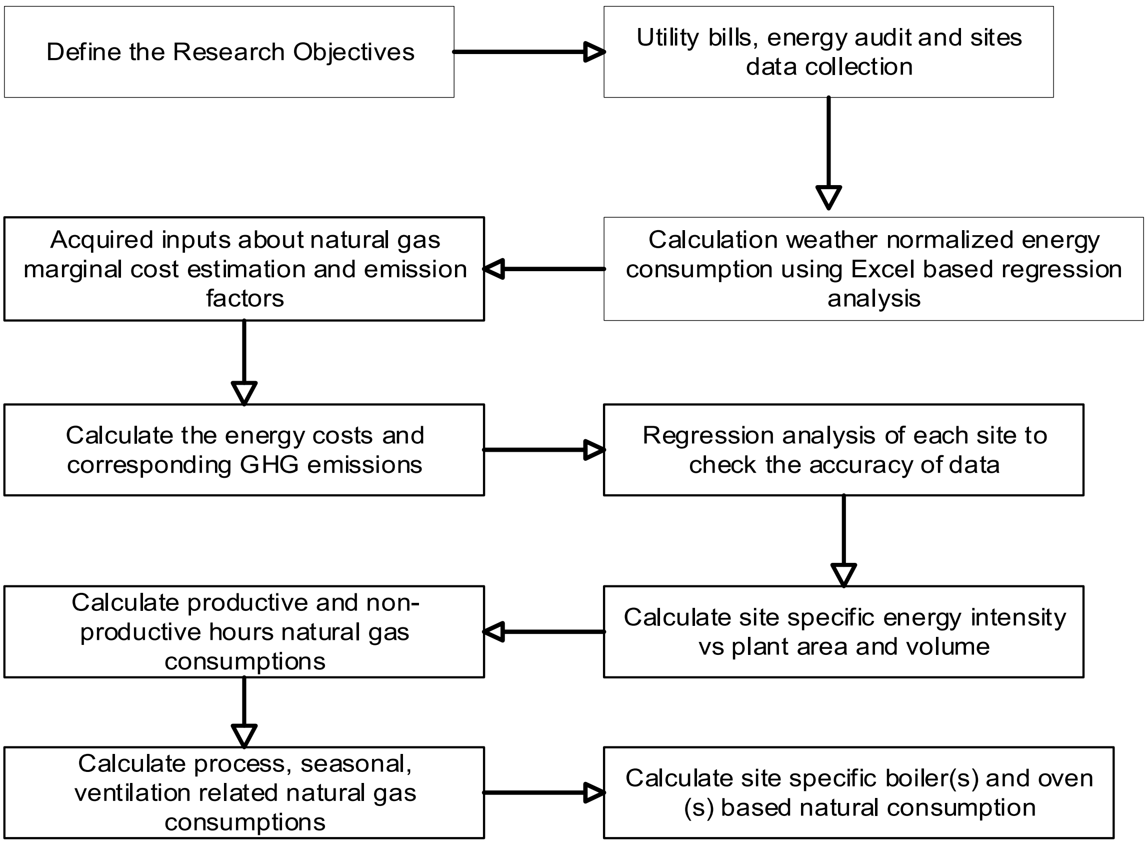

Figure 1. Flowchart of natural gas energy consumption audit of the chosen industrial plants.

2.1. Site Selection and Data Collection

Enbridge Gas Distribution Inc. conducted energy audits on selected sites belonging to the food industry, packaged goods, or finishing process (powder-coating industry). The intent was to identify trends in energy consumption for specific industrial sectors. To maintain confidentiality, a non-disclosure agreement (NDA) was signed for each industrial site, and they were each assigned an alphabetical letter (Site A, Site B, etc.).

2.2. Natural Gas Consumption Analysis

Over a period of three years, the research team gathered data on natural gas utility bills, as well as information on plant operational hours, site area, energy end-uses, and the age of industrial plants. Using these data, the authors calculated overall gas consumption, average annual gas consumption, average monthly gas consumption, and gas consumption per unit area. The team also collected plant data on hourly, daily, and monthly gas consumptions, which were used to calculate productive and non-productive plant operation gas consumptions.

2.3. Productive and Non-Productive Consumption

Industrial facilities have two types of energy consumption: productive and non-productive. Productive time refers to periods when the facility is operational, while non-productive time refers to periods when it is not. To reduce energy consumption during non-productive times, the plant's weekly production schedules determine non-operational hours, such as holidays or weekly off days. It is necessary to know the operational hours of the plant and energy consumption data during operational time in such cases. If there are daily or hourly consumption data available, then it is possible to determine the consumption for productive and non-productive times by correlating the consumption with working days and operational hours.

2.4. Weather Normalized Energy Consumption

Weather normalization is the process of estimating energy consumption based on the outside dry-bulb temperature, and the predicted energy consumption is known as the weather-normalized energy consumption. Two critical factors affect weather normalization: heating degree days (HDDs) and cooling degree days (CDDs). Heating degree days (HDDs) represent the weather conditions and space heating requirements in winter, while cooling degree days (CDDs) reflect summer weather conditions and the cooling requirements of the building. Since this study focused on natural gas consumption 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 necessary for a building. The reference temperature varies based on the building type, occupancy level, wall thickness, building envelope, and internal heat generation [21,22]. For this study, RETScreen 4 version 4 was used for the weather-normalization analysis for the natural gas consumption of the industrial buildings presented in this study [23,24].

The energy consumed by a building is divided into two parts—base load and weather-dependent load. For the regression model, energy consumption was taken as the dependent variable while heating degree day was selected as the independent variable. The correlation between these two variables was determined using the coefficient of correlation, R^2. The value of R^2 ranges between 0 and 1, where 0 means that there is no relationship between two variables and 1 indicates a perfect correlation between them. In order to obtain a reliable estimate for normalized annual consumption (NAC), the R^2 value should be higher than 0.7 and the coefficient of variation (CV) should be less than 7% [25,26].

Data for daily mean temperatures from the Toronto weather station over the past 30 years were retrieved from Environment Canada's Climate Data and Information Archive [27]. The daily mean temperatures were used to calculate the long-term heating degree days.

The normalized annual consumption (NAC) can be determined using Equation (1).

$$\begin{gathered}\text{NAC} = \text{Process consumption} + \text{Space heating consumption} + \text{Space cooling consumption} \\ \text{NAC} = 365\ \alpha + \delta_h\ \beta_h\ H_o(\tau_h) + \delta_c\ \beta_c\ C_o(\tau_c)\end{gathered} \tag{1}$$

where

α—daily base level consumption;
β_h—daily consumption per heating degree day;
β_c—daily consumption per cooling degree day;
$H_o(\tau_h)$—long-term average heating degree days per year;
$C_o(\tau_c)$—long-term average cooling degree days per year;
δ_h—'1′ for heating only (HO) and "combined heating and cooling" (HC) model, otherwise zero;
δ_c—'1′ for cooling only (CO) and "combined heating and cooling" (HC) model, otherwise zero.

