Novel method for benchmarking the energy performance of industrial refrigeration facilities

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I. Abstract

An alternative "bottom-up" approach is proposed as a novel and sustainable method for benchmarking the energetic performance of industrial refrigeration facilities. The limitations of conventional benchmarking are highlighted and summarized with real case studies. The research presented reveals the primary energy components within specific types of industrial refrigeration facilities which include both refrigeration energy and non-refrigeration energy. Unlike the conventional method which considers the total facility consumption, the proposed method splits the refrigeration energy into two secondary components: Essential Energy and Wasted Energy. Essential energy represents the minimum energy required to satisfy a facility's essential refrigeration load. With the essential energy defined, an energy performance metric called Benchmark Energy Factor (BEF) is introduced. The unitless BEF of a facility compares the actual energy used by the refrigeration system relative to the minimum energy required to satisfy the essential needs of the facility. Unlike conventional performance metrics, the BEF is a normalized performance indicator which takes into account the variable independent parameters unique to each facility.

An essential energy model is introduced and used to calculate the essential refrigeration load and the essential refrigeration energy for a given facility. Analyses of 10 facilities are presented, which does a comparison between the postulated performances of the facilities based on conventional benchmarking methods, and the proposed essential energy benchmarking using the benchmark energy factor. The analysis suggests that the conventional method does not accurately reflect the actual performance of the facility. On-site data collection, detailed history of demand side management activities and actual measurement and verification data for all 10 facilities revealed the true top and poor performing facilities which coincided closely with the proposed performance metric.

Selected facilities are benchmarked before and after energy conservation measures were implemented, and the proposed essential energy benchmarking methodology is used to calculate the total energy savings achieved. The calculated energy savings are then compared against actual measured and verified energy savings. The analysis demonstrates that the proposed essential energy benchmarking can accurately estimate energy savings of implemented energy conservation measures and may be a more cost effective approach than traditional measurement and verification activities.

Canadian Utilities and Natural Resources Canada used the outcomes of this research in setting a new Canadian Standards Association standard: "C500 - Guide on monitoring and energy performance measurement of industrial refrigeration systems using benchmark energy factor concepts".

Keywords: Benchmarking, Energy Efficiency, Industrial Refrigeration Systems, Systems Engineering, Mathematical Model, Specific Energy Consumption.

II. Acknowledgments

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V. Abbreviations

BAT:	Best Available Technology
BEF:	Benchmark Energy Factor
BEP:	Best Efficiency Point
DSM:	Demand Side Management
ECM:	Energy Conservation Measure
EEB:	Essential Energy Benchmarking
EPI:	Energy Performance Indicator
EPM:	Essential Performance Metric
EUI:	Energy Use Intensity
HVAC:	Heating, Ventilation and Air Conditioning
ICE-E:	Improving Cold Storage Equipment in Europe
IEEE:	Institute of Electrical and Electronic Engineers
IPMVP:	International Performance Measurement and Verification Protocols
IRF:	Industrial Refrigeration Facility
ISP:	Industrial System and/or Process
M&V:	Measurement and Verification
NRCan:	Natural Resources Canada
SEC:	Specific Energy Consumption
TR:	Tons of Refrigeration

VI. Definitions

Wasted Energy	The energy consumed beyond the essential energy of an ISP that is potentially controllable through implementation of energy conservation measures.
Essential Energy	Essential energy is the ideal energy plus the incremental energy due to unavoidable losses and is determined using essential performance metrics.
Essential Load	The minimum load accomplished by the ISP that is defined by the independent parameters. Independent parameters are controlled by business drivers, environment or by essential performance metrics.
Essential Performance Metric	Represents an industry accepted performance metric based on best available technology and practice. These metrics are used to determine the essential load or essential energy of an industrial system or process.
Ideal Energy	Minimum energy required to accomplish the task at hand. Calculated based on physical laws that govern the physical process.
Normalization	The process of adjusting measured values to account for independent variable parameters in order to allow for accurate comparison.

Chapter 1: Introduction

Industrial corporations often have the perception that they are highly energy efficient. It is accepted that benchmarking provides a tool to test this perception using accepted benchmark values for specific technologies and processes [1].

Benchmarking is an on-going process of identifying and comparing standards of excellence for products, services or processes, in order to improve one's own performance through implementation of improvement measures, commonly called "best practices" [2].

Traditional energy performance benchmarking for industrial systems focuses on a comparative analysis of energy use per unit of physical production, otherwise known as Energy Use Intensity (EUI). EUI's can be applied to a wide range of different types of industrial systems and processes such as; cement manufacturing, mining, veneer drying and even industrial refrigeration systems commonly used in refrigerated warehouses.

The research and investigation presented in this study shows that these traditional types of energy performance indicators paint a different picture than the actual reality. Among the literature presented in Chapter 2, a study by Scofield [3] suggests that the widely used US Department of Energy's ENERGY STAR™ program, which is based on EUI benchmarking, yields highly uncertain performance ratings that are not statistically meaningful.

The author's past research has demonstrated that benchmarking based on using best practice as a reference, is not a reliable method due to large variability of benchmarking factors (i.e. independent parameters defined by the creation of a system boundary). These parameters, requiring "adjustments" according to the International Performance Measurement and Verification Protocol (IPMVP) [4], cause baseline inaccuracies which require on-going and tedious normalization activities.

It is a reality that studies of energetic performances of Industrial Systems and Processes (ISPs) and industries have lagged behind those used in the commercial and institutional sectors [5]. Industry leaders have also expressed their concern with the lack of energy performance benchmarks available in industrial sectors [6]. The reasons can be grouped as follows:

a) Large variability and complexity of ISPs.
b) Variability of independent parameters such as material and environmental conditions.
c) The absence of a large population of comparable data required for a regression-based approach that would enable the normalization of material and environmental conditions, and thus allow for a useful comparison of energy performance at the process level.
d) The reluctance of industrial firms to share data on industrial processes as it is often considered proprietary information and may be subject to ethical and legal implications.

1.1 Research Purpose

Over 40% of the world's electricity consumption (amounted in 2015 at 20,200 TWh)**,** is consumed by industrial systems [7]. With overall efficiencies ranging from 80% to as low as 25%**,** for an average efficiency value of 55% [8], the wasted energy by industrial systems is estimated at 3,818 TWh/year (almost the entire consumption of the United States alone in 2015 [7]).

In an actual economic environment, business sustainability requires high-efficiency technological processes that will increase their competitiveness. In other words, businesses must optimize their processes to allow them to increase production while consuming less energy.

The main drivers of energy efficiency are considered to be [1]:

- Rising energy prices
- Energy security
- Climate change
- Green jobs

One of the main barriers to energy efficiency programs is the lack of a real benchmarking methodology. Industrial energy benchmarking is used by governments, energy utilities and industrial firms enabling a useful comparison of relative performance and the identification of energy savings potential. Current forms of benchmarking industrial systems and processes rely on a comparison of performance metrics which are limited by the fact that variations in operating conditions are not considered [9]. Furthermore, the lack of benchmarking partners makes it difficult to constitute what's energy efficient [6].

Currently, utility Demand Side Management (DSM) programs require verification of annual energy savings of implemented Energy Conservation Measures (ECMs) by using Measurement and Verification (M&V) [4] or other types of on-site activities. On the other hand, the cost[1] and time requirements of M&V need to be balanced against the benefits it provides by increasing the certainty of savings estimates. It is for this reason that not all utility funded projects and programs undergo full measurement and verification activities. It is generally considered that a benchmarking methodology should be based on technical and scientific principles [1]. The large variability in independent parameters that affect energy consumption must be taken into account when benchmarking the electro-energetic performance of industrial systems and processes.

Industrial refrigeration systems are such systems that require accurate performance benchmarking in order to successfully undertake energy efficiency improvement. As presented in this dissertation, current forms of benchmarking for these types of systems can yield misleading results, causing missed opportunities and poor energy management. The primary objective of this research is to demonstrate the limitations of current forms of benchmarking and how it applies to industrial refrigeration facilities, and to present an alternative methodology for benchmarking the energy performance of industrial systems and processes.

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[1] M&V costs can range between 3% and 5% of total project costs or up to 10% of the annual value of energy savings being reported (depending on different considerations that vary between options) [37].

1.2 Dissertation Structure

Benchmarking is an extensively studied topic with a wide range of applications. Before going into benchmarking industrial refrigeration systems, the general concepts of benchmarking are first introduced. This dissertation is structured to provide a broad overview of benchmarking starting with the basic forms and concepts of benchmarking for general processes in any sector or industry. With every chapter, the focus is narrowed down further to benchmarking industrial systems and processes and finally to benchmarking refrigeration systems.

Chapter 2 summarizes the literature found through research on benchmarking. This chapter also serves to provide general understanding of conventional benchmarking methodologies and how they have evolved over time. Starting at a high level, the research narrows down to benchmarking industrial systems and processes and how current demand side management programs in industry use benchmarking to measure the energy performance of specific facilities. Based on this globally accepted methodology, this chapter presents research highlighting the limitations of conventional benchmarking activities specific to industrial systems and processes.

Chapter 3 introduces industrial refrigeration systems as being a typical industrial system or process that can be benchmarked for performance. The conventional methodology for benchmarking industrial refrigeration facilities are introduced with reference to published research articles specific to this industry. The literature referenced in this section further highlights the limitations of conventional benchmarking methodologies and how they relate to industrial refrigeration facilities.

The hypothesis is introduced in Chapter 4 and its direct application to industrial refrigeration facilities. In order to highlight the strengths of the proposed essential energy benchmarking, the chapter provides the energy flow within an industrial refrigeration facility. A development background and history is presented in Chapter 4.3 for a tool (or mathematical model) that is used to apply essential energy benchmarking to industrial refrigeration facilities.

Chapter 5 provides the methodology used to conduct the research which involves site selection, field data gathering and data compilation and analysis. In order to test the hypothesis, test requirements are listed which describe the expected outcomes of the research and their interpretations.

The results of the research are presented in Chapter 6 for 10 industrial refrigeration facilities. Specific known operating characteristics of each facility are presented and are used to test the results of conventional benchmarking and the proposed essential energy benchmarking processes.

Chapter 2: Background

This chapter gives an overview of benchmarking and focuses on current benchmarking methodologies and their limitations. References are introduced and discussed throughout various chapters where relevant. The focus of this dissertation is on benchmarking the energy performance of industrial systems and/or processes and its application on industrial refrigeration facilities.

Based on the review of the literature presented in this chapter, it is in the author's opinion that benchmarking has been widely studied for decades and despite the extensive research in this field, there is yet to be a methodology that is universally accepted.

The literature presented in this chapter, which highlight the limitations of current forms of benchmarking as it relates to energy performance of industrial systems or processes, refer to two basic methods of benchmarking: "top-down" method and "bottom-up" method. The fundamental difference between conventional benchmarking and the proposed essential energy benchmarking is that the conventional method is based on a top-down approach, while the proposed method is based on a bottom-up approach. The top-down method is based on comparing a performance metric (typically; energy per unit of production e.g. kWh/kg or kWh/m^3) of one facility against its peers who are considered leaders in the industry. The bottom-up approach differs in that it is focused on comparing a facility's (or specific system's/process's) energy consumption to its theoretical (or ideal) state of operation based on the facility's (or specific system's/process's) unique operating conditions. These conditions are typically set by business drivers and other factors which are considered non-controllable by the end-user, however, still have impacts on energy use and performance.

Past independent studies and publications are presented which highlight the limitations of top-down benchmarking and introduce the bottom-up method as an alternative, and in some cases, a more reliable approach for benchmarking specific systems or processes, including commercial buildings.

2.1 Benchmarking

Elmuti and Kathawala [10] describe traditional benchmarking as an on-going process of identifying and comparing standards of excellence for products, services, or processes in order to improve one's own performance through implementation of improvement measures, commonly called best practices.

In 1992, after consulting about 100 corporations, the International Benchmarking Clearinghouse Design Steering Committee concluded and represented the consensus defining benchmarking as: "A systematic and continuous measurement process; a process of continuously measuring and comparing an organization's business processes against business process leaders anywhere in the world to gain information which will help the organization take action to improve its performance." [11].

The definition reveals that benchmarking has two components [11]:

- Measurement process that results in a comparative performance measure, and
- Description of how exceptional performance is attained

Ajelabi and Tang [11] define exceptional performance as a measure of performance indicators which are called benchmarks. Camp [12] calls the activities that facilitate the exceptional performance, enablers. It is implied that exceptional performance is obtained through enablers identified in a benchmarking study. In other words, benchmarks can be achieved by attaining enablers [12].

Many benchmarking models and methods used today have been evolved from the original process proposed by W.E Deming [13] in the 1940's and 1950's, referred to as the "Deming" cycle, which includes a minimum of four phases: *Plan-Do-Check-Act*. Ajelabi and Tang [11], Bhutta and Huq [14] and Elmuti and Kathawala [10] have various but similar descriptions of the Deming cycle. The continuous recurring cycle starts with planning the benchmarking study to determine which systems will be researched. In the case of industrial systems, a system boundary is created. Next, the study is conducted on the system and data is collected. In the third phase, the data is analyzed and improvement measures are identified. Finally, actions with measurable outcomes are taken on the system.

Kyro [15] refers to benchmarking as an evaluation tool which has undergone several generations of development, starting with what was called "Reverse Benchmarking" or "Reverse Engineering" introduced in the 1940s and was focused on the comparison of finished products only. She suggests that reverse benchmarking was focused on the end-use equipment and is still used today to uncover the characteristics, functionality and performance of products. Since then, there have been seven generations of benchmarking with the latest called "Network Benchmarking" which shifts the focus to cooperation rather than competition [11], [12], [15]. Network benchmarking enables businesses from different industries to collaborate and to solve mutual problems related to quality and performance [15]. Figure 1 shows Kyro's interpretations of Ahmed and Rafiq [16] of the evolution of the level of sophistication of different types of benchmarking over time [15].