For the heating-only model, Equation (2) is revised since no natural gas consumption occurs for cooling.

$$\text{NAC} = 365\ \alpha + \delta_h\ \beta_h\ H_o(\tau_h) \tag{2}$$

$$\text{NAC} = \text{Process Consumption} + \text{Seasonal Consumption} \tag{3}$$

Seasonal consumption can be classified into two categories: consumption for ventilation and consumption for space heating. The consumption for ventilation can be calculated using Equation (4).

$$\text{Consumption for ventilation} = \frac{1.08 * \text{CFM} * \left(\tau - \overline{\text{T}}_{\text{od}}\right) * \text{hours of operation}}{\eta_{\text{equipment}} * \text{HHV}_{\text{V}}} \tag{4}$$

where

CFM—ventilation rate;
τ—reference temperature from the regression analysis;
$\eta_{\text{equipment}}$—thermal efficiency of make-up air unit (%);
HHV_{V}—higher heating value of natural gas on volume basis;
$\overline{\text{T}}_{\text{od}}$—long term average outdoor temperature.

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

2.5. Marginal Cost of Natural Gas

To determine the value of natural gas savings, it was essential to figure out how much the total gas utility bills changed due to the change in natural gas consumption. This change in the cost per unit of gas consumption is known as the marginal cost of natural gas. The marginal cost was calculated by adding all the consumption-dependent charges on the gas utility bill, such as gas supply, cost adjustment, transportation, and storage and delivery charges. Fixed charges, which are the monthly charges that are not dependent on gas consumption, were not included in the marginal cost calculation. (Table 1).

Table 1. Monthly charges and rates for industrial customers of Enbridge Gas [28].

Monthly Charges	Monthly Rates 1 January 2014
Customer charge	CAD 70
Gas supply charge	CAD 0.127159/m^3
Delivery to customer	See breakdown in Table 2
Transportation to Enbridge	CAD 0.49665/m^3

The delivery charges to the customer vary with the natural gas consumption. The delivery charge for the first 500 m^3 of natural gas consumed is CAD 0.81357/m^3 but falls to CAD 0.39853/m^3 for natural gas consumption of over 28,300 m^3. A complete breakdown of the variation in delivery charges is shown in Table 2. Since the chosen industrial customers consumed well over 28,300 m^3, the delivery charge used in the study for the calculation of marginal cost was CAD 0.39853/m^3.

The monthly charges for industrial customers of Enbridge Gas include a cost adjustment charge, which covers the cost of gas supply, transportation, and delivery. The breakdown of the cost adjustment charge is shown in Table 3. Based on the assumption and rates mentioned above, the marginal cost of natural gas for industrial customers of Enbridge Gas at the time of this study was 20.72 cents (CAD) per cubic meter (m^3), as indicated in Table 4. This means that any increase or decrease of 1 m^3 in the consumption of natural gas would result in a corresponding increase or decrease of 20.72 cents (CAD) in the fuel cost for the customer.

Table 2. Breakdown of delivery charges [28].

Delivery to Customer Breakdown	
Amount of gas used per month in cubic meters	Cost in CAD cents per cubic meter (¢/m^3)
First 500	8.1357
Next 1050	6.4065
Next 4500	5.1958
Next 7000	3.10177
Next 15,250	4.0721
Over 28,300	3.9853

Table 3. Cost adjustment along with the individual components [28].

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

Table 4. Marginal cost to industrial customers of Enbridge Gas [28].

Charge	**Rate (¢/m^3) (CAD)**
Gas supply charge	12.7159
Transportation to Enbridge	3.15665
Cost adjustment	0.8620
Delivery to Customer	3.9853
Total Marginal Cost	20.72

2.6. Greenhouse Gas Emission Factor

Energy conservation has the additional advantage of reducing greenhouse gas emissions. The greenhouse gas emission factors, measured in grams of carbon dioxide per cubic meter of natural gas in Canada, were documented in Canada's National Inventory Report 1990–2009 [17]. According to the report, Ontario's greenhouse gas emission factor for natural gas is 1879 g of CO_2 per cubic meter, which was taken for this study's analysis.

3. Results and Discussion

The following section presents the results of energy audits analysis conducted on selected SMEs, divided into two sections: natural gas consumption and major equipment powered by natural gas. As stated earlier, to maintain confidentiality, the industrial sites have been given alphabetical letters. Additionally, the results have been tabulated to allow similar industrial sites to be grouped together. For example, Sites A through D belong to the food manufacturing sector, Sites E and F belong to the packaged goods sector, and the rest belong to the finishing process industry (Table 5). The results of energy audits conducted at each site are presented in the following sections.

3.1. Natural Gas Consumption

The study analyzed the consumption of NG at the audited sites to evaluate different performance indicators. These indicators include the annual natural gas consumption, energy intensity, annual cost of natural gas, yearly greenhouse gas emissions, the natural gas consumption during productive and non-productive hours of the plant, the base level (or process) energy consumption, and the weather-dependent energy consumption.

Table 5. Average annual natural gas consumption, associated annual cost, greenhouse gas emissions, and energy intensities for the audited sites.

Site	Type of Industry	Natural Gas Consumption (m^3/Year)	Cost (CAD /Year)	GHG Emission (Tonnes CO_2/Year)	Site Area (ft^2)	Energy Intensity (m^3/ft^2)
A	Food	3,369,563	759,152	6331	190,008	17.73
B		676,090	152,321	1270	60,000	11.27
C		1,040,399	234,399	1955	186,026	5.59
D		544,200	122,607	1023	40,000	13.61
E	Packaged Goods	987,794	222,547	1856	186,500	5.30
F		628,339	141,563	1181	270,000	2.33
G	Finishing Process	625,765	140,983	1176	70,000	8.94
H		340,017	76,605	639	100,000	3.40
I		447,889	100,908	842	46,609	9.61
J		492,795	111,025	926	65,000	7.58
K		290,981	65,557	547	110,270	2.64
L		1,283,047	289,067	2411	213,668	6.00
M		886,747	199,781	1666	121,762	7.28
N		373,955	84,251	703	61,756	6.06
O		153,529	34,590	288	10,573	14.52

3.1.1. Natural Gas Consumption from the Collected Data

The preliminary results from the utility bills data show the average annual natural gas consumption, associated annual cost, and annual greenhouse gas emissions for all the audited plants. Table 5 shows that Site A has the highest natural gas consumption among all the sites, with an average of close to 3.4 million m^3. As a result, Site A not only has the largest annual cost but also the highest greenhouse gas emissions. Excluding Site A, the audited sites belonging to the food sector had annual natural gas consumption ranging between 500,000 m^3 and 1,000,000 m^3. Annual natural gas consumption for sites belonging to the packaged goods sector (i.e., Sites E and F) remained below 1,000,000 m^3. Annual natural gas consumption for the finishing process industries was found to vary from 153,529 m^3 for Site O to 1,283,047 m^3 for Site L. The audited sites vary in size, operational hours, and equipment performance. The effects of these parameters were studied and presented in the subsequent sections.

The annual natural gas consumption of any facility is dependent on the size of the plant and production level and its internal processes and equipment. The greater the size of the plant, the greater the natural gas consumption. The natural gas consumption per unit area, also called energy intensity, was calculated. The energy intensities of the audited sites are also presented in Table 5 (and Figure 2). Site A had the highest energy intensity at 17.73 m^3/ft^2, while Site F had the lowest energy intensity at 2.33 m^3/ft^2. The high-energy-intensity range of similar industries (such as those of food production plants, which vary from 5.59 m^3/ft^2 to 17.73 m^3/ft^2) implies potential for improved energy consumption through similar industries by better technology integration.

3.1.2. Natural Gas Consumption and Hours of Operation

Annual natural gas consumption is also affected by the number of hours the plant operates. The plant's natural gas consumption per hour of operation has been presented in Table 6. Site L had the highest natural gas consumption per hour of operation at 642 m^3/h, while Site O had the lowest consumption per hour at 49 m^3/h. Excluding Site A, the consumption of the food sector industries ranged between 73 m^3/h and 167 m^3/h. The packaged goods industries had consumption between 75 m^3/h and 158 m^3/h. The consumption of the finishing process industries ranged from 49 m^3/h to 641 m^3/h. The high energy intensity of similar industries suggests significant potential for energy savings through technological integration and better plant operation practices.

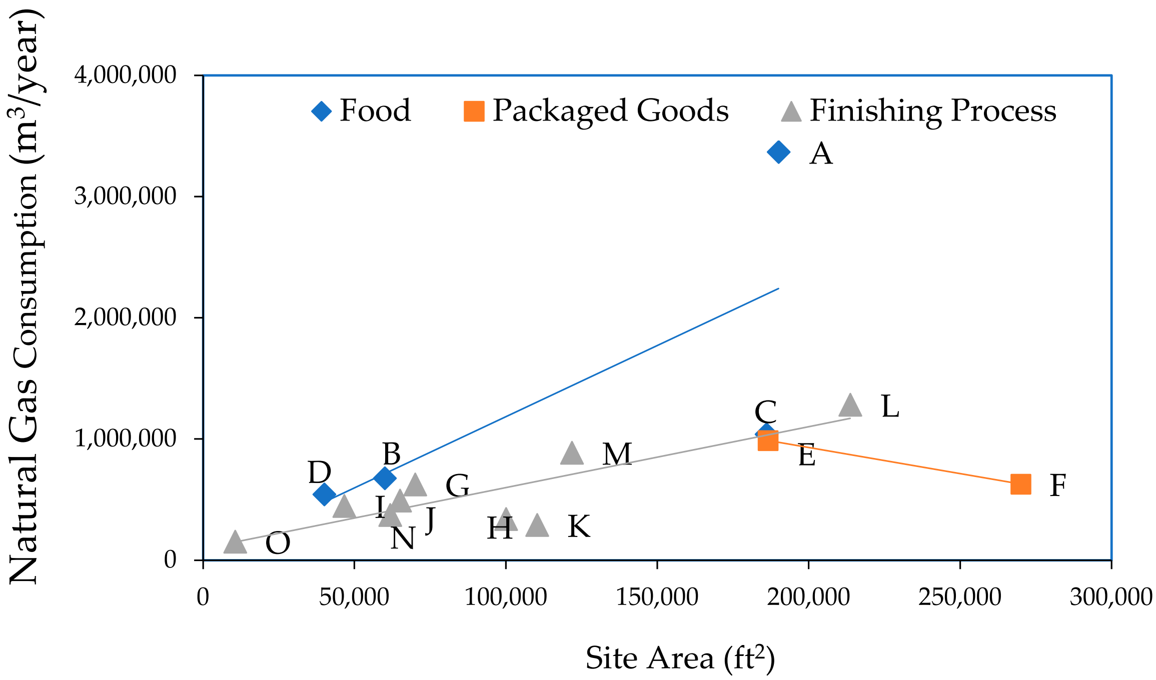

Figure 2. Annual natural gas consumption vs. site area.

Table 6. Natural gas consumption per hour of operation for audited sites.

Site	Type of Industry	Average Annual Consumption (m^3/Year)	Annual Hours of Operation (h/Year)	Energy Per Hour of Operation (m^3/h)
A	Food	3,369,563	6240	540
B		676,090	5616	120
C		1,040,399	6240	167
D		544,200	7488	73
E	Packaged Goods	987,794	6240	158
F		628,339	8400	75
G	Finishing Process	625,765	2500	250
H		340,017	3640	93
I		447,889	2210	203
J		492,795	2080	237
K		290,981	2000	145
L		1,283,047	2000	642
M		886,747	8320	107
N		373,955	2600	144
O		153,529	3120	49

Figure 3 shows the natural gas consumption for the audited sites, plotted against hours of operation. It can be observed that the sites operating less than 5000 h per year had natural gas consumption of less than 650,000 m^3 per year. However, Site L was an exception, with 2000 h of operation and a consumption of 1,283,047 m^3. For sites operating for more than 5000 h per year, the lowest natural gas consumption was 544,200 m^3 for Site D, while the highest was 3,369,563 m^3 for Site A.

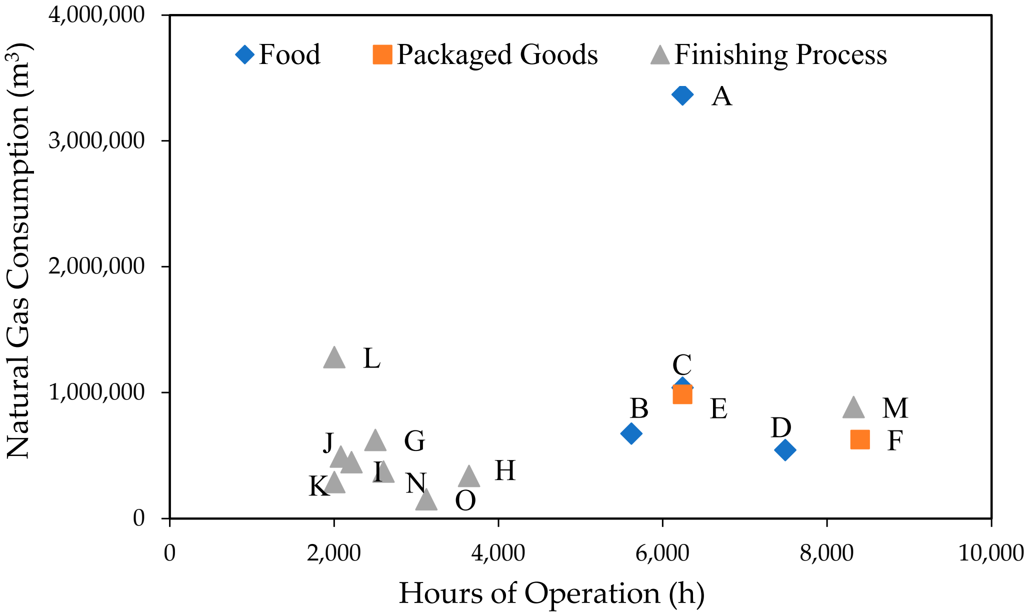

Figure 3. Annual natural gas consumption vs. hours of operation.

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 4. Energy intensity per hour of operation for the sites belonging to the food sector increased 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 the 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 an increase in area for site areas less than 150,000 ft^2. However, Site L, which had a site area greater than 200,000 ft^2, showed a high energy intensity per unit hour of operation.