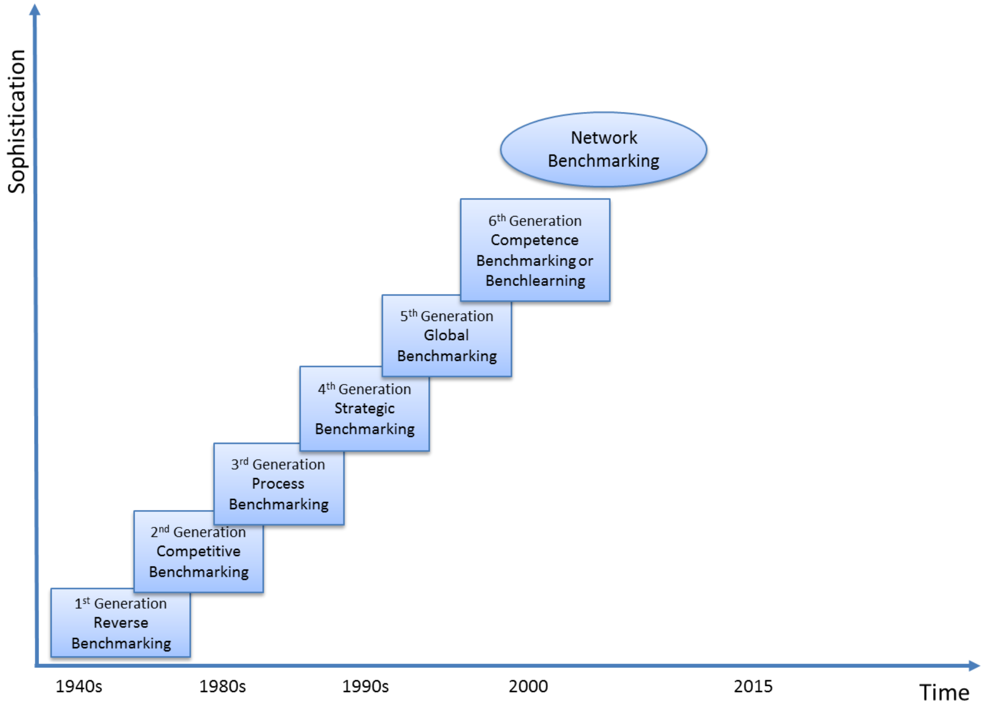

Figure 1: Evolution of benchmarking (from [15]*)*

Bhutta and Huq [14] suggests that all types of conventional benchmarking can be defined based on:

- What is being compared (for example: performance, process or strategy) and,
- Whom it is compared against (for example: same market, same industry or own company)

Andersen [17] suggests that different types of benchmarking are complementary rather than being mutually exclusive. Comparisons of different benchmarks and against whom, can be combined into a benchmarking study with a given purpose [17]. Their combinations are based on the relevance of the type of benchmarking to a specific context. Table 1 shows which combinations of the different types of benchmarking will yield the level of value gained from a benchmarking study:

Table 1: Value of different combinations of benchmarking types (adapted from [14]*)*

Comparing what	**Comparing against whom** Same Market (Competitive)	 Same Industry (Functional)	 Own Company (Internal)
Performance	**High**	Medium	Medium
Process	Low	**High**	Medium
Strategy	**High**	Low	Low

As can be seen in Table 1, some combinations of benchmarking types are more relevant than others and can either produce meaningless results or a plethora of useful information with many avenues for improvement. The combinations and their relevance apply to general benchmarking and are not specific to an energetic system or a particular industry.

The following combinations of what to benchmark and against whom, explain the recommended relevance of each type of combination:

- When organizations are competing to produce a more superior product at the highest performance level in order to gain market share, it becomes evident that a benchmarking study on those organizations can uncover performance and strategy improvement opportunities for under-performing candidates.

- Consider two food manufacturing plants with one producing food products for adults while the other is producing baby food. Benchmarking the process of food production (i.e. the function) will in most cases yield more valuable results than benchmarking the performance of the function itself.

- Process benchmarking against competitors is very difficult and will rarely be viable due to the ethical and legal issues related to exchanging proprietary information about business processes.

- Comparing strategic measures internally will, in most cases, yield meaningless results as opposed to comparing strategies between competitive organizations.

Kyro [15] attempts to revise the concepts and forms of benchmarking in order to adapt with the evolutionary growth of benchmarking forms, content and targets. Her introduction of more sophisticated benchmarking types (i.e. competence and network benchmarking, shown in Figure 1) encourages revision of the current understanding of the theoretical bases of benchmarking, while thinking of the potential growth of benchmarking to take on new forms and methodologies.

The work of Anderson [17], Bhutta and Huq [14], Kelessidis [2], Ajelabi and Tang [11] and Fernandez [18] all define similar benchmarking types as described earlier in this chapter; each includes a list of their advantages and disadvantages. Some of the prominent challenges include difficulty in the benchmarking process (for example: high costs and time consuming), reliability in performance of benchmarking partners, and the legal and ethical aspects involved with sharing of information among organizations.

Based on the understanding of the literature with regards to types of benchmarking and their ultimate goals, this traditional benchmarking process needs the following to be successful:

- To be performed continuously,
- One needs to understand one's own company and processes,
- To have access to best practice organizations to benchmark against,
- To have a systematic method for collecting data,
- To be able to implement the improvement measures once the gaps have been identified, and
- To be able to "re-benchmark" to determine the impact of the implemented measures.

The concepts of conventional benchmarking presented here apply to any kind of organization, process, or function. The purpose is to provide an introduction of the general benchmarking concept, both its objectives and limitations.

These methods are widely adopted by governments and utilities around the world and are used to identify energy efficiency opportunities, provide incentive funding for projects, record energy savings and to reward and certify organizations that are considered top energy performers.

The focus of this dissertation is on energy performance benchmarking of industrial systems and processes, specifically applied to industrial refrigeration facilities. The following sections introduce current benchmarking methods for industrial systems or processes and commercial buildings.

2.2 Energy Efficiency Programs in Industry

Generally, it is recognized that the benchmarking process provides insight in the energy efficiency relative to a reference (or benchmark) performance/technology. It is intended to help enterprises identify inefficiencies and also assist in their search for more efficient technology opportunities.

The following sub sections provide a brief overview of the current energy efficiency programs in North America and how benchmarking is used to classify performance ratings of industrial systems or processes and commercial buildings.

2.2.1 ENERGY STAR™ certification program

Established by the US Department of Energy and the US Environmental Protection Agency in 1992, the Energy Star™ certification program is a joint voluntary program with a goal to help consumers, businesses and industry save money and protect the environment through the adoption of energy efficient products and by implementing what is considered to be defined as best practice [19].

Based on traditional methodologies used in assessing system efficiencies, the Energy Star™ program provides industry specific Energy Performance Indicators (EPIs) to help benchmark the energy performance of an industrial plant. EPIs are developed using total annual plant energy and production data [19]. The EPIs are compared against other similar plants, in a specific industry, and an energy performance score is generated (also known as Energy Star™ 1-100 score). A certificate is awarded as recognition for top performing plants for their superior energy performance.

2.2.2 Superior Energy Performance program

Developed in collaboration with the US Council for Energy Efficient Manufacturing and currently administered by the US Department of Energy, the superior energy performance is a voluntary certification program that verifies improvements in energy performance in industrial facilities [20].

The certification requires the facility to meet all requirements of ISO 50001 [20], [21]. Its central element is the implementation of a facility energy management system. It is suggested that implementing a global energy management system will enable facilities to realize greater persistence in energy savings and higher returns on energy efficiency investments. It is anticipated that corporations, supply chain partnerships, utilities, and energy service companies will use ISO 50001 as a tool to improve energy performance and reduce carbon emissions in their own facilities as well as those belonging to their customers or suppliers. The standard does not prescribe specific performance criteria or results with respect to energy efficiency.

The program uses the concept of energy performance indicators or benchmark ratings for different types of industrial facilities. These indicators are claimed to be a more accurate metric than traditional energy intensity. This is accomplished by normalizing the data for independent factors that may affect energy consumption at the facility such as weather, production, operating hours and other factors.

2.2.3 Natural Resources Canada benchmarking programs

The Canadian Industry Program for Energy Conservation and its partners have developed two benchmarking programs for Canada's industrial sectors, in support with Natural Resourced Canada (NRCan):

A. *Energy Performance Benchmarking*

   Energy performance benchmarking focuses on a comparative analysis of energy use per unit of physical production, otherwise known as energy use intensity [19]. The program offers a step by step process and guide to benchmark energy performance of an industrial plant for a wide range of sectors such as aluminum, cement, brewery, food & beverage and many other industrial systems and processes. Plant owners are able to compare their plant's energy intensity with other facilities in the same industry through the Canadian Industrial Energy Efficiency Data and Analysis Centre at Simon Fraser University which is supported by NRCan.

B. *Energy Best Practices Benchmarking*

   Adopted from US industry programs, best practices benchmarking involves comparing operations and systems of a facility to best-in-class operations [19]. This benchmarking process follows a similar methodology as the energy performance benchmarking process. This type of benchmarking focuses more on comparing how processes are performed versus how well they are performed.

Best practices benchmarking involves comparing operations and systems within one's facility to best-in-class operations. The quest is obtaining information that will help the organization identify and implement improvements. This activity raises collateral issues related to ethical and legal aspects related to the benchmarking process.

Based on Andersen's [17] discussion on the ethical and legal aspects, benchmarking is considered relatively difficult when using suppliers, customers, or competitors as benchmarking partners[2]. As Ke et al. [22] explain, organizations are often reluctant to share information that is considered proprietary and confidential such as production and energy use data, therefore, data availability is often a challenge for industrial energy benchmarking efforts. Furthermore, the accuracy of obtainable data is also an issue as companies often misreport energy usage data, while high quality and sufficient data are crucial to a successful and meaningful benchmarking analysis.

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[2] According to Andersen [17], while USA and Canada legislation, at least not yet, pose any difficulties for benchmarking organizations, the same might not be completely true in Europe. Article 85 of the European Treaty prohibits any agreement or conduct coordinated with others that can distort competition or have an effect on trade within the European market.

2.2.4 International Performance Measurement and Verification Protocol

Since 1997, Efficiency Valuation Organization develops, maintains, improves and publishes the International Performance Measurement and Verification Protocol (IPMVP) [4]. Essentially, the IPMVP provides guidelines and procedures for conducting measurements and verification to estimate energy savings of implemented energy conservation measures.

The published methods are widely adopted internationally and have become a standard for measurement and verification activities for government and utilities DSM programs.

Energy savings are calculated by the following IPMVP fundamental equation:

$$Energy\ Savings = Baseline\ Energy - Post\ Retrofit\ Energy\ \pm Adjustments \tag{1}$$

The “Adjustments” term brings the pre- and post-ECM periods energy use to the same set of conditions. As IPMVP states, “adjustments are derived from identifiable physical facts”. These identifiable physical facts are related to the independent (non-controllable) parameters that affect the energy efficiency performance of industrial systems. Their influence is accounted for only via normalization processes (adjustments under IPMVP) when benchmarking is performed.

2.3 Articles Highlighting Limitations of Conventional Benchmarking

Several articles [3], [23], [24], [25] presented in this chapter highlight some of the limitations of existing top-down benchmarking methodologies and propose an alternative bottom-up approach where the minimum or ideal energy is modelled and defined as the benchmark value.

A study on benchmarking approaches for buildings by Burman et al. [26], suggests that specific characteristics of buildings are not fully captured by top-down methods. The study also suggests that a key limitation of top-down methods is the difficulty in acquiring adequate data that make up the data bank of best practice performance indicators.

The US Green Building Council has adopted the Energy Star™ rating system for buildings, for judging energy efficiency in connection with its popular green-building certification program [19]. Based on traditional benchmarking, the rating system is based on comparing a particular building’s energy use intensity[3] with gross EUIs for US buildings of the same type (i.e. top-down method) [19]. The data set of different types of buildings is made available by the Commercial Building Energy Consumption Survey[4] [19].

Due to insufficient information available on different building types, regression analysis is applied on the data for benchmarking purposes [3]. The intent is that the resulting regression coefficients can then be used to predict the energy use of a hypothetical building with characteristics similar to those of the one to be benchmarked.

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[3] EUI for buildings is calculated by dividing the building’s annual energy use by its total gross square footage.

[4] Administered by the US Energy Information Administration the Commercial Building Energy Consumption Survey conducts surveys every 4-5 years since 1989, on 20 different building types [3].

An 18 month investigation study by Scofield [3], was conducted as part of a summer study at the American Council for an Energy Efficient Economy. Through extensive regression analysis, Scofield concludes that Energy Star™ scores for 10 out of the 11 conventional building types were found to be uncertain by +/- 35 points. "These uncertainties are consequences of the large standard errors in model regression coefficients" [3]. "With such large uncertainties there is no statistically meaningful distinction between an Energy Star™ score of 75 and one of 50" [3].

Statistical benchmarking, where the EUI or specific energy consumption of a system or process is compared against a data bank of similar systems, is widely used for estimation of the energy efficiency improvement potential in industrial processes and buildings [19]. Federspiel [25] suggests that there are two fundamental limitations of this approach:

A. Only similar types of systems can be compared while the operating conditions are not fully taken into account, and
B. The entire data bank of "similar" systems may be inefficient, which would cause inefficient systems to be rated as efficient ones.

Sardeshpande [23] introduces model-based benchmarking for glass furnaces as an alternative and more reliable methodology for benchmarking. His research suggests that in many industrial systems or processes, it is necessary to understand the process details in order to achieve the benchmark [23]. In other words, the focus needs to be shifted to the end-use system/process, similar to the first generation of benchmarking "Reverse Benchmarking". The model enables the calculation of the energy performance for a given a furnace design by determining the minimum energy required based on the furnace design and operating conditions [23]. The proposed essential energy benchmarking in this study is based on model-based benchmarking whereby the minimum energy required to accomplish the task, the system or process was originally designed for, is calculated and compared against the actual energy used.

With regards to M&V for determining energy savings of implemented energy conservation measures, a 2013 Berkeley Lab report [27] reviews M&V guidelines from six different countries, including the United States, and highlights the issues that need to be addressed to support DSM programs. Some of these issues include defining the system boundary and determining the normalization process to take into account the variable independent parameters that impact energy use [27].

The research done by Scofield [3], Federspiel [25] and Sardeshpande [23] highlight the issues and challenges with current forms of benchmarking the energy performance of industrial systems or processes and buildings. These are summarized as follows:

- The energy performance indicator of a facility does not take into account its unique operating conditions. In other words, it is not a normalized metric that can be used to reliably compare performance of a facility with a partner facility (or reference).

- The reference facility may be of a different type than the one being benchmarked resulting in an inappropriate comparison of performance.

- The reference partner may not actually be a “top energy performer” due to the limited data available required to truly gauge the performance of a facility.

- The data bank of potential benchmarking partners (or references) is limited and in some cases altered due to the legal and ethical issues with sharing proprietary data, which cause a further lack of participation in the benchmarking community. This issue makes it especially difficult to apply regression models to a population in order to make predictions of facilities with changing operating conditions.

- In order to determine energy savings of implemented energy conservation measures, costly and time consuming M&V activities are required to quantify savings. The process involves logging potentially sensitive data and applying adjustments to a hypothetical or previously measured baseline, in order to normalize for the ever-changing operating conditions.

2.4 Benchmarking Activities

In general, the activities for formal benchmarking follow a similar process for performance and best practice benchmarking [2]. The wide interest and acceptance of benchmarking has led to the emergence of a range of benchmarking methodologies. For this reason, there is no single benchmarking methodology that has been universally adopted.

Anderson’s paper [17] lists typical activities for a benchmarking study of an organization’s business processes. Using the same approach and applying it to industrial systems or processes for performance or best practice benchmarking, the following activities are listed: (Steps 1 through 8 is the entire benchmarking process which results in a comparative analysis of performance indicators. The analysis uncovers opportunities which can be implemented to achieve energy savings, which are then verified and awarded, as described in steps 9 through 12.)

1. Choose the ISP under test.
2. Identify the areas for improvement that will benefit most from the benchmarking study.
3. Research and identify the key factors and variables to be used to measure the ISP (setting EPIs and independent parameters[5]).
4. Determine if the data is already available or how it will be obtained.
5. Analyze the data.
6. Identify the best practice or performance indicator by selecting the best-in-class category (e.g. companies that perform each function at the lowest cost, with the highest efficiency).

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[5] Some of the independent parameters to be considered:

- Specific technological parameters
- Production volume
- Product type
- Material condition, environmental conditions, personnel, equipment condition, thermal insulation condition, transportation, lighting, etc.

7. Process the data and normalize to take into account the differences in the independent parameters which characterize the reference for the specific ISP.
8. Perform conventional benchmarking using EPIs.
9. Identify the energy conservation measures (actions) that can achieve best practice performance, while taking into account the conditions (related to independent parameters) under which the best practice can be achieved.
10. Implement the best practice adapted to specific conditions of the ISP under test:
    - Set specific improvement targets and deadlines.
    - Develop a continuous process to monitor, review, update and analyze the data.
    - Provide a basis for the monitoring, revision and recalibration of the measurements for future benchmarking studies.
11. Perform measurement and verification activities using IPMVP methods, including normalization and routine adjustments.
12. Apply for certification.

This laborious and tedious benchmarking methodology must be repeated each time the reference or ISP conditions (independent parameters) are changed.

The benchmarking process described in steps 1 through 8 above is graphically represented in Figure 2 to show the inputs and outputs for key activities/processes.

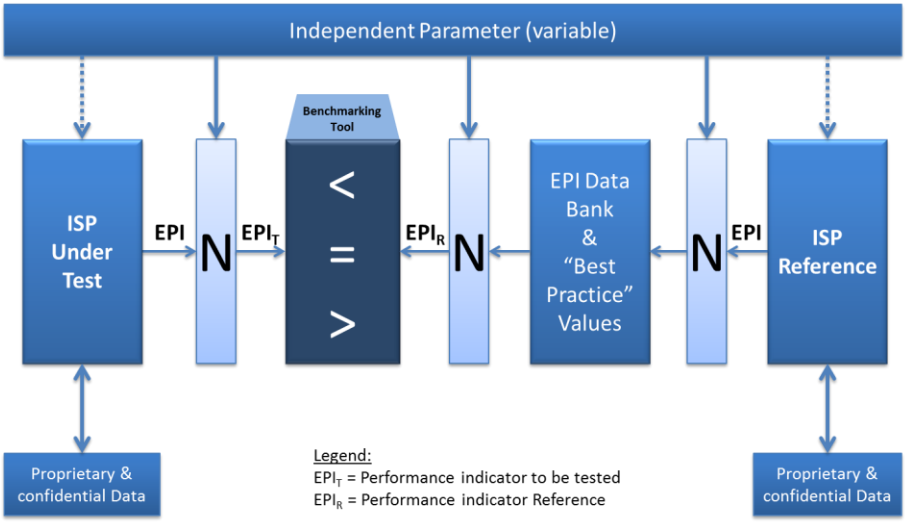

Figure 2: Schematic representation of conventional benchmarking process

As depicted in Figure 2, the EPI values of the ISP Under Test and the ISP Reference go through normalization processes (marked by ‘N’ blocks) so that they can be compared against each other in the Benchmarking Tool. The independent parameters play an important role in influencing the EPI estimations. Top-down benchmarking compares the ISP under test against a data bank of reference EPIs. These EPI values represent the performance of ISP’s which are considered to be best practice.

Before the EPI value is registered in the data bank, it must first undergo a normalization process to ensure that it is comparable to the data bank's normalized conditions from an operational and characteristic perspective. Andersen [17] suggests that the normalization process can often be complicated and is unique to each data set.

For the ISP under test to be benchmarked against best practice, its EPI value must be normalized to take into account its unique operating characteristics (i.e. influence of independent parameters), resulting in a new value denoted as EPI_T. These characteristics are not common in the data bank for that particular type of ISP and therefore must be taken into account to allow for an accurate comparison. The EPI reference value (denoted as EPI_R) is the result of a second iteration of a normalization process to ensure that the data bank EPI values can be accurately compared with the ISP under test in the actual benchmarking tool. Meanwhile, the EPI values are intentionally altered to avoid the sharing of proprietary and confidential information. Andersen [17] discusses the legal and ethical aspects of conventional benchmarking and suggests to take caution when using potential competitors, suppliers or customers as benchmarking partners.

As Boyd et al. explain [19] the normalization process is typically done through a regression analysis to predict energy consumption of a facility based on various independent variables that are known to have an impact on energy consumption. The regression models used are similar to those used for Energy Star™ ratings as mentioned in Chapter 2.3, with its limitations highlighted. Once a regression model is developed for a particular industry, the model is used to normalize the EPI value of a facility based on the independent parameters and conditions of the facility (or data bank) that is being compared against. The purpose of the normalization process is to ensure a relevant and meaningful comparison.

The entire benchmarking process described is tedious, time consuming, costly and must be repeated every time the ISP is changed.

According to the International Energy Agency [28]:

> To understand the impact of using specific energy efficiency indicators, it is necessary to separate the impact of changes in activity, economic structure and other exogenous factors that influence the demand for energy from changes in energy intensities which are proxy for energy efficiency. This is done using a decomposition approach that separates and quantifies the impacts of the individual factors of changes in activity, structure and energy intensities on final consumption in these specific industrial systems.

2.5 Chapter Summary

This chapter provided an overview of current benchmarking concepts and how energy efficiency programs in industry use EUI as a performance indicator for industrial systems or processes and buildings. The literature commonly highlights limitations and challenges with this approach which are listed in Chapter 2.3.

This chapter indicates that that the development of state-of-the-art indicators is not a straightforward process. It requires financial and human resources to collect detailed data and analyze the information. It is proposed that this task can be accomplished by using essential energy benchmarking.

Chapter 3: Industrial Refrigeration Systems

3.1 Introduction to Industrial Systems and/or Processes

As a set of interacting or interdependent parts, an industrial system includes machinery, resources, activities, processes, workers and interdependencies that support the creation and delivery of products and services. The design and the engineering of these industrial systems are complex.

Important research efforts have been made during the last decade to better understand several important families of homogeneous industrial systems that can be handled by a large variety of models and tools [29]. One of these models could be the output energy in the form of essential energy. These are described as transfer functions involving basic physical laws that take into effect the independent parameters, while system components are running at the best efficiency point within a defined boundary.

In this dissertation, ISP refers only to physical systems. These types of systems are transforming physical parameters of specific materials. These systems are, indeed, systems of systems that can be recursively decomposed into sub-systems, until arriving to elementary components that are simple enough to be handled entirely.

Industrial systems are characterised by the integration of various components. In such systems, material of a certain quality entering the system is being transformed to a material/product that leaves the system. Typically, the material produced is of higher value. Among other inputs, energy is used to process the material. A graphical representation of an ISP is shown in Figure 3 [5].

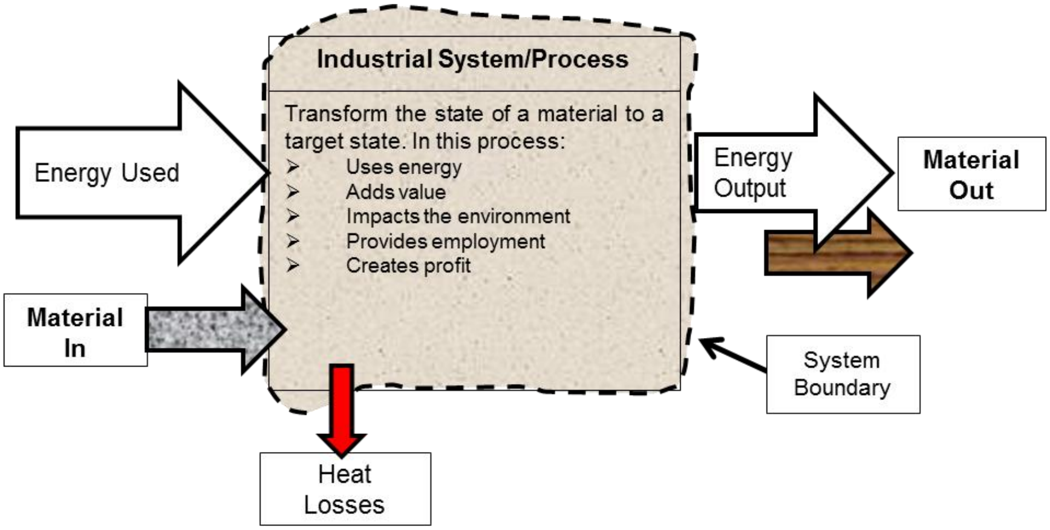

Figure 3: General schematic of an industrial system or process (from [5]*)*

It becomes apparent that the energy consumption for a given industrial process does not depend on the equipment and the system design alone, but also by the boundary conditions such as Material In, Material Out, Energy Used and Heat Losses (or wasted energy).

3.2 Industrial Refrigeration Facilities

Chapter 3.1 defined a typical industrial system or process. Industrial refrigeration systems are a type of ISP. Industrial refrigeration facilities such as cold storage warehouses, provide cold and/or frozen bulk storage for food and beverage products. Some facilities may include other food processing in addition to storage, such as blast freezing or packaging. Cooling is provided by a refrigeration system designed to meet the annual peak refrigeration load of the facility.

3.2.1 Types of IRFs

The research conducted by the author revealed that industrial refrigeration facilities have different operating characteristics which can be grouped into facility types. These unique characteristics may include variability in production profile, operating hours or they may involve specialized refrigerated processes aside from just storage. These special operating conditions are typically related to facility objective and business drivers, and impact the energy performance of the facility.

Three main types of facilities that utilize mechanical refrigeration to maintain space temperature and/or provide refrigerated processing or product cooling are identified.

Type 1: Distribution Facility

- Facility is used to maintain space temperature for short and long term storage of refrigerated products.
- Products are received at a temperature close to the target temperature (±3 °C).
- Steady or frequent level of additional activities impacting refrigeration energy use (high product turnover).

Type 2: Storage Warehouse

- Facility used to maintain space temperature for short and long term storage of refrigerated products.
- Products are received at a temperature close to the target temperature (± 3 °C). When seasonal products are received at a higher temperature, the actual refrigeration energy used for product cooling and maintaining space temperature cannot be measured separately.
- Seasonal or limited additional activities impacting refrigeration energy use (low product turnover).

Type 3: Processing Facility

- Facility used for refrigerated processing or cooling of products with significant additional activities impacting refrigeration energy use.
- The actual refrigeration energy used for product cooling and maintaining space temperature cannot be measured separately.
- Product entering temperature is higher (>5 °C) than product storage temperature.

3.2.2 Industrial refrigeration systems

The configuration of an industrial refrigeration system includes a primary refrigeration circuit related directly to the refrigeration process and secondary circuits as auxiliaries. From an energetic point of view, the primary circuit typically consists of the following equipment:

- Compressors
- Condenser fans and pumps
- Evaporator fans
- Liquid refrigerant pumps

A schematic representation of an industrial refrigeration system is shown in Figure 4.

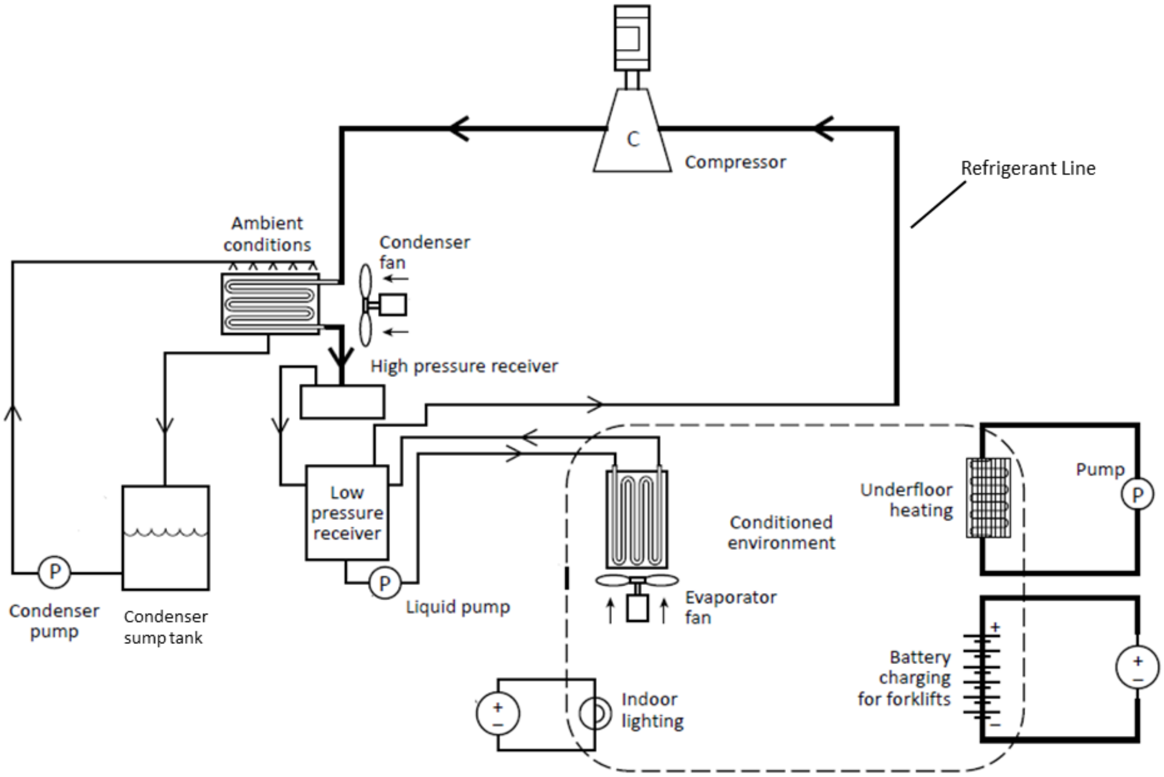

Figure 4: Industrial refrigeration system schematic diagram[6]

The underlying strategy for satisfying the refrigeration load is based on the vapor-compression refrigeration cycle. A system's compressor(s) creates suction, which draws low pressure, low temperature refrigerant vapour from the evaporator(s). The compressor then increases the temperature and pressure of the vapour refrigerant, and sends it to the system's condenser(s).

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[6] Figure 4 has been adapted from the CSA C500 standard for benchmarking industrial refrigeration facilities, due to be published in 2018 and will be available for purchase at http://www.csagroup.org/codes-standards/.

The condenser(s) utilize air or water to condense the vapour to a high pressure liquid. This liquid then undergoes an expansion process that drops the pressure and corresponding saturation temperature of the refrigerant such that the liquid refrigerant can provide the necessary cooling. This expansion process will usually occur at a separator vessel which will provide a liquid volume to be pumped to the evaporators with the flash gas resulting from expansion being directed to the compressor.