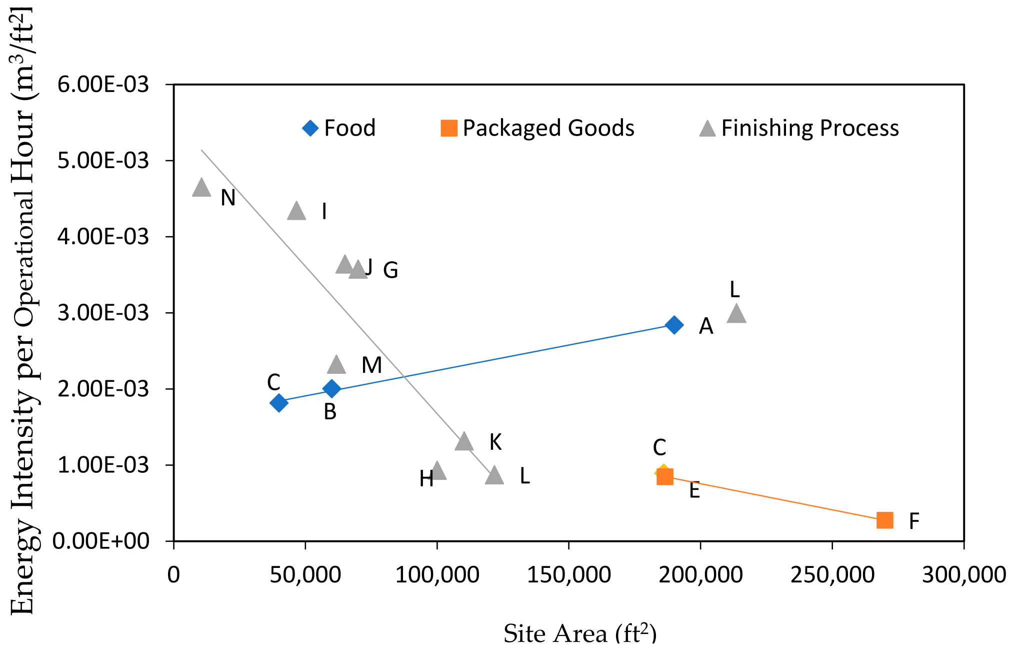

Figure 4. Energy intensity per unit hour of operation vs. site area.

3.1.3. Productive and Non-Productive Natural Gas Consumption

The annual non-productive consumption of the audited sites is presented in Table 7. It can be seen that Site A had the highest non-productive consumption at 677,810 m^3 (20% of the annual consumption) for 2520 of the non-productive hours (i.e., 29% of the hours in a year). This implied that 20% of the annual natural gas consumption and fuel costs were incurred during 29% of the time in the year when the site was not making any products or income. Sites J and L had an even higher percentage of 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., 6680 h (76% of the year) and 6760 h (77% of the year), respectively. On the other hand, Site F had the lowest non-productive consumption at 12,798 m^3 for 360 h 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 h daily schedule, only shutting down on statutory holidays or for scheduled maintenance.

Table 7. Average annual non-productive natural gas consumption.

Site	Average Annual Non-Productive Consumption (m^3/Year)	Percentage of Annual Consumption (%)	Average Annual Non-Productive Time (h/Year)	Percentage of Total Hours in a Year (%)
A	677,810	20	2520	29
D	49,166	9	1272	15
E	75,710	8	2520	29
F	12,798	2	360	4
G	844,18	13	6260	71
H	28,719	8	5120	58
I	56,490	13	6550	75
J	123,000	25	6680	76
L	273,395	21	6760	77
N	53,885	14	6160	64

The relationship between the percentage of non-productive time and the percentage of non-productive consumption is presented in Figure 5. Generally, with the increase in the percentage of non-productive time, the percentage of non-productive consumption also increased. The percentage of non-productive time for the sites belonging to the food and packaged goods sectors remained below 30% of the time in a year. The non-productive consumption for food and packaged goods sites remained below 20% of the annual natural gas consumption. For the sites in the finishing process sector, the non-productive times accounted for 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 natural-gas-fired equipment was kept running and/or in standby mode. Therefore, there is an opportunity to achieve considerable natural gas savings by reducing non-productive natural gas consumption through better management and housekeeping practices.

Average daily non-productive consumption was calculated and compared to average productive consumption for each audited site. Non-productive consumption has been presented as a percentage of productive consumption in Table 8. The percentage of non-productive consumption ranged from 29% to 72% of the productive consumption. This meant that, even when the industrial plants were not in operation, they still consumed considerable natural gas. This indicated that the audited sites were incurring substantial costs for natural gas consumption even when there was no production.

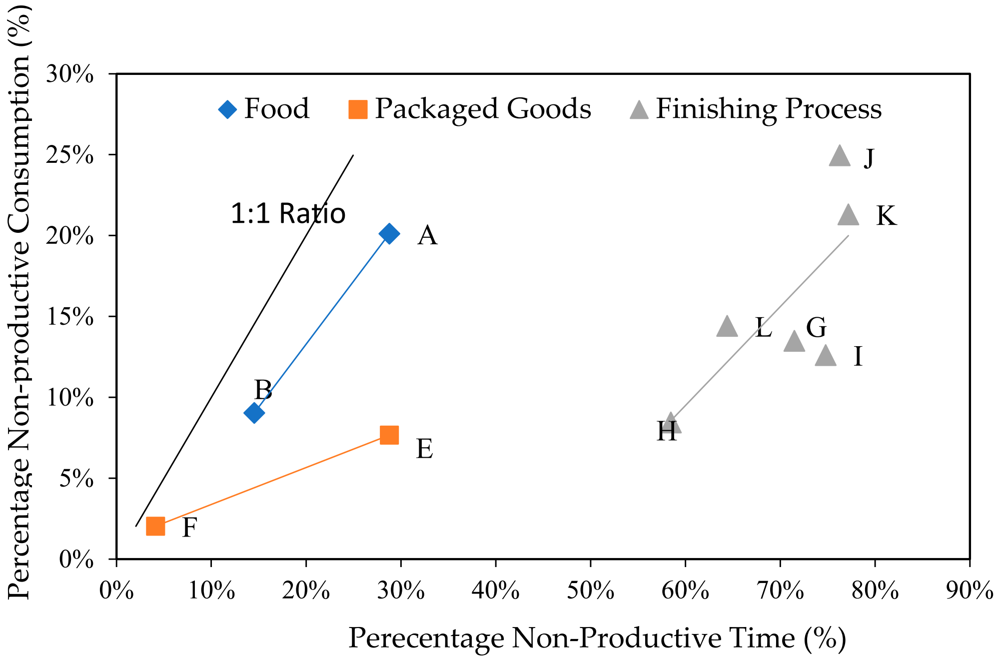

Figure 5. Percentage non-productive time and percentage non-productive consumption.

Table 8. 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	6368	59
D	1630	806	49
E	2250	670	30
F	1768	1422	72
H	1239	365	29
I	1537	620	40
J	1715	683	40
L	11,837	7139	60
N	1385	922	70

3.1.4. Normalized Natural Gas Consumption

Energy consumption in any facility is influenced by the processes and activities going on inside the facility and outside weather conditions. As the outside temperature 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 RETScreen was conducted. Heating degree days calculated from historical weather data from 1 January 1978 to 31 May 2013 were taken as the independent variable and the natural gas consumption obtained from utility bills was taken as the dependent variable for each site. The linear regression analysis provided base-level and weather-dependent consumption for each audited site. The base-level consumption was termed "process consumption", while the weather-dependent consumption was termed "seasonal consumption". The reference temperature for heating for an industrial site is the value for when no heating is required. When the outside temperature drops below the reference temperature, heating would be required to maintain the indoor temperature. The results of the RETScreen analysis are presented in Table 9.