Generally, an excess of liquid refrigerant, more than is required for the actual refrigeration load, is pumped to an evaporator. This excess ensures maximum evaporator heat transfer performance and requires separation from the vapour prior to the vapour proceeding to the compressor. The evaporator is a heat exchanger where the cooling occurs. The most common type of evaporator is an air unit which is utilized to cool the space in a cold storage warehouse application and many process freezing applications such as blast freezers, freeze tunnels, and spiral freezers.

Within the boundaries of an IRF there are other functional areas such as administrative offices, dry storage space and other areas with end-uses such as Heating, Ventilation and Air Conditioning (HVAC), lighting, plug loads etc. which are consuming electrical energy. This electrical energy consumption makes up part of the total facility energy at the main meter and is considered to be non-refrigeration energy, as it does not contribute to the actual energy use of the refrigeration system required to satisfy the refrigeration load.

3.3 Conventional Benchmarking of Industrial Refrigeration Facilities

Various studies on measuring energy performance have been conducted for IRFs. In 2006, the California Energy Commission implemented a public interest energy research program for energy efficiency and conservation in refrigerated warehouses. The final project report prepared by Singh [30] presents the results of the research study. The study, consistent with other reported studies, calculates the energy performance of a refrigerated warehouse based on Specific Energy Consumption (SEC), also known as energy use intensity.

The SEC for refrigerated warehouses is defined as the total annual site energy consumption per unit of storage volume, and is given by the following equation:

$$SEC = \frac{Total\ Annual\ Site\ Consumption}{Storage\ Space\ Volume} \qquad \frac{[kWh]}{[m^3]} \tag{2}$$

In accordance with conventional benchmarking, the facility is benchmarked by comparing its SEC value against a limited database of SECs of other facilities and as a result, the best practice is identified[7]. Singh recommends that additional surveys be conducted regularly to further enhance the database and the value of the benchmarking process. This further confirms the limitation highlighted in Chapter 2.3, that the data bank of SECs is not always a reliable benchmark. Furthermore, it requires regular participation from industry partners, which are in fact reluctant to participate to avoid sharing their sensitive information.

Another study prepared by Singh and Prakash [31] in 2008, highlights the fact that the major challenge in benchmarking refrigerated warehouses is the lack of suitable energy consumption benchmark data. In addition, the differences in facilities characteristics make it inappropriate to compare one facility to another. For these reasons, the study looks at developing an energy benchmarking model for refrigerated warehouses. The model calculates the theoretical SEC of a facility based on facility characteristics and operating conditions. The effect of each characteristic on the variability of the calculated SEC value is analyzed. An interesting observation, from their study, is the effect of storage space volume on the SEC, as shown in Figure 5.

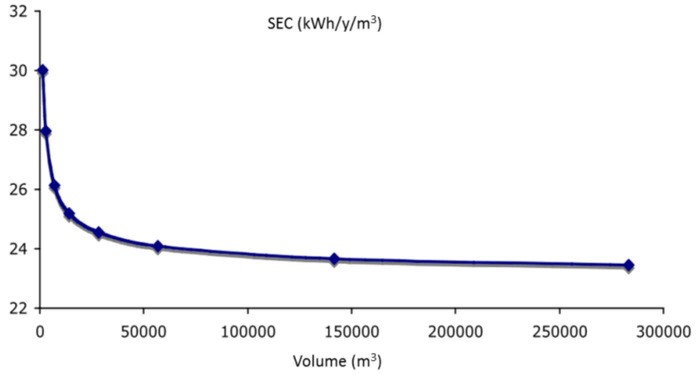

Figure 5: Dependence of SEC on warehouse storage size (from [31]*)*

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[7] The California energy commission developed a web-based benchmarking tool for refrigerated warehouses. The tool is publically available at http://rpaulsingh.com/research/WarehouseEnergy.swf.

The data suggests that the SEC varies significantly for facilities smaller than 50,000 m^3, however, is relatively constant for facilities greater than 100,000 m^3. This observation is similar with findings presented by Evans [32] where data from 329 refrigerated warehouses was collected and a model was used to calculate the theoretical SEC of a facility based on its unique characteristics and operating conditions. Evans' work was part of a project called Improving Cold Storage Equipment in Europe (ICE-E), with the objective to benchmark the performance of cold stores in Europe.

Evans' research examined the relationship of total annual facility energy and the store volume for different types of facilities; chilled stores, frozen stores and mixed stores. The results suggest that the SEC values reduce as the store size increases for frozen and mixed stores. However, the reduction in SEC was only apparent at low store volumes. As can be seen in Figure 6 from Evans' study, there is a low correlation with increase in size with a non-linear regression model resulting in an R^2 value of 66%. Furthermore, Evans indicated that approximately 34% of the variability in annual energy consumption for frozen stores was related to factors that were not considered.

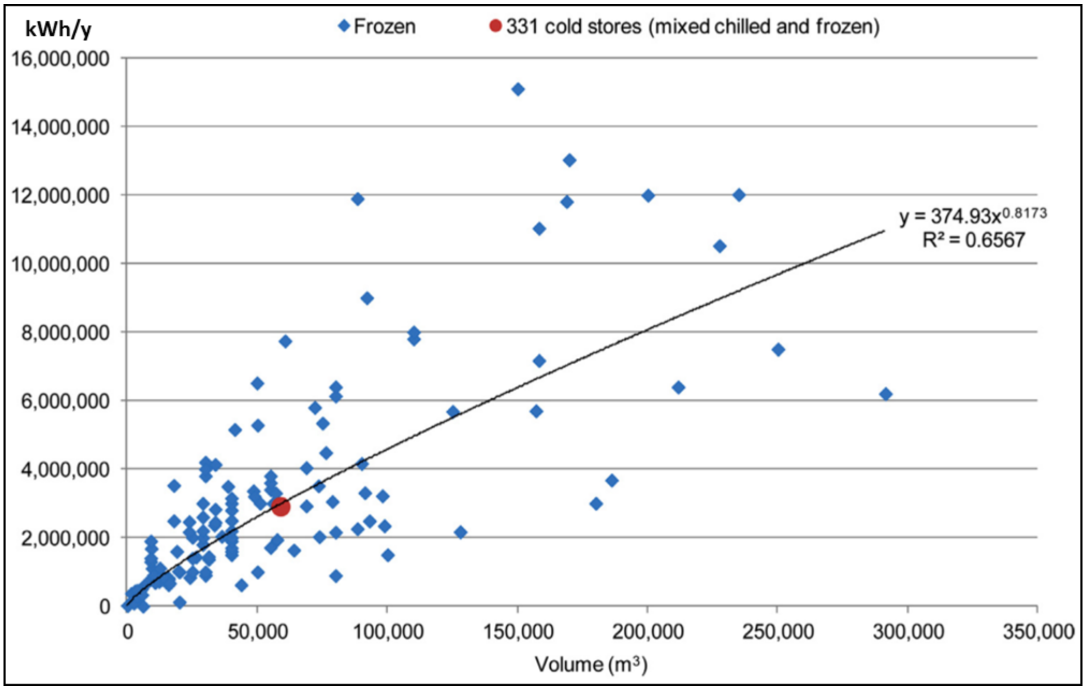

Figure 6: Relationship between store volume and total annual facility energy (from [32]*)*

The literature suggests that the SEC values of an IRF are highly variable due to independent factors unique to each facility and its operating conditions. Furthermore, once the SEC value is determined, comparing it against SEC values of other facilities in a data bank populated with unreliable data can result in inaccurate or even meaningless results.

Part of the ICE-E project included the development of a mathematical model used to predict the energy consumption of a cold store given facility specific independent parameters [33]. The model requires user entered facility specific data that is used to calculate the total annual heat load (kW) of a facility. The model then estimates the Coefficient of System Performance by dividing the calculated total annual heat load by the total energy consumed by the refrigeration system equipment which includes compressor, condenser, evaporator, defrosts and any other refrigeration ancillaries.

Another research study by Evans [34] uses the ICE-E model to estimate potential energy savings of a facility. Based on extensive on-site data collection which included data logging, actual equipment specifications and operating conditions of the facility, potential energy savings were estimated by comparing actual equipment performance with new equipment using manufacturers' data. Evans' research concludes that information on typical energy conservation measures alone is of limited use for cold stores. Instead, cold stores require facility specific assessments to determine their potential for energy savings.

As a performance metric, the SEC value is an indicator for energy efficiency improvement. In other words, we would expect to see improvement in SEC values with implemented energy conservation measures. The case studies presented in Chapter 6.2 demonstrates that the SEC value of an IRF is not directly correlated with the operational energy efficiency performance of the refrigeration system.

From Equation (2), it can be seen that the SEC is merely focused on facility size and total site consumption. Based on this, the following issues are identified:

i. **Independent variables** such as facility location, site layout, weather, operational characteristics and production throughput are not taken into account to calculate the performance of the facility.

ii. **Production throughput and output** can vary significantly between types of facilities and types of product moved. Type and mass of product can have an effect on the overall performance of a facility and therefore must be taken into account in the benchmarking process.

iii. **The SEC** of a facility will decrease with increasing storage indicating that larger warehouses are more energy efficient.

iv. **The ethical and legal issues** present in obtaining proprietary and sensitive information from facility owners, such as production information, to enable normalization of benchmarks.

v. **The reference** (or benchmark) is unreliable since:

    a. It may be referring to a facility of a different type other than the one currently being compared against, or the reference facility is not as efficient as it claimed to be.

    b. The total annual site consumption, the numerator in Equation (2), is made up of both refrigeration and non-refrigeration[8] energy. The research data, later presented in Chapter 6, suggests that up to 50% of a refrigerated warehouse's total annual site consumption is not related to the refrigeration process.

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[8] Non-refrigeration energy may include lighting and HVAC for on-site offices, forklift battery charging, underfloor heating, exterior lighting and other on-site auxiliaries not directly related to the refrigeration process.

Chapter 4: Essential Energy Benchmarking

4.1 Introduction to Essential Energy Benchmarking

While demand side management industry programs consider the total energy consumption (E_{used}) of an industrial system and/or process as a whole, the proposed concept splits the energy in two specific components: Essential Energy (E_{ess}) and Wasted Energy (E_w). Considering these two components of energy, the Benchmark Energy Factor (BEF) is defined. Figure 7 graphically represents the energy components that make up the total energy flow in an ISP. The essential energy represents the minimum energy required to accomplish the ISP task taking into account uncontrollable losses in the system. This is further explained in subsequent chapters where the concept is applied to industrial refrigeration systems.

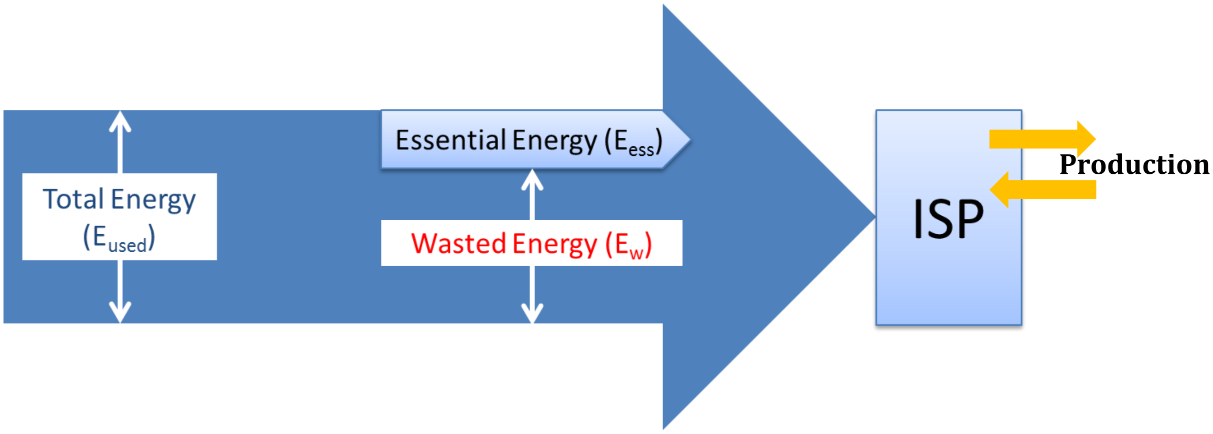

Figure 7: Energy flow and split for an industrial system or process (from [1]*)*

As defined by Equation (3), the BEF represents the overall invested energy (E_{used}) compared to the minimum energy (E_{ess}) required to obtain the desired output of the ISP. The BEF rating is solely based on how close the true energy consumption within an industrial system or process is to the essential energy.

$$\boldsymbol{BEF_{system} = \left.\frac{E_{used}}{E_{ess}}\right|_{given\ input\ parameters}} \tag{3}$$

Although it can never be achieved, a BEF value of 1.0 indicates that E_{used} is equal to the minimum energy required E_{ess}. The essential energy is calculated using a mathematical model that represents the description of the ISP and the task being performed, while taking into account the effects of the non-controllable independent parameters that are unique to the ISP. The independent parameters may include material type, production quantity, environmental conditions, personnel, equipment condition, thermal insulation, transportation, lighting, etc. As input values are introduced in the model over the specified operating time of the ISP, the essential energy is recalculated to account for the influence of the independent parameters. A sample model output showing the annual energy profile for a particular type of ISP is shown in Figure 8.

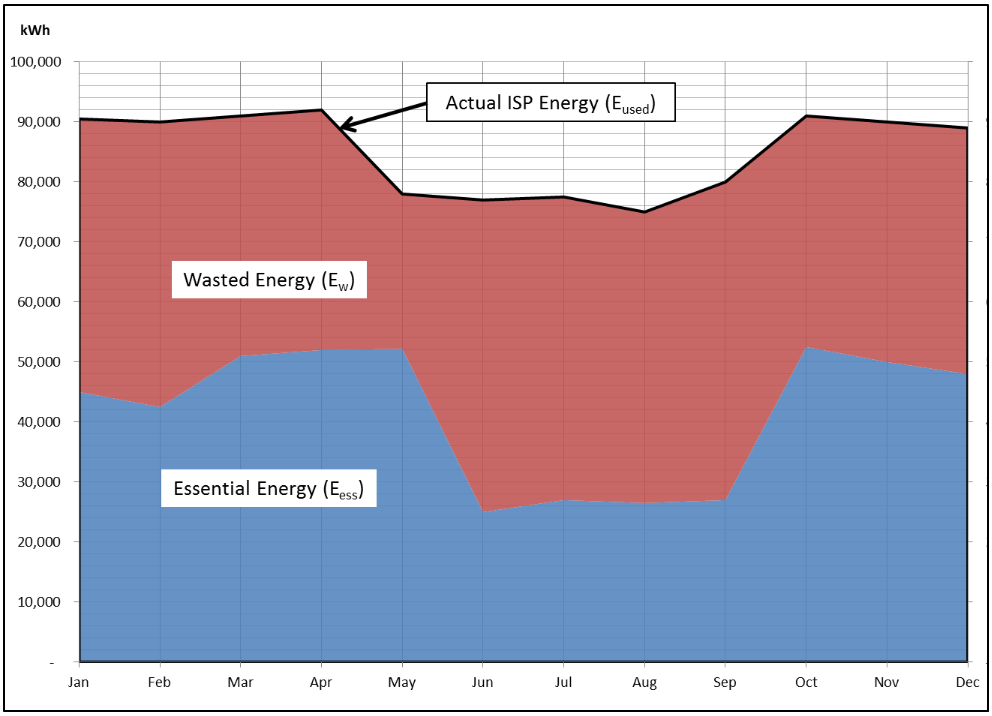

Figure 8: Sample output of essential energy model (from [1]*)*

The essential energy is calculated from the bottom-up by first calculating the theoretical ideal energy of the ISP. The ideal energy can be calculated accurately by using well known laws of physics chosen as a function of the work type performed by the end-use system. It must be quantifiable by its fundamental thermal, mechanical and/or chemical energy components.

The model represents a description of an industrial system or process by using mathematical concepts and language in terms of predicting energy output which is the essential energy (E_{ess}) value that can be used for the benchmarking process.

The essential energy model helps to explain system behaviour and to study the effects of different components, the influence of independent parameters and to also make predictions. The essential energy model is developed considering theoretical concepts and practical applications and shall agree with results of repeatable experiments.

By using the BEF concept for evaluating the energetic performance of a system before and after ECMs are implemented, with compelling evidence and real case studies, the BEF concept can:

- Describe what did happen, after an ECM is implemented, with higher comparability due to normalization of all major independent parameters that impact energy use.
- Allow better estimates of what would have happened in the absence of an ECM (M&V and baseline adjustments).
- Predict what should happen with an ECM being implemented (explain variance).
- Evaluate what could happen with best practice (conservation potential).

With regards to M&V activities for DSM programs, the BEF concept can complement the verification process by acting as a modelling tool that can estimate energy savings and conservation potential. Once the modelling tool is set up for a particular ISP, for example for industrial refrigeration facilities, the model can be used to benchmark any facility and automatically normalize based on user entered parameters. This significantly reduces the costs associated with traditional M&V and it also improves accuracy by minimizing modelling uncertainties that arise due to on-site realities.

Essential Energy Benchmarking (EEB) using Benchmark Energy Factor (BEF), shown in Figure 9, is proposed as the next generation of benchmarking, using more sophisticated and complex mathematical models to set the benchmark value. This type of benchmarking is focused on typical industrial systems and/or processes (or end-uses). One can see the similarities to the first generation of reverse benchmarking where the focus is shifted to the end-use equipment, which starts by first defining the task being accomplished by the system or process.

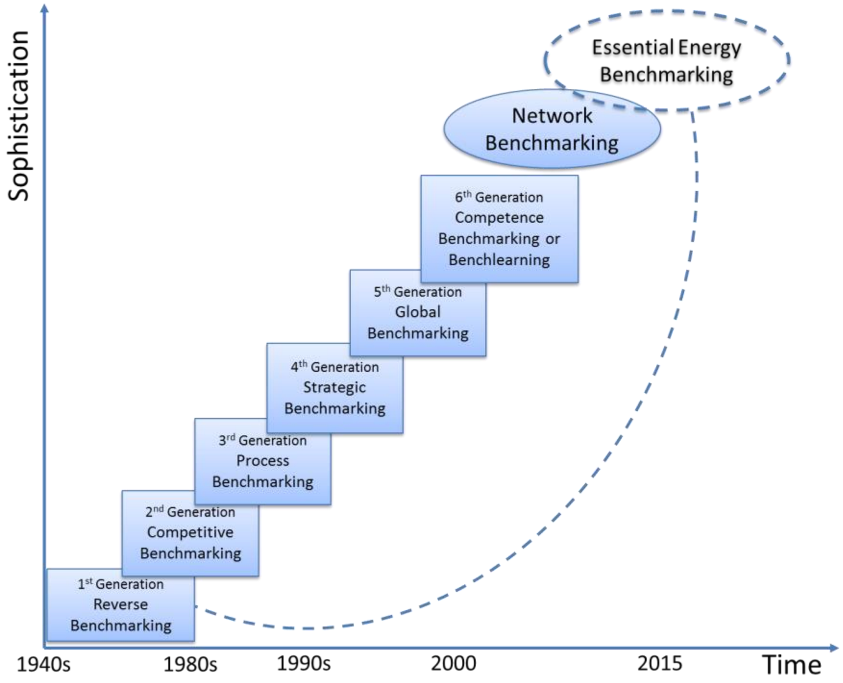

Figure 9: Evolution of benchmarking to essential energy benchmarking (modified from [15]*)*

With a modelled benchmark in place, the ethical and legal issues involved with traditional benchmarking can be avoided. Confidential and proprietary information related to the ISP is not required to be shared externally. As a result, the proposed concept will ensure better accuracy of the benchmarking process.

In this dissertation, the BEF concept is applied to electrical energy; however, it can also be used for benchmarking with respect to any other energy sources (e.g. gas, oil, coal, etc.). This dissertation demonstrates how the energy performance of industrial refrigeration facilities can be benchmarked using the BEF as an indicator, and compared with conventional benchmarking methodologies in real case studies.

4.2 Energy Considerations for an Industrial Refrigeration Facility

In order to apply essential energy benchmarking to IRFs, we must first understand and deconstruct the energy flow within the facility. There are various independent parameters that impact energy use within an IRF and it becomes important to list these parameters and decide what is essential and non-essential to the refrigeration process. The refrigeration process is the process where cooling is provided to the zone within the facility. A zone is defined as a confined space with a controlled temperature.

Upon setting the system boundary for IRFs, which encompasses the entire facility, we can identify the different components that make up the total facility (metered) energy. The energy flow can be characterized as represented in Figure 10.

Setting the system boundary also enables defining the independent parameters that need to be considered for the normalization process, similarly described in the IPMVP fundamental equation [4], and are derived from identifiable physical facts.

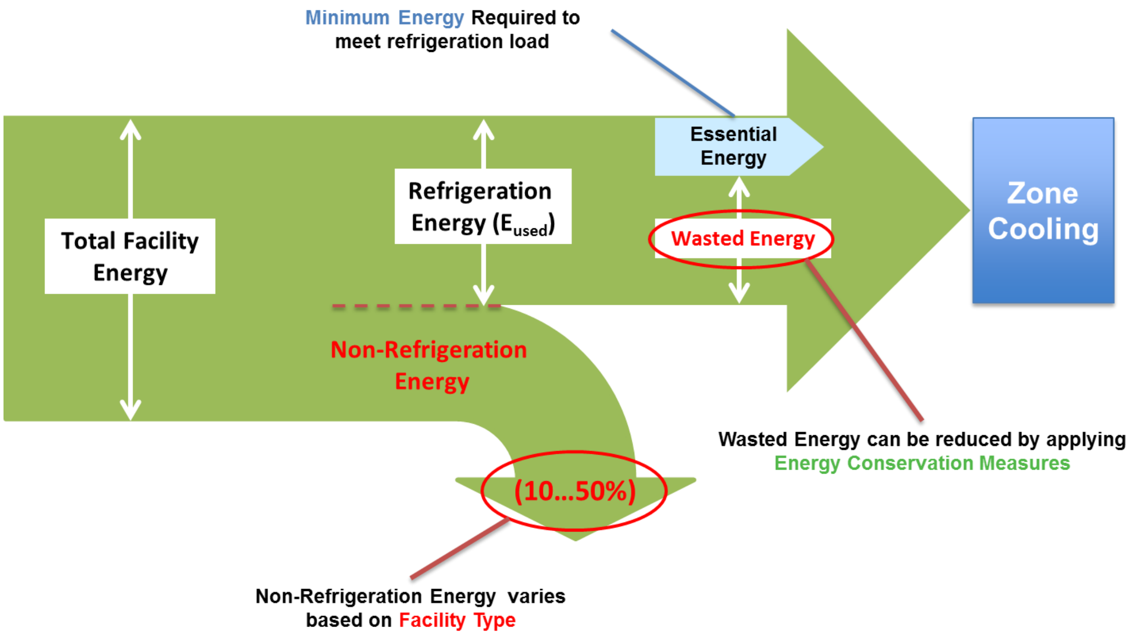

Figure 10: Energy flow within an industrial refrigeration facility (from [1]*)*

It can be seen that the total facility energy is broken down to various components until finally serving the IRF's main purpose: maintaining a set point temperature in the zone by providing the necessary cooling.

Part of the dissertation research data of 10 facilities, presented in Figure 11, suggests that up to 50% of an IRF's total facility energy serves non-refrigeration related end-uses such as office space lighting, HVAC equipment and forklift battery charging. Another research study on refrigerated warehouses [32] suggests that refrigeration energy can account for 60-70% of the total facility energy.

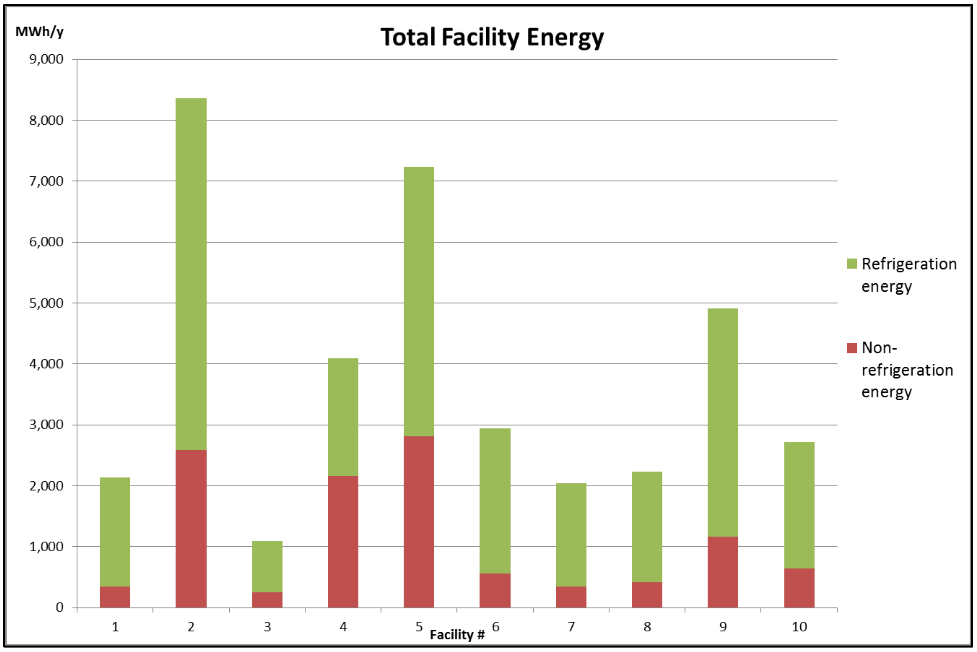

Figure 11: Research findings of refrigeration and non-refrigeration energy split per facility

Total facility energy consumption is typically the metered site consumption and is available from monthly billing data. However, the actual refrigeration energy is not as easily obtained. Actual refrigeration energy can be obtained by either direct measurement of all the energy consumed by the refrigeration system components, or indirectly by determining the non-refrigeration energy and subtracting it from the total facility consumption, as shown by Equation (4).

$$Refrigeration\ Energy\ [kWh] = Total\ Facility\ Energy - Non\ Refrigeration\ Energy \qquad (4)$$

Directly measuring refrigeration energy would require special data logging and sub-metering equipment which may be too costly to obtain. Refrigeration energy varies throughout a typical operating year with changes in production patterns and ambient temperatures, among other factors. Therefore, a full year of data logging would be required to accurately measure an IRF's annual refrigeration energy consumption.

An IRF's non-refrigeration energy is consumed by areas such administrative offices and other non-refrigerated space in the facility. The non-refrigeration systems may include HVAC, plug loads, interior and exterior lighting and forklift battery charging. Minimal variation is expected throughout a typical operating year and is directly correlated with ambient temperature and operating hours, which are both easily obtainable parameters. The non-refrigeration energy can be accurately calculated based on information collected on-site and by using typical energy use intensities for administrative offices. Although not as accurate as directly measuring the refrigeration energy, using the indirect method to determine the refrigeration energy was found to be accurate to within +/-10%. This was verified during the study where actual measured data was used to verify estimates on select facilities.

The refrigeration energy is the energy consumed by the refrigeration system components, as described in Chapter 3.2, consisting of compressors, condensers, evaporators and lighting. The refrigeration energy is required to account for the total refrigeration load on the system. The refrigeration load is essentially the heat loads in the temperature controlled zones and is generated by different entities acting on or within the refrigerated space. A diagrammatical representation of a refrigerated warehouse with typical heat loads is shown in Figure 12.

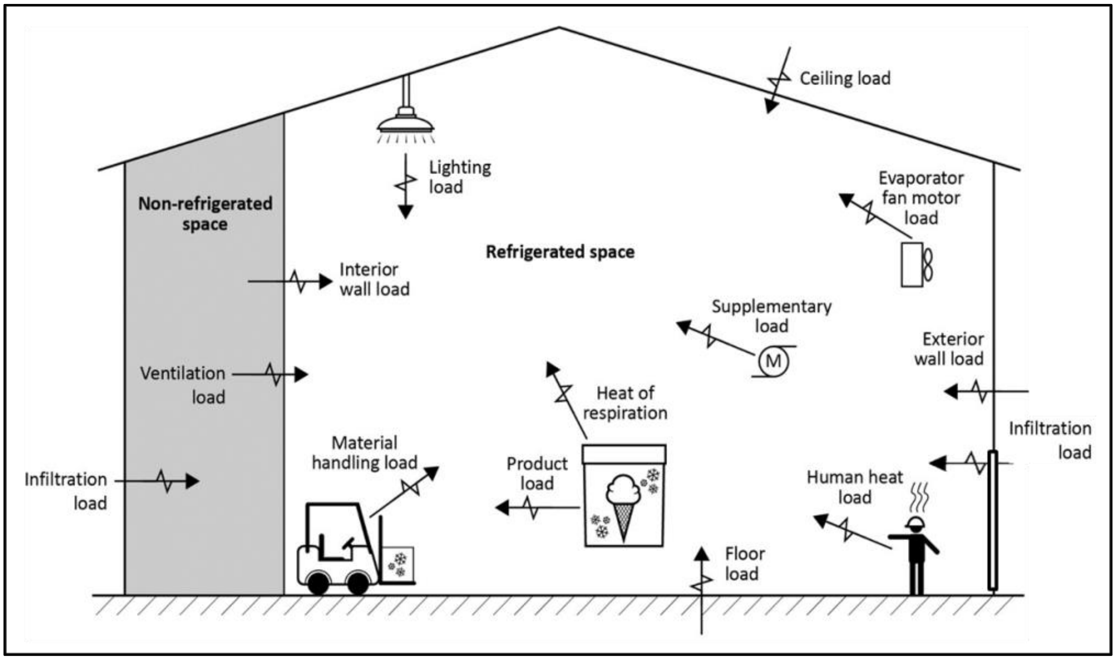

Figure 12: Typical heat loads in a refrigerated warehouse[9]

There are various heat loads within the refrigerated space that contribute to the total refrigeration load, however only a small number of these loads are considered essential to the facility.