Table 9. Results of linear regression analysis from RETScreen.

Site	Normalized Annual Consumption (NAC) (m^3/Year)	Process Consumption (m^3/Year)	Seasonal Consumption (m^3/Year)	Coefficient of Correlation (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 RETScreen allowed the natural gas consumption to be classified into two distinctly identifiable categories, i.e., process and seasonal consumption, presented in Figure 6. In addition, it also provided the normalized annual consumption based on historical weather data for the past 35 years.

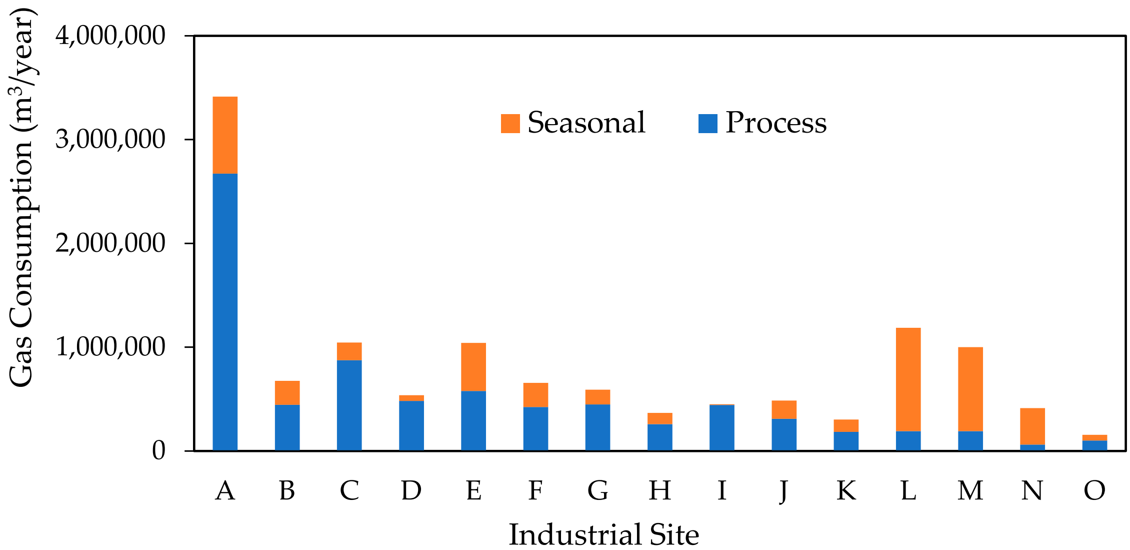

Figure 6. Process and seasonal natural gas consumption.

It is evident from Figure 6 that a major portion of natural gas consumption is for process end-use. Only Sites L, M, and N, which conducted a lot of drying and curing activities 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 are plotted in Figures 7 and 8.

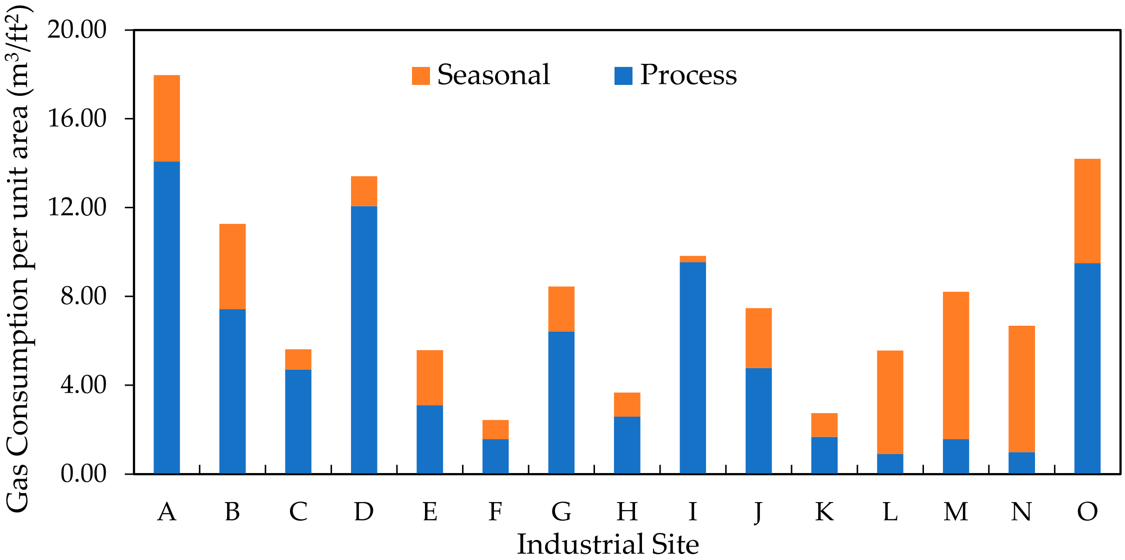

Figure 7. Process and seasonal natural gas consumption per unit area.

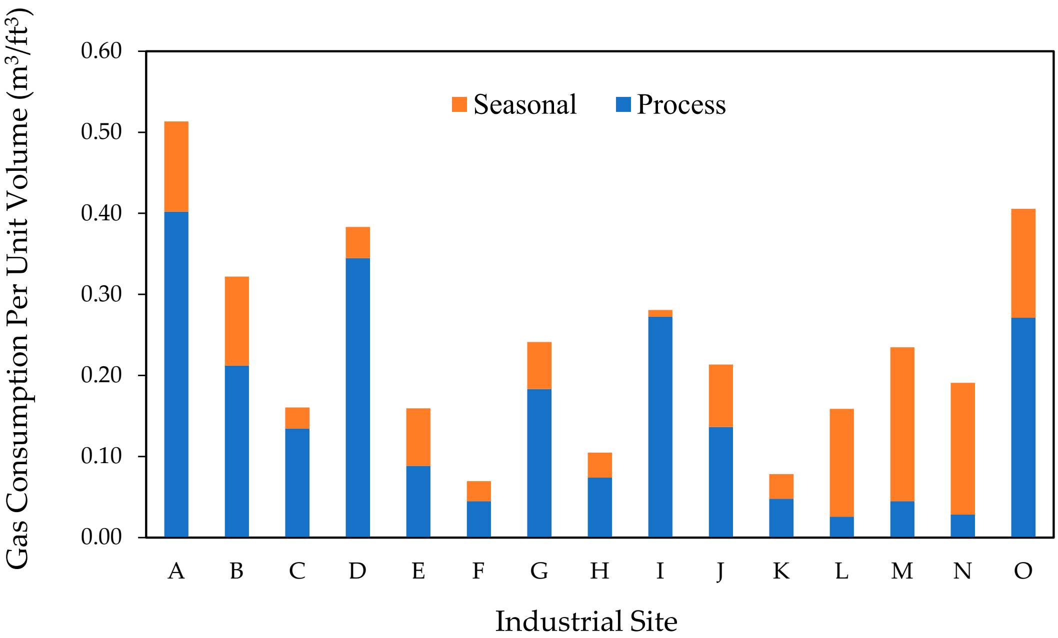

Figure 8. Process and seasonal natural gas consumption per unit volume.