During the initial development of the essential energy model (background presented in Chapter 4.3), the model was developed to take into account only four loads which are considered essential to the IRF. These are the loads contributed by the building envelope which include floor and ceiling, refrigerated space lighting, evaporator fan motor load and finally, the load of the actual product being cooled. The remaining loads were either considered to be insignificant contributors to the total load or are non-essential to the IRF's operating conditions and therefore are not taken into account in the essential energy model.

Note that one of the features of essential energy benchmarking is the ability to change how the essential energy is calculated. Every facility has its own unique operating conditions and therefore has unique essential requirements that are otherwise non-controllable for the purpose of energy efficiency. The ability to benchmark a facility's operation against its unique and ideal operating conditions given their non-controllable parameters, is one of the main features of essential energy benchmarking, and allows for a true understanding of the energy conservation potential of the IRF under test.

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[9] Figure 12 has been adapted from the CSA C500 standard for benchmarking industrial refrigeration facilities, due to be published in 2018 and will be available for purchase at http://www.csagroup.org/codes-standards/.

As described in more detail in Chapter 4.4, the essential loads are calculated based on best available technology for envelope, lighting and evaporator fan motor. The dissertation research data presented in Chapter 6 suggests a percent range of total for each essential load and is graphically represented in Figure 13.

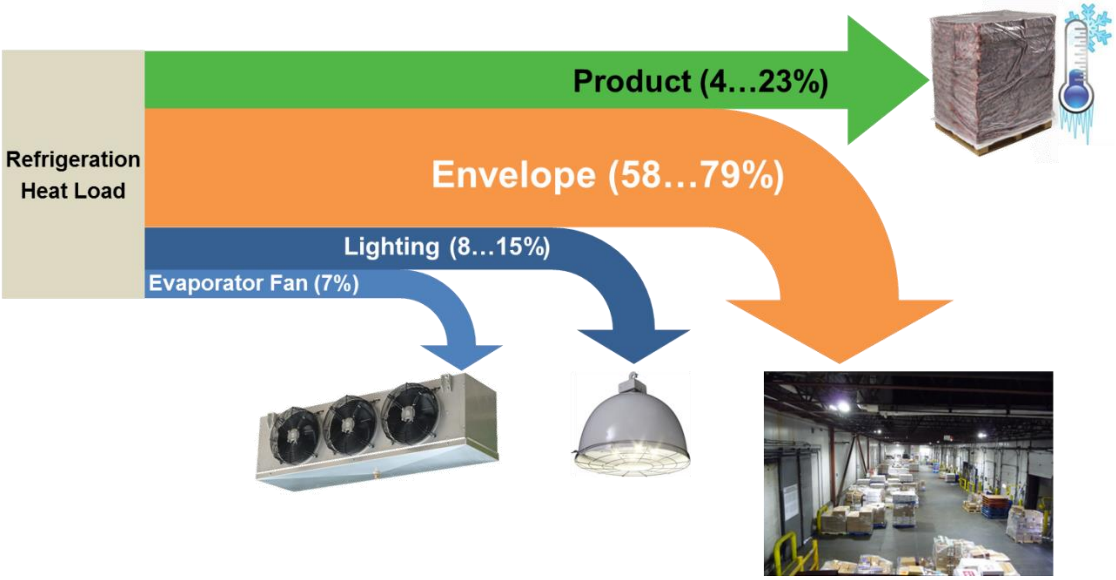

Figure 13: Distribution of essential refrigeration loads for 10 distribution type facilities

As depicted by Figure 13, a distribution facility's envelope load makes up the bulk of the refrigeration loads and in some cases, can account for up to 79% of the total load. The data suggests that as little as 4% of the total refrigeration load is due to cooling the product, which is actually the primary purpose of the industrial refrigeration facility.

Energy efficient technologies aim to reduce the refrigeration load by installing for example: LED lighting capable of maintaining adequate lighting at lower power consumption, automatic cycling and speed reduction of evaporator fans to reduce runtimes and load and thus lowering heat dissipation, and higher insulation to reduce heat transmission through walls, ceiling and floor. The research results presented in Chapter 6 provides data for actual facilities with implemented energy conservation measures and their verified energy savings.

4.3 Background of Research and Development Activities

During the past 3 years, dedicated papers on the BEF concept were presented by the author at various international conferences including the Institute of Electrical and Electronic Engineers (IEEE). The paper [1] describing the BEF concept was awarded 'Best Paper – 1st place' by the 2015 IEEE International Systems Conference. The papers [1] and [35] describe the fundamental elements of essential energy benchmarking and introduced BEF as a normalized performance metric that can be used for benchmarking the energy performance of industrial systems or processes. The papers served as a reference and guide in future developments of essential energy benchmarking for industrial applications.

In 2014, a dedicated mathematical model (BEF tool) for industrial refrigeration systems was developed based on the BEF concept, with sponsorship from several Canadian utilities including BC Hydro Power Smart. Development of the model was managed by the Centre for Energy Advancement through Technological Innovation[10] under project # 7062. The Excel based tool was used to calculate the essential refrigeration load and the essential energy for a given industrial refrigeration facility. The methodology described in Chapter 4.4 is based on the BEF tool.

BC Hydro Power Smart tasked a team of four Engineers including the author of this dissertation, with the development of the model. As one of the original pioneers of the BEF concept, the author provided input and feedback to ensure that the model output represents the essential energy for an industrial refrigeration facility, as defined by the BEF concept.

Further improvements of the mathematical model and verification and validation activities have been undertaken by the author under a pilot project carried out in 2014/2015, sponsored by BC Hydro Power Smart. During this period of time, major features of the BEF concept were studied and defined by the author and published by IEEE [1]. The data collected during the pilot project is presented and analyzed in more depth in Chapter 6.

Based on the results of the pilot project, the Canadian Standards Association (CSA Group) – Technical Committee TC402 developed proposals for a new set of customer orientated standards that are based on the proposed BEF concept. The standards currently being developed are for Slurry Pumps, Data Centres and also Industrial Refrigeration Facilities. Since April 2016, the author has been serving on the technical sub-committee for CSA standard C500 – Benchmarking Industrial Refrigeration Systems using the BEF concept. The standard is expected to be published in 2018. The author has provided the seed document for the development of the standard along with two whitepapers that provide an overarching guideline for applying essential energy benchmarking to any industrial system or process.

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[10] The Centre for Energy Advancement through Technological Advancements brings partners together to collaborate on technical projects with a strong practical focus. Currently, over 120 utilities from all six of the world's continents are represented in the centre's 18 interest groups and task forces.

The development of the model began with defining the system boundary of the refrigeration system in a typical facility. Key system components were identified as being the primary energy consumers, as presented in Chapter 3.2, which would make up part of a facility's essential energy. In order to determine the essential energy, the essential refrigeration load was first determined. This proved to be a challenging aspect of the software since agreement is required between parties involved in the benchmarking process to decide on which heat loads within a temperature controlled zone are considered to be essential to the IRF. This means that they cannot be controlled beyond a minimum threshold. Four specific contributors to the total essential heat load were identified and are described in Chapter 4.4.

Except for product heat load, for every other essential heat load and essential energy component, an Essential Performance Metric (EPM) was required to be decided on. The EPM values needed to represent the best available technology operating at its best efficiency point. The EPM value for each system component is presented in Chapter 4.5.

4.4 Essential Load and Energy for Industrial Refrigeration Facilities

The essential energy for an IRF is calculated based on meeting the total essential refrigeration load of the facility. The process of calculating the essential energy is a two-step process (A and B):

A. The following equations are presented in metric units and therefore the refrigeration heat loads are expressed in kW. The essential refrigeration load is the sum of the following heat load components and is based on facility specific independent parameters and pre-set essential energy standards for best available technology:

I. Envelope load

The envelope load is based on the construction of each zone. The walls, floor, and ceiling contribute to the envelope load. The total facility envelope load is the sum of each of the zone loads. The walls, floors and ceiling loads are calculated each separately using the following equation:

$$Q_{envelope} = \frac{1}{RSI_{ess}} \times A \times \left(T_{opp} - T_{target}\right) \times \frac{1}{1000} \tag{4}$$

where;

$Q_{envelope}$:	Essential envelope load averaged over 24 hours	kW
T_{target} :	Target temperature	°C
A :	Wall/Ceiling/Floor area	m^2
RSI_{ess}:	Wall/Ceiling/Floor essential R value	m^2 °C/W
T_{opp}:	Daily average opposite side wall temperature	°C

II. Lighting load

The lighting load in an IRF is the load created by lighting fixtures within the refrigerated space (or zone). The number of hours during which the zone is occupied per day is required to be recorded, from which the daily average load is calculated. The model assumes that lights are off when a zone is unoccupied, and 100% of light energy contributes to the refrigeration load. The following equations are used:

$$P_{lighting} = A_{zone} \times EPM_{light} \times \frac{1}{1000} \tag{5}$$

$$Q_{lighting} = P_{lighting} \times t_{occupied} \times \frac{1}{24} \tag{6}$$

where;

$Q_{lighting}$:	Essential zone lighting load averaged over 24 hours	kW
$P_{lighting}$:	Zone lighting power	kW
A_{zone} :	Zone area	m^2
$t_{occupied}$:	Number of hours zone is occupied per day	h
EPM_{light} :	Lighting essential performance metric	W/m^2

III. Product load

Product load accounts for product that is cooled and/or frozen to a final target temperature. Examples include, product that arrives at a distribution facility at a temperature exceeding the target temperature and process freezing of product, such as blast freezing. The equation assumes the rate at which a product enters a zone is constant through a day. Depending on whether the product is received below or above freezing, the following equations are used:

$$Q_{product} = Q_{aboveF} + Q_{latent} + Q_{belowF} \tag{7}$$

$$Q_{aboveF} = LR \times C_{aboveF} \times \left(T_{entering} - T_{freezing\ point}\right) \times \frac{1}{3600 \times 24} \tag{8}$$

$$Q_{latent} = LR \times L_{latent} \times \frac{1}{3600 \times 24} \tag{9}$$

$$Q_{belowF} = LR \times C_{belowF} \times \left(T_{freezing\ point} - T_{target}\right) \times \frac{1}{3600 \times 24} \tag{10}$$

where;

$Q_{product}$:	Essential product load averaged over 24 hours	kW
LR :	Average product loading rate	kg/day
T_{target} :	Target temperature	°C
$T_{entering}$:	Product entry temperature	°C
$T_{freezing\ point}$:	Freezing point temperature	°C
C_{aboveF} :	Specific heat above freezing	kJ/kg°C
L_{latent} :	Latent heat	kJ/kg
C_{belowF} :	Specific heat below freezing	kJ/kg°C
Q_{aboveF} :	Load above freezing	kW
Q_{latent} :	Latent load	kW
Q_{belowF} :	Load below freezing	kW

IV. Evaporator fan motor load

The evaporator fan motor load is the heat dissipated into the refrigerated space from the fan motor and is calculated as follows:

$$Q_{fan\ motor} = \left(Q_{envelope} + Q_{lighting} + Q_{product}\right) \times EPM_{evap} \tag{11}$$

where;

$Q_{fan\ motor}$:	Essential fan motor load averaged over 24 hours	kW
$Q_{envelope}$:	Essential envelope load	kW
$Q_{lighting}$:	Essential lighting load	kW
$Q_{product}$:	Essential product load	kW
EPM_{evap} :	Evaporator essential performance metric	kW/kW

V. Total essential refrigeration load

The total essential refrigeration load is the sum of all the essential heat load components and is calculated as follows:

$$Q_{total} = Q_{envelope} + Q_{lighting} + Q_{product} + Q_{fan\,motor} \tag{11}$$

where;

Q_{total} :	Total essential refrigeration load averaged over 24 hours	kW
$Q_{envelope}$:	Essential envelope load	kW
$Q_{lighting}$:	Essential lighting load	kW
$Q_{product}$:	Essential product load	kW
$Q_{fan\,motor}$:	Essential fan motor load	kW

B. Calculation of essential refrigeration energy (kWh), required for meeting the essential refrigeration load (kW), is based on the sum of refrigeration energy components which are based on facility specific independent parameters and pre-set essential energy standards for best available technology.

Using a bottom-up approach, the work being accomplished by the ISP (in this case the refrigeration system), can be defined based on the second law of thermodynamics. In the case of the refrigeration process, it states that heat flow from a cold reservoir (zone) to a hot reservoir (ambient) requires work to be done on the dynamic fluid (refrigerant).

Even an ideal refrigeration system is not 100% efficient, which is demonstrated by the reversed Carnot cycle. A Carnot refrigerator is considered as the most efficient refrigeration cycle operating between the cold zone temperature (T_2) via an evaporator and the hot ambient temperature (T_1) via a condenser and its efficiency is defined by the following equation [36]:

$$\eta_{reverse\ Carnot} = \frac{T_2}{T_1 - T_2} \tag{12}$$

The ideal vapour-compression cycle assumes that:

- Refrigerant flows at constant pressure through the two heat exchangers (evaporator and condenser)
- The compression process is isentropic (adiabatic reversible)
- No frictional pressure drops occur
- Heat losses to the surroundings are ignored

The Carnot refrigerator efficiency defines the ideal energy of the refrigeration system as a whole. As described earlier, the essential energy model is designed to provide a realistic benchmark value that represents the best available technology currently on the market. It does this by calculating the various essential energy components representing each of the equipment in the system, which are required to meet the essential load on the system.

In the case of IRFs, the energy components are those consumed by each of the refrigeration system equipment plus the lighting in the refrigerated space.

As part of the original development of the essential energy model, a significant amount of time and effort was spent on deciding the Essential Performance Metrics (EPMs) that are used to represent the best available technology for each system component. The EPM value for each system component is used to calculate the essential load and essential energy. The EPM values and a description of how they were determined are presented in Chapter 4.5.

I. Compressor essential energy

The compressor essential energy is calculated based on the best available technology that has the highest isentropic efficiency. The compressor essential energy is determined based on operating at peak efficiency for the optimum suction and discharge conditions. Efficiency reduction at reduced load is not considered to be part of a facility's essential energy.

$$P_{compressor} = EPM_{comp} \times Q_{total} \times \frac{1}{\eta_{comp.motor}} \tag{13}$$

$$E_{compressor} = P_{compressor} \times 24 \tag{14}$$

where;

$E_{compressor}$:	Daily compressor energy	kWh
$P_{compressor}$:	Essential compressor power averaged over 24 hours	kW
EPM_{comp}:	Compressor essential performance metric	kW/kW
Q_{total} :	Total essential refrigeration load	kW
$\eta_{comp.motor}$:	Essential compressor motor efficiency	%

II. Condenser fan and pump essential energy

The condenser essential energy is determined by using a predetermined condenser efficiency factor, corrected for actual wet bulb temperature and optimal condensing temperature. The model assumes that the condenser(s) utilizes evaporative water cooling to condense the vapour to a high pressure liquid. The condenser fan and pump essential energy is defined as follows:

$$E_{condenser} = \left(P_{compressor} \times \eta_{comp.motor} + \ Q_{total}\right) \times EPM_{cond.} \times 24 \tag{15}$$

where;

$E_{condenser}$:	Daily condenser energy	kWh
$P_{compressor}$:	Essential compressor power averaged over 24 hours	kW
$\eta_{comp.motor}$:	Essential compressor motor efficiency	%
EPM_{cond}:	Condenser essential performance metric	kW/kW
Q_{total} :	Total essential refrigeration load	kW

III. Evaporator fan essential energy

The evaporator essential energy is determined by using a predetermined evaporator efficiency factor. It is assumed that air unit evaporators are utilized. The evaporator fan essential energy is defined as follow:

$$E_{evaporator} = EPM_{evap.} \times Q_{total} \times 24 \tag{16}$$

where;

$E_{evaporator}$:	Daily evaporator fan energy	kWh
$EPM_{evap.}$:	Evaporator essential performance metric	kW/kW
Q_{total} :	Total essential refrigeration load	kW

IV. Lighting essential energy – in refrigerated space only

The number of hours during which the zone is occupied per month is required to calculate the lighting essential energy. The model assumes that lights are off when a zone is unoccupied. The lighting essential energy is defined as follows:

$$E_{lighting} = P_{lighting} \times t_{occupied} \tag{17}$$

where;

$E_{lighting}$:	Daily lighting essential energy	kWh
$P_{lighting}$:	Zone lighting power (calculated from lighting load Equation (5))	kW
$t_{occupied}$:	Zone daily hours occupied	h

V. Total essential refrigeration energy

The total essential refrigeration energy is the sum of all the essential energy components and is calculated as follows:

$$E_{total} = E_{compressor} + E_{condenser} + E_{evaporator} + E_{lighting} \tag{18}$$

4.5 Essential Performance Metrics

Essential performance metrics are in essence, energy performance indicators or energy use intensities for specific components within an ISP, in this case, industrial refrigeration systems.

The EPM represents the performance of a system component that is equipped with best available technology, and capable of operating at its best efficiency point.

For any industrial system or process, the EPM values are crucial to set the essential energy for that particular ISP. In other words, it sets the benchmark value that the ISP is striving to achieve. When a standard is being developed, these EPM values are to be determined through a consensus of a non-profit professional committee comprised of industry experts. The EPMs for a particular ISP need to be revised and updated regularly to ensure that the benchmark (essential energy) represents the most current best available technology.

For industrial refrigeration facilities, the EPM values were determined during the development of the essential energy model and were obtained from manufacturer's data. Performance specifications of different manufactures for each system component were gathered and the highest performance metric was selected. Table 2 summarizes the EPM values for each IRF system component:

Table 2: Essential performance metrics for industrial refrigeration facilities

Essential Performance Metric (EPM)	Symbol	Value	Units
Walls Insulation*	RSI_{ess}	6.34	m^2C/W
Ceiling Insulation*		7.04	
Floor Insulation*		6.16	
Lighting**	EPM_{light}	2.37	W/m^2
Evaporator***	EPM_{evap}	0.071	kW/kW
Condenser****	EPM_{cond}	0.025	
Compressor*****	EPM_{comp}	1.2	
Motor Efficiency	$\eta_{comp.motor}$	95	%

*The effective RSI values for walls, ceiling and floor are sourced from the 2016 Building Energy Efficiency Standards – California Energy Commission Title 24, Section 120.6 – Mandatory Requirements for Covered Processes – Table 120.6-A Refrigerated Warehouse Insulation.

**The California Energy Commission Title 24 states a maximum allowable lighting power density of 10.8 W/m^2 for industrial warehouses. Independent energy studies revealed a lighting power density of 2.37 W/m^2 was achieved at an actual facility.

***Evaluating a data set of 2000 evaporator models from Evapco, an industry leading manufacturing company for evaporative cooling, revealed a range of evaporator efficiencies from 0.04 kW/kW to 0.34 kW/kW with an average of 0.09 kW/kW.

****The condenser fan and pump packaged efficiency factor was selected based on the evaluation of 10 condenser models. The factor assumes that 10% of the heat rejection capacity of the condenser is contributed by the condenser pump. Therefore 90% of the heat rejection capacity is handled by the fans running at 50% speed representing peak efficiency.

*****The tool assumes there is a 15 °C temperature differential between the refrigerant and the lowest zone temperature for the suction group. For instance, if a zone is at -10 °C then the suction pressure will be -25 °C. To determine the condensing temperature, the tool assumes a floating wet bulb approach with a 15 °C differential between the ambient wet bulb and refrigerant temperature. A minimum condensing temperature of 13 °C is assumed. Compressor curvefits are used to find the compressor efficiency at a certain suction and condensing pressure. Compressor curvefits are derived from manufacturers' data using a regression model. A general essential energy curvefit is created by averaging the full load ratings for compressors from three different manufacturers. This curvefit is then used to find the required compressor brake horsepower (bhp) to satisfy each total suction system refrigeration load. A 95% compressor motor efficiency is assumed to convert shaft power (bhp) to total power (kW).

The essential energy model analyzes the compressor setup in the most efficient manner. While it is generally more efficient to utilize multiple stages of compression for any application, the difference between the efficiency of single-stage and two-stage compression lessens as the compression ratio gets smaller. For each suction group evaluated, the efficiency of single-stage compression is compared to two-stage compression. If single-stage compression is determined to require 10% or greater energy than two-stage compression, then two-stage compression is assumed as the basis for essential energy.

Chapter 5: Research Methodology

After reviewing over 30 industrial refrigeration facilities located in British Columbia, Canada, 10 facilities were selected for the BEF testing pilot project sponsored by BC Hydro Power Smart. The pilot project consisted of the following four stages:

Stage 1: Facility review & site visit setup

- Review facility details and past DSM project documentation including energy studies and M&V reports if available.
- Determine if facility is suitable for BEF testing and classify the type of facility.
- Decide on-site scope of work.
- Contact the facility's representative. Provide brief overview of the BEF concept and explain the scope of work for the pilot project, objectives and the potential benefits.

Stage 2: Site visit and data collection

- Travel to site and meet with the facility representative to discuss technical facility details.
- Review design plans and drawings and collect necessary facility data.
- Walk through facility and identify key refrigeration system components, determine loading profile, and operating time.
- Identify non-refrigeration components.
- Photograph components and record nameplate details.
- Collect energy consumption data from billing data and M&V data (if available).

Stage 3: Data compilation and BEF simulation

- Review site data and estimate refrigeration and non-refrigeration energy consumption.
- Create appropriate spreadsheets for collected data for BEF tool entry.
- Run BEF tool and document results.

Stage 4: BEF results analysis

- Analyze simulated BEF values for the selected facility.
- Simulate BEF pre- and post-ECMs and analyze results.
- Use M&V data (if available) to verify non-refrigeration energy consumption – request for further information from the facility if required.
- Compare BEF tool results with other sites and identify gaps and inconsistencies in the essential energy model and non-refrigeration energy consumption estimates.
- Prepare methodology for comparing BEF values with other facilities of the same type.
- Document and report findings.

The vast amount of data collected and the studies conducted by the author during the past 3 years is used as the basis for this dissertation. The data for 10 IRFs are presented and findings are summarized in Chapter 6.

5.1 Issues Addressed

During the development of the essential energy model, and throughout the pilot testing, several issues arose, some of which were unexpected and are related to the realities observed during the site visits and in discussions with the facility operators. These issues include:

- Establishment of a system boundary for industrial refrigeration facilities.
- Defining refrigeration and non-refrigeration energy in refrigeration facilities.
- Defining the variable independent parameters impacting the energy consumption of facilities.
- Setting the essential performance metrics to calculate the essential refrigeration load taking into account all the relevant independent parameters.
- Setting the essential performance metrics to calculate the essential energy required to meet the essential refrigeration load, when the system is equipped with the best available technology equipment on the market, running at its best efficiency point[11].
- Computing the BEF and comparison with SEC benchmarks.
- Using BEF to estimate energy savings and impact of energy conservation projects.
- Validating the results obtained from the BEF concept using real case study projects that have gone through M&V activities.
- Assessing the conservation potential after a project by computing the BEF before and after ECMs are implemented.
- Evaluating impact on M&V costs for utility funded programs when using essential energy benchmarking to verify energy savings versus conventional M&V methods.

5.2 Test Requirements

The relationships of the various energy components of an industrial refrigeration facility, with changes in refrigeration loads, were analyzed for a single site and for multiple sites as a test group. Similar to the Evans [32] and Singh [31] research studies, the data is expected to demonstrate a relationship between the total site consumption and changes in volume. However, we expect to see a stronger relationship between refrigeration energy and volume since any increase in volume results in a direct increase in envelope load which directly impacts the refrigeration energy. The essential energy is expected to be even more closely correlated with volume since the essential energy is precisely calculated based on the user entered specifications that defines the essential refrigeration loads. One of the primary essential loads is the envelope load which is calculated according to the size (or volume) of the refrigerated space. Therefore, any variation in volume should be directly reflected in the essential energy.

The SEC and BEF of 10 selected facilities were calculated based on conventional benchmarking and essential energy benchmarking, respectively. The SEC and BEF values are first compared against each other to see how they represent the energy performance of the facility. This is determined by comparing the level of performance of facilities with facilities that are known to be operating at high

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[11] As an example, for a refrigeration system, the best equipment available on the market should be related to an ideal facility with best insulation and use of “premium” equipment: refrigeration compressor types, condensers, and evaporators for primary circuit running on controlled mode at best efficiency point.

performance due to the implemented ECMs and energy management practices. The performance of one facility relative to another is analyzed by comparing their respective BEF and SEC values.

For facilities with known energy conservation measures applied and with available M&V data, the SEC and BEF values are calculated before and after the ECMs were implemented. Energy savings for the implemented ECM is estimated using the proposed essential energy benchmarking methodology, and estimates are compared against actual M&V data where available. We expect the BEF methodology to accurately estimate energy savings and the facility's conservation potential. Although we expect to see improvement in SEC before and after ECMs are implemented, the variability and magnitude of the total site consumption relative to the energy savings may be too high to distinguish between system noise and energy savings.

As a measure of performance, the BEF and SEC of a facility should provide insight into the conservation potential for a given facility. Relatively high BEF and SEC values indicate an opportunity for energy savings while relatively low BEF and SEC values indicate that the facility is operating efficiently. The conservation potential of select facilities are analyzed and compared.

This dissertation also looks at alternative methods of calculating the SEC by changing the numerator in Equation (2) to refrigeration energy and essential energy. Alternative SEC values may prove to be more accurate at determining performance levels and to make predictions based on variability in storage volume.

Chapter 6: Results

The data presented in this chapter covers 10 selected distribution type industrial refrigeration facilities. The data was collected through onsite investigation, communication with the facility operator, and review of past energy efficiency feasibility studies and M&V data for implemented ECMs where available.

A summary of the characteristics of the 10 IRF sites that were tested and numbered 1 to 10 is listed in Table 3. The selected IRFs employ a number of temperature controlled zones that vary in temperature set points and store various food products including produce, meats, dairy and other beverage and non-beverage food products.

Table 3: Summary of 10 distribution type IRFs characteristics

IRF site #	# of cold zones	Zone temperatures max/min (^oC)	Total storage volume (m^3)	Annual total facility energy (MWh)
1	5	11 / 1	131,400	2,136
2	14	13 / -26	283,192	8,366
3	2	2 / -26	20,886	1,095
4	5	12 / -18	126,509	4,090
5	11	13 / -22	144,783	7,231
6	3	6 / -26	111,780	2,943
7	5	4 / -21	82,086	2,045
8	4	3 / -29	66,865	2,228
9	7	10 / -22	112,026	4,912
10	5	7 / -23	117,615	2,713

As presented in Chapter 3.2, the refrigeration energy is consumed by the refrigeration compressors, condenser fans and pumps, evaporator fan motors and zone lighting. The total facility energy is determined from the facility's billing data and is comprised of refrigeration energy and non-refrigeration energy. Where available, M&V data was used to determine the refrigeration energy, otherwise the refrigeration energy was calculated as the difference between total facility energy and non-refrigeration energy, as described in Chapter 3.2. The energy components of the 10 IRF sites are summarized in Table 4.

Table 4: Summary of total facility energy components

IRF site #	Annual refrigeration energy (MWh)	Annual non-refrigeration energy (MWh)
1	1,794	342
2	5,778	2,588
3	844	251
4	1,927	2,163
5	4,421	2,810
6	2,380	563
7	1,695	350
8	1,815	413
9	3,749	1,163
10	2,077	637

The essential load for each IRF was calculated using the essential energy model, based on inputs that describe the unique physical and operating characteristics of the IRF. These inputs include refrigeration system specifications, geographical location of the IRF, storage space dimensions, production, set point temperatures and operating hours. A summary of the essential refrigeration loads, in tons of refrigeration (TR)[12], is calculated for each IRF using the equations described in Chapter 4.4 and are shown in Table 5. The kW value for each load is converted to TR by multiplying by 0.284.

Table 5: Summary of daily average essential refrigeration loads

IRF site #	Envelope load (TR)	Product load (TR)	Lighting load (TR)	Evaporator fan motor load (TR)	Total load (TR)
1	9	4	6	1	21
2	36	61	15	8	119
3	5	2	1	1	9
4	22	0	7	2	31
5	27	9	7	3	47
6	28	1	4	2	35
7	19	4	2	2	27
8	21	1	4	2	27
9	39	1	7	3	49
10	23	2	4	2	31

Figure 14 shows the average distribution of essential refrigeration loads and indicates that the envelope makes up the bulk of the load at 58%, followed by the product load at 21% and finally the lighting and evaporator fan motor loads at 14% and 7%, respectively. It is clear that the size of the refrigerated storage space has the strongest impact on energy consumption of a distribution type IRF.

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[12] Tons of Refrigeration (TR) represents the unit of refrigeration heat load most commonly used in North America. 1 TR is equivalent to 12,000 Btu/h or 3.52 kW.