The process consumption, normalized with respect to the area for the industries from the food sector, was from 5 to 14 m^3/ft^2; meanwhile, the normalized seasonal consumption was between 1 and 4 m^3/ft^2. For the industries belonging to the packaged food industries, the normalized process consumption was between 1.5 and 3 m^3/ft^2; meanwhile, the normalized seasonal consumption was between 1 and 2.5 m^3/ft^2.

In the finishing process sector, the process consumption per plant area of sites was between 1 and 9.5 m^3/ft^2. The seasonal consumption per unit area varied from 0.3 to 7 m^3/ft^2. Sites L, M, N, and O had higher normalized seasonal consumption values compared to the other industries in the group. Site O, which was among the lowest consumers 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.

The process consumption, normalized with respect to plant volume for the industries from the food sector, was from 0.1 to 0.4 m^3/ft^3; meanwhile, the normalized consumption was between 0.03 and 0.11 m^3/ft^3. For the industries belonging to the packaged food industries, the normalized process consumption was between 0.09 and 0.34 m^3/ft^3; meanwhile, the normalized seasonal consumption was between 0.02 and 0.07 m^3/ft^3. In the finishing process sector, the normalized process consumption of the sites was between 0.03 and 0.3 m^3/ft^3. Site O emerged as one of the highest consumers in terms of seasonal consumption when normalized with respect to area and volume. In addition to the statistical results, RETScreen also returned three important physical parameters for each audited site. These parameters were daily base level consumption (α_h), daily weather-dependent consumption (β_h), and reference temperature (τ) for heating; space heating needs to switch "on" to maintain the set point temperature. These results are shown in Table 10.

Table 10. Physical parameters obtained from RETScreen analysis.

Site	Daily Base Consumption Level (α_h) (m^3/Day)	Consumption per Heating Degree Day (β_h) (m^3/°C-Day)	Reference Temperature (τ) (°C)
A	7377.2	189.8	16.0
B	1273	28.5	26.0
C	2396.5	72	9.0
D	1317.9	43.5	6.0
E	1594.3	158.1	14.2
F	1076.9	79.2	16.5
G	1261.3	31.3	18.0
H	713.0	48.6	10.8
I	1222.8	2.5	14.2
J	825.6	50.5	17.0
K	451.2	49.2	13.5
L	604.1	345.6	14.1
M	489.0	308.4	12.5
N	199.0	68.9	21.5
O	212.0	6.8	17.0

Seasonal consumption was further classified into consumption for ventilation and consumption for space heating. Ventilation-based natural gas consumption was calculated by using Equation (4). These were plotted against the site area, as shown in Figures 9 and 10.

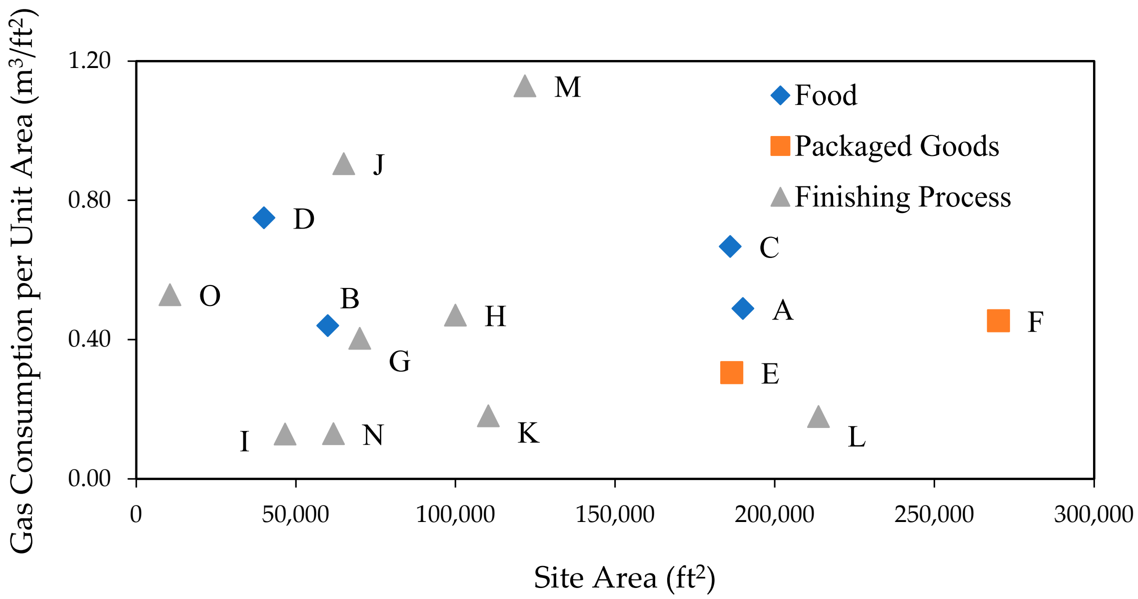

Figure 9. Natural gas consumption for ventilation per unit area vs. site area.

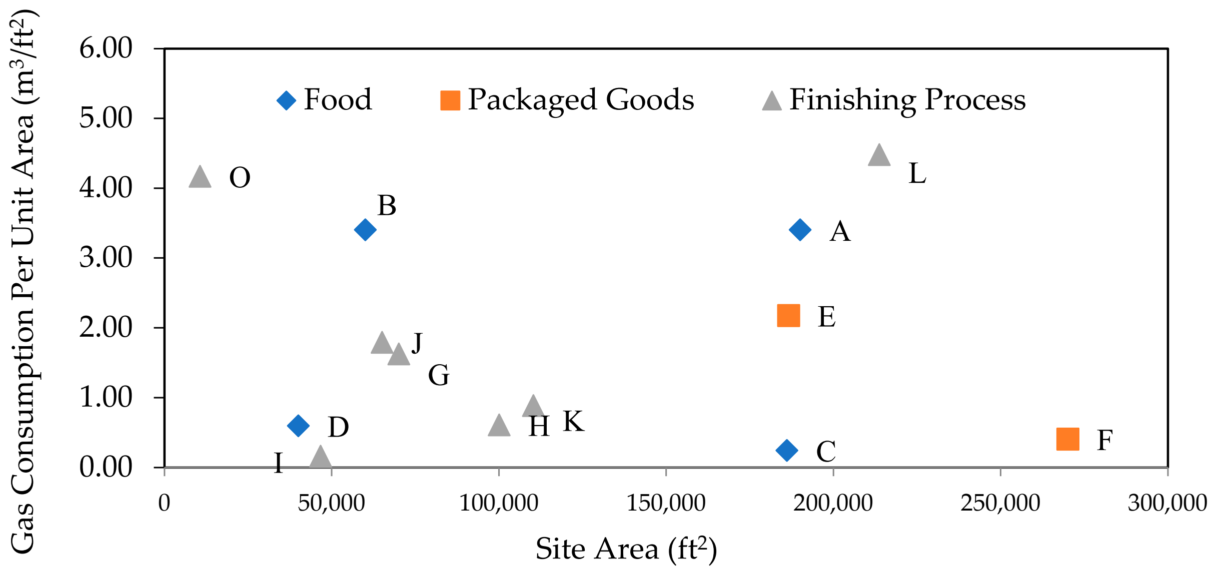

Figure 10. Natural gas consumption for space heating per unit area vs. site area.

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

Natural gas consumption for space heating per unit plant area for the food sector was found to be between 0.24 m^3/ft^2 year and 3.40 m^3/ft^2 year. Industries from the packaged goods sector showed a decreasing trend with increases in the plant area. In the finishing process sector, consumption was found to be between 0.1 m^3/ft^2 year and 5.50 m^3/ft^2 year.

For the RETScreen linear regression analysis to have a good correlation, it is necessary that the coefficient of correlation is higher than 0.7. Out of the 15 audited sites, 8 had an R^2 value higher than 0.7, which implied a good correlation between heating degree days and natural gas consumption. However, there were seven sites that had values lower than 0.7. It could be concluded that the assumption of a 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; hence, the multivariable regression analysis could not be conducted.

3.2. Major-Gas-Fired Equipment

The major-gas-fired equipment observed during site audits comprised boilers and ovens. The performances of the equipment were analyzed to identify energy saving opportunities.

3.2.1. Boiler Performance

There were six sites that had at least one boiler. The combustion and fuel–steam efficiencies of each of the boilers tested at those sites are presented in Table 11.

The efficiencies of the boilers are plotted along with their operational ages in a quadrant chart shown in Figure 11. Each point on the chart is labeled by the letter that represents the industrial site at which the boiler was located. Furthermore, wherever there was more than one boiler at one site, the boiler number was added to the label after the site name, e.g., a label C1 represents boiler number ‘1′ at Site C. The charts are plotted using age on the horizontal axes while the efficiencies are shown along the vertical axes.

Table 11. Combustion and fuel–steam efficiencies of boilers at audited sites.

Site	Boiler Number	Combustion Efficiency (%)	Fuel–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

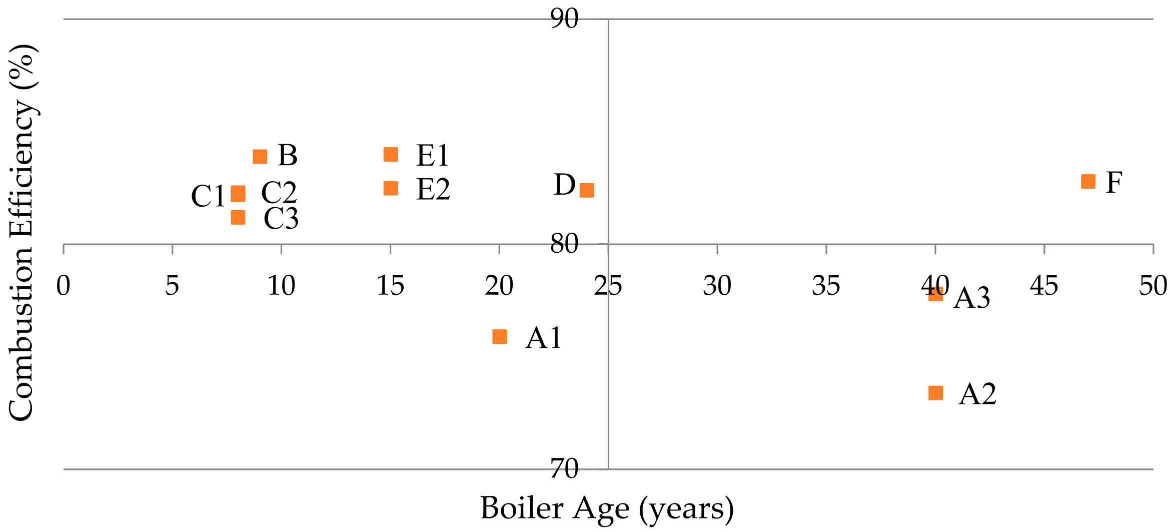

Figure 11. Boiler combustion efficiency vs. operational age.

In Figure 11, the first quadrant (upper right) represents boilers over 25 years old but which still have high efficiency. The chosen threshold for combustion efficiency was 80. This quadrant represents the boilers that had been maintained well enough to have high efficiencies. The second quadrant (upper left) shows 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 where newly installed boilers are expected to be. The third quadrant (lower left) shows boilers that were less than 25 years old but also had lower efficiencies, most likely due to malfunction. The fourth quadrant shows boilers that were more than 25 years old and had lower efficiencies. The boilers near the end of their life were expected to be in this quadrant.

It is evident from Figure 11 that most of the boilers tested had more than 80% combustion efficiency. The boilers from Site A were the exception and had combustion efficiencies lower than 80%. 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. The low efficiency for that boiler was indicative of malfunction. The only boiler at Site F had an efficiency higher than 80% despite being 47 years old. This implied that the boiler was properly maintained and was still capable of operating with high efficiency.

The natural gas consumptions of the boilers were estimated using information such as firing rates and hours of operation from the boiler logs. The natural gas consumptions of the boilers were compared against the annual consumption of the audited sites and are tabulated in Table 12.

Table 12. Estimated natural gas consumption of boiler as a percentage of total annual natural gas consumption of the site.

Site	Consumption (m^3/Year)	Cost (CAD/Year)	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% for Site D to 59% for Site C. Therefore, it was justifiable to focus on the boilers to identify energy saving opportunities.

3.2.2. Ovens

Eleven out of the fifteen audited sites were found to have ovens. The ovens seen at the sites belonging to the food sector were bake ovens, while the ones found at the finishing process industry sites 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 13.

Table 13. Estimated natural gas consumptions of ovens as a percentage of annual natural gas consumption of audited sites.

Site	Type	Consumption (m^3/Year)	Cost (CAD/Year)	Oven Consumption as a Percentage of Annual Consumption (%)	Combined Oven Consumption of Oven as a Percentage of Annual Consumption (%)
A	bake oven	848,676	191,546	25	25
D	bake oven	366,000	82,606	54	54
G	dry-off cure	121,134 140,804	27,340 31,780	19 23	42
H	dry-off cure	119,317 121,134	26,930 27,340	35 36	71
I	dry-off cure	90,000 100,000	10,157 11,285	20 22	42
J	dry-off cure	90,596 119,509	20,448 26,973	18 24	42
K	dry-off cure	68,143 100,394	15,380 22,659	23 35	58
L	dry-off cure	313,444 288,369	70,744 65,085	24 22	46
M	dry-off cure	221,687 310,361	50,035 70,049	25 35	60
N	dry-off cure	183,365 88,015	41,385 19,865	49 24	73
O	dry-off cure	32,565 52,809	7350 11,919	21 34	55

4. Conclusions

During the study, 15 on-site energy audits were conducted in the GTA's food, packaged goods, and finishing processes sectors. The purpose of the study was to gain valuable insights into natural gas consumption in SME plants and to identify opportunities to save energy. The findings revealed that natural gas consumption in industrial plants can be categorized into process use and seasonal use. Analyzing hourly metered data can help identify productive and non-productive natural gas consumption patterns.

The study also identified sector-specific trends for energy intensity per unit of operational hour. The energy intensity for food processing sites increased with the site area, while the packaged goods and finishing process industries showed a decreasing trend. The study found that non-productive consumption due to equipment not being switched off accounted for as much as 25% of the total annual natural gas consumption.

The natural gas consumption analysis identified statistical methods such as linear regression to accurately analyze natural gas consumption for industrial plants with consistent production. Heating degree days can be used to estimate weather-dependent and process consumption. The study found that R^2 values were higher than 0.5 for 12 audited sites, with 8 sites having R^2 values of 0.7 or higher. However, sites with unsteady demand and production needed to show a better correlation. Energy-saving measures such as tuning up boilers had the potential to reduce annual consumption and increase savings for most boilers in the study.

5. Limitation of Study and Further Scope

To participate in the utility demand-side management program, an industrial customer must take the initiative and make use of government- and utility-supported initiatives. However, one of the limitations of this study was a result of the limited information provided by some of the industrial plants. For instance, more production data were needed to analyze the industrial sites. With more data, the model's accuracy could be improved. Without comprehensive production data, regression analysis was conducted using the region's utility bills and weather data. This study focused on only three industrial sectors: food, packaging, and finishing. But it could be expanded to include other energy-intensive industrial streams. Further investigation into bigger-scale industrial plants is required to improve the accuracy of the Excel-based analysis.

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References

1. Bataille, C.; Melton, N. Energy efficiency and economic growth: A retrospective CGE analysis for Canada from 2002 to 2012. *Energy Econ.* **2017**, *64*, 118–130. [CrossRef]
2. Bosu, I.; Mahmoud, H.; Hassan, H. Energy audit and management of an industrial site based on energy efficiency, economic, and environmental analysis. *Appl. Energy* **2023**, *333*, 120619. [CrossRef]
3. World SME Forum (WSF). About World SME Forum. 2020. Available online: http://www.worldsmeforum.org/about/ (accessed on 29 March 2024).
4. Pansiri, J.; Temtime, Z.T. Assessing managerial skills in SMEs for capacity building. *J. Manag. Dev.* **2008**, *27*, 251–260. [CrossRef]

5. Calogirou, C.; Sørensen, S.Y.; Larsen, P.B.; Pedersen, K.; Kristiansen, K.R.; Mogensen, J.; Alexopoulou, S.; Marie Papageorgiou, M. SMEs and the Environment in the European Union. Planet SA and Danish Technological Institute for European Commission, DG Enterprise and Industry 2010, Brussels. Available online: https://op.europa.eu/en/publication-detail/-/publication/aa507ab8-1a2a-4bf1-86de-5a60d14a3977 (accessed on 30 March 2024).
6. Hillary, R. Environmental management systems and the smaller enterprise. *J. Clean. Prod.* **2004**, *12*, 561–569. [CrossRef]
7. McKenzie, R. Canada's National Partnership Strategy for Industrial Energy Efficiency. In Proceedings of the International Energy Agency, Conference Proceedings—Industrial Energy Efficiency: Policies and Programs, Washington, DC, USA, 26–27 May 1994; Available online: https://www.osti.gov/biblio/20001853 (accessed on 3 February 2015).
8. Akan, M.M.; Fung, A.S.; Kumar, R. Process energy analysis and saving opportunities in small and medium size enterprises for cleaner industrial production. *J. Clean. Prod.* **2019**, *233*, 43–55. [CrossRef]
9. Khan, S.A.R.; Sheikh, A.A.; Ahmad, Z. Developing the interconnection between green employee behavior, tax avoidance, green capability, and sustainable performance of SMEs through corporate social responsibility. *J. Clean. Prod.* **2023**, *419*, 138236. [CrossRef]
10. Jago, P. The Canadian Industry Program for Energy Conservation (CIPEC): The dynamics of a 24-year partnership between government and industry. In Proceedings of the 1999 American Council for an Energy-Efficient Economy Summer Study on Energy Efficiency in Industry, Albany, NY, USA, 15–18 June 1999.
11. Sambor, D.J.; Penn, H.; Jacobson, M.Z. Energy optimization of a food-energy-water microgrid living laboratory in Yukon, Canada. *Energy Nexus* **2023**, *10*, 100200. [CrossRef]
12. Anderson, S.T.; Newell, R.G. Information programs for technology adoption: The case of energy–efficiency audits. *Resour. Energy Econ.* **2004**, *26*, 27–50. [CrossRef]
13. Barbose, G.L.; Goldman, C.A.; Hoffman, I.M.; Billingsley, M. The future of utility customer–funded energy efficiency programs in the USA: Projected spending and savings to 2025. *Energy Effic.* **2013**, *6*, 475–493. [CrossRef]
14. Thollander, P.; Danestig, M.; Rohdin, P. Energy policies for increased industrial energy efficiency: Evaluation of a local energy programme for manufacturing SMEs. *Energy Policy* **2007**, *35*, 5774–5783. [CrossRef]
15. Ahmed, T.; Fung, A.S.; Kumar, R. Energy benchmarking and ventilation related energy saving potentials for SMEs in Greater Toronto Area. *J. Clean. Prod.* **2020**, *246*, 118961. [CrossRef]
16. Boyd, G.A. Motivating Auto Manufacturing Energy Efficiency Through Performance-based Indicators. *J. Engines* **2006**, *115*, 284–289.
17. Government of Canada. Emission Factors and Reference Values. Government of Canada 2023. Available online: https://www.canada.ca/en/environment-climate-change/services/climate-change/pricing-pollution-how-it-will-work/output-based-pricing-system/federal-greenhouse-gas-offset-system/emission-factors-reference-values.html (accessed on 24 December 2023).
18. Andersson, E.; Arfwidsson, O.; Thollander, P. Benchmarking energy performance of industrial small and medium-sized enterprises using an energy efficiency index: Results based on an energy audit policy program. *J. Clean. Prod.* **2018**, *182*, 883–895. [CrossRef]
19. Baig, A.A. Analysis of Natural Gas Consumption and Energy Saving Measures for Small and Medium-Sized Industries in the Greater Toronto Area (GTA). Master's Thesis, Ryerson University, Toronto, ON, Canada, 2014.
20. Enbridge Gas Distribution Inc. Purchasing Gas from Enbridge. Enbridge Gas Distribution Inc. 2015. Available online: https://www.enbridgegas (accessed on 3 February 2015).
21. Rachlin, J.; Fels, M.F.; Socolow, R.H. The Stability of PRISM Estimates. *Energy Build.* **1986**, *9*, 149–157. [CrossRef]
22. ASHRAE. Thermal Environmental Conditions for Human Occupancy. American Society of Heating, Refrigerating and Air Conditioning Engineers. ANSI/ASHRAE 55-2010. Available online: https://www.ashrae.org/technical-resources/bookstore/standard-55-thermal-environmental-conditions-for-human-occupancy (accessed on 3 February 2015).
23. RETScreen. Natural Resources Canada. Available online: https://www.nrcan.gc.ca/energy/software-tools/7465 (accessed on 3 February 2015).
24. Energy Efficiency and Renewable Energy Software Tools, U.S Department of Energy. Available online: https://www.energy.gov/eere/amo/software-tools (accessed on 3 February 2015).
25. Fels, M.F. PRISM: An introduction. *Energy Build.* **1986**, *9*, 5–18. [CrossRef]
26. Fels, M.; Kissock, K.; Marean, M.; Reynolds, C. *Description of PRISM® (Advanced Version 1.0)—Users' Guide*; Center for Energy and Environmental Studies; Princeton University: Princeton, NJ, USA, 1995.
27. Climate Data and Information Archive. Daily Data Report. Retrieved from Environment Canada. Available online: https://climate.weather.gc.ca/historical_data/search_historic_data_e.html (accessed on 3 February 2015).
28. Enbridge Gas, Commercial and Industrial. Available online: https://www.enbridgegas.com/business-industrial (accessed on 1 January 2014).