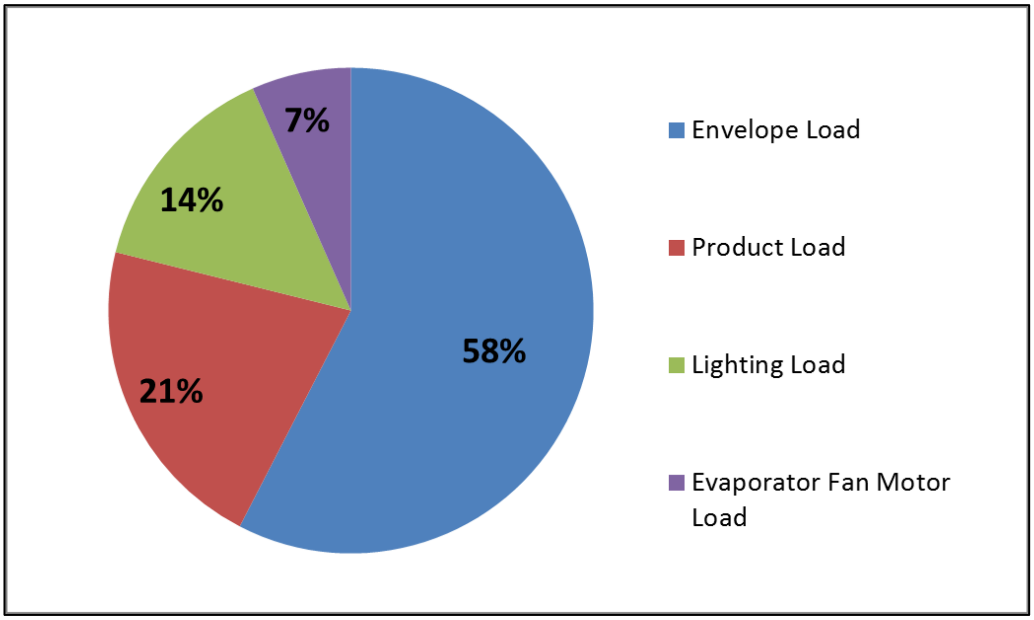

Figure 14: Average distribution of essential refrigeration loads of 10 IRFs

The essential energy of each IRF was calculated using the essential energy model and it is considered as the minimum energy required to satisfy the facility's essential refrigeration load. The wasted energy is calculated as the difference between the refrigeration energy and the essential energy. The results are shown in Table 6.

Table 6: Essential and wasted energy

IRF site #	Annual essential energy (MWh)	Annual wasted energy (MWh)
1	375	1,419
2	1,665	4,113
3	130	714
4	551	1,376
5	698	3,723
6	588	1,792
7	426	1,269
8	517	1,299
9	770	2,979
10	515	1,562

The average distribution in essential energy components for the 10 IRFs is shown in Figure 15. Approximately 43% of the essential energy is consumed by the compressor, followed by lighting at 26% and finally the evaporator fan motors and the condenser fan/pump motors at 18% and 13%, respectively. As expected, the bulk of the essential energy is due to the compressors.

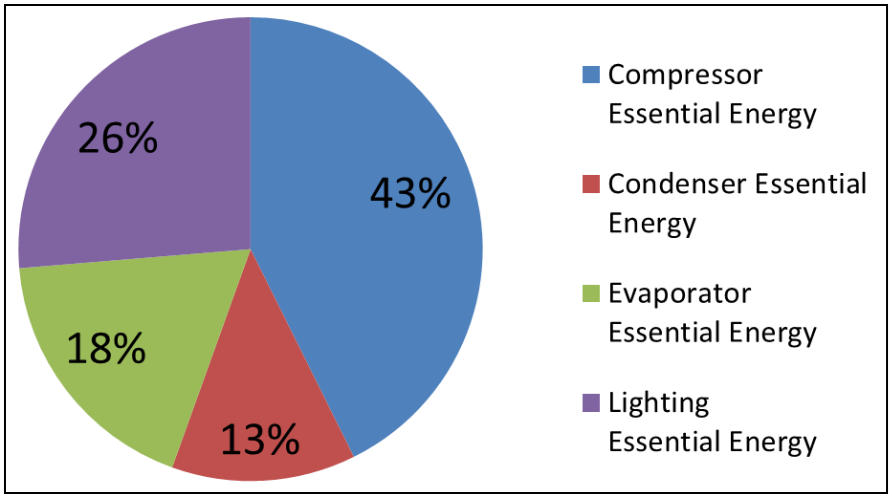

Figure 15: Average essential energy components of 10 IRFs

6.1 Energy and Load Correlations

The correlation between the various energy components of an IRF and the storage space volume is graphically represented in Figure 16. A non-linear 2nd order polynomial regression is applied for each energy component and volume. The data shows a regression R^2 value of 71% for total facility energy. However, as expected, we see a higher R^2 value for refrigeration and an even higher level for essential energy at 89%. This is because the total facility energy is comprised of non-refrigeration energy which is not impacted by the size of the refrigerated storage space, while the refrigeration and essential energies are proportional to the volume since the refrigeration load increases with storage space volume.

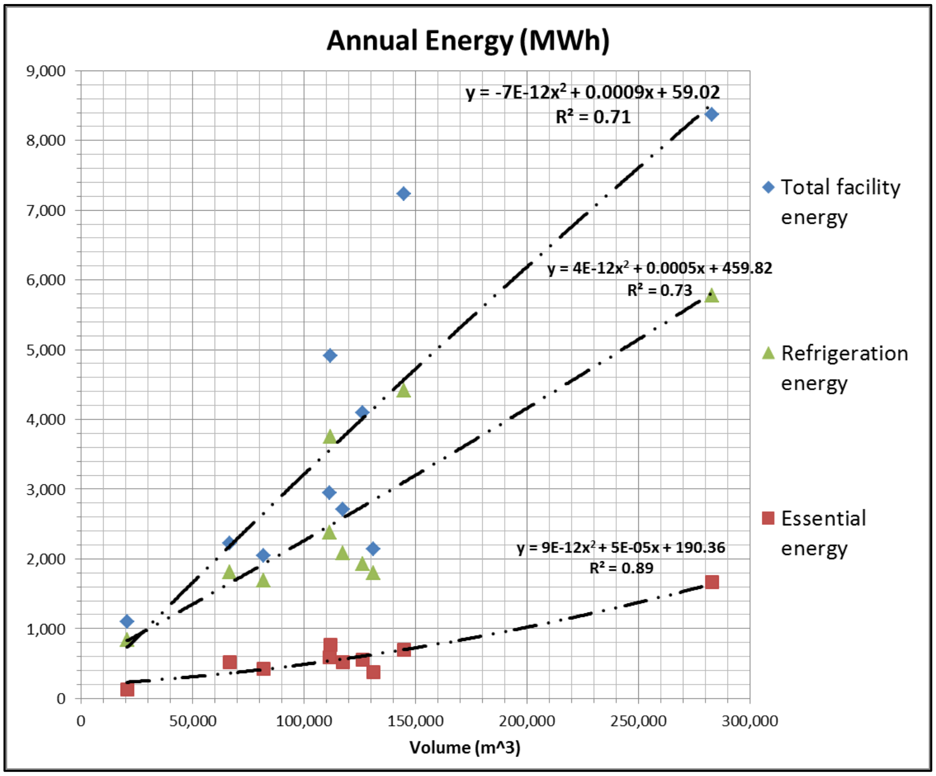

Figure 16: Graphical correlation between annual energies and storage space volume

Although storage volume (i.e. envelope load) makes up the bulk of the total load as described in Chapter 3.2, especially in distribution type facilities, the other essential loads are also factors that need to be considered when looking at relationships of energy and load. Figure 17 shows the correlation of the relevant annual energy components with total essential refrigeration load which includes product, envelope, lighting, and evaporator fan motor.

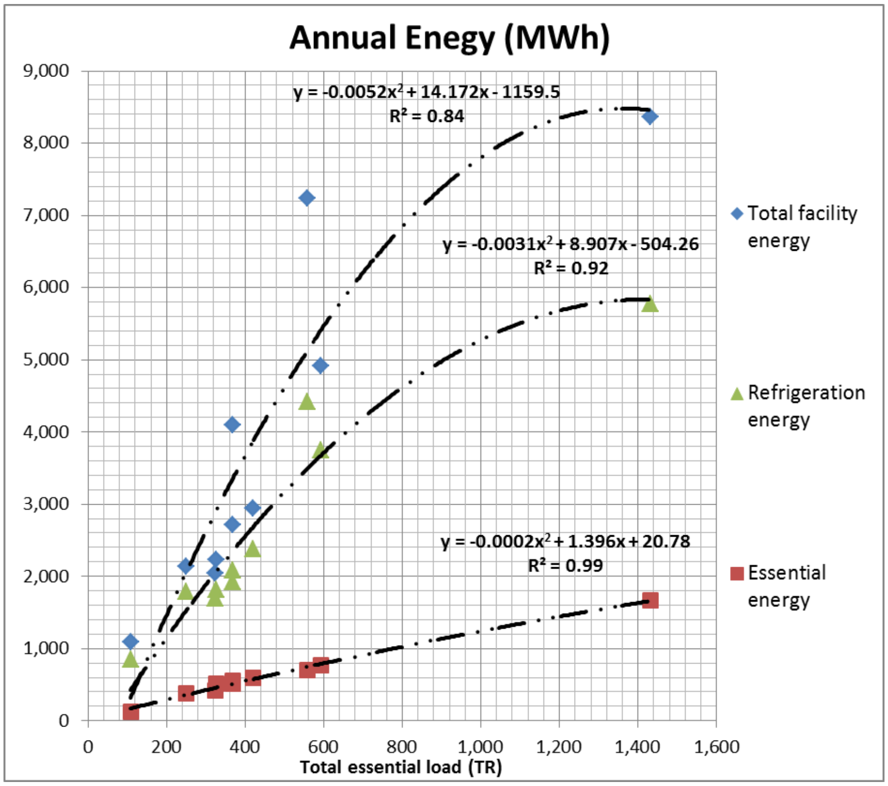

Figure 17: Graphical correlation between annual energies and total essential refrigeration load

The correlation analysis shown in Figure 17 further confirms that total refrigeration load has a direct impact on energy consumption. It is also worth noting that refrigeration energy has a higher correlation with variability in load, than the total facility energy. The essential energy on the other hand has a near 100% correlation with the essential refrigeration load.

Using the regression model in Evans' analysis of 329 refrigeration facilities [32], also shown in Figure 6, the annual consumption of each of the 10 facilities is predicted based on storage volume. This normalizes the annual energy consumptions of the 10 facilities based on the conditions of the facilities used to develop Evans' regression model. The normalized SEC values for each of the 10 facilities are also calculated. The results are shown in Table 7.

Table 7: Normalized SEC values for 10 IRFs based on Evans' regression model

IRF site #	Predicted annual consumption (kWh)	Normalized SEC (kWh/m^3)	Actual SEC (kWh/m^3)
1	5,719,757	43.5	16.26
2	10,713,620	37.8	29.54
3	1,272,239	60.9	52.42
4	5,545,167	43.8	32.33
5	6,191,626	42.8	49.95
6	5,011,621	44.8	26.33
7	3,893,859	47.4	24.91
8	3,292,950	49.2	33.32
9	5,020,628	44.8	43.85
10	5,224,449	44.4	23.07

The graphical comparison between the normalized and actual SEC values, shown in Figure 18, suggests that the normalized SEC values for some sites in some cases actually improved relative to other sites. This suggests that a regression model using annual consumption and storage volume cannot accurately predict annual site consumption and therefore cannot be used for normalization.

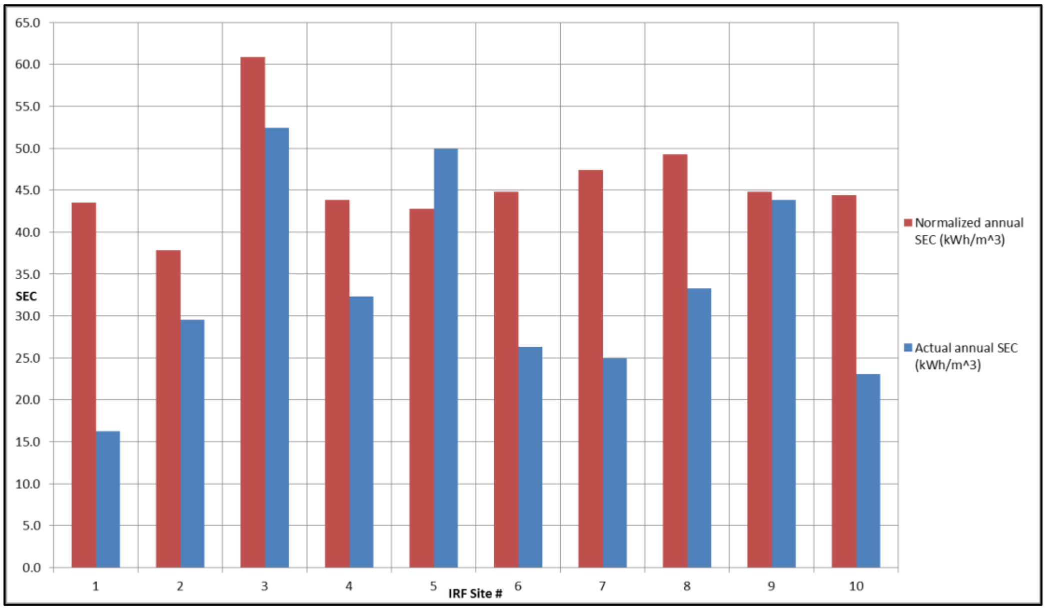

Figure 18: Comparison of normalized and actual SEC values

6.1.1 Summary of energy and load correlation analysis

The data suggests that some of the IRF energy components have a stronger relationship with refrigeration load allowing for more accurate predictions based on variability in the load. The data leads to the conclusion that in order to study an IRF's performance, we need to look at other energy components besides the total facility energy. The actual energy used by the refrigeration system only (i.e. refrigeration energy) or the minimum energy required to satisfy the facility's essential needs (i.e. essential energy), in terms of performance measurement can yield more accurate and reliable results.

6.2 BEF vs. SEC

In this section, the SEC and BEF values are presented and analyzed to see how each metric represents the energy performance for each IRF. The SEC value is calculated using Equation (2) and the BEF value is calculated using Equation (3) with the refrigeration energy representing the numerator E_{used}. Table 8 shows the calculated SEC and BEF values for each site.

Table 8: Summary of SEC and BEF values

IRF site #	**Annual specific energy consumption (SEC) – kWh/m^3**	**Annual average benchmark energy factor (BEF) - Unitless**
1	16.3	4.78
2	29.5	3.47
3	52.4	6.50
4	32.3	3.50
5	49.9	6.33
6	26.3	4.05
7	24.9	3.98
8	33.3	3.51
9	43.8	4.90
10	23.1	3.80

To better understand the performance representation for each site, Table 9 provides a brief summary of the specific energy efficiency characteristics found during site investigations for each IRF.

Table 9: Summary of energy efficiency characteristics

IRF site #	**Characteristic**
1	Oversized system capacity and storage volume design with outdated controls.
2	Implemented and operational ECMs with updated control system.
3	Storage space is subject to high infiltration load due to space layout design.
4	Implemented ECMs and control system allowing for improved part-load[13] performance.
5	Old system with no known ECMs applied and outdated control system.
6	Implemented ECMs however are not fully operational due to outdated control system.
7	Implemented ECMs however are not fully operational due to outdated control system.
8	Implemented ECMs and control system allowing for improved part-load performance.
9	Old system with only lighting ECM applied however outdated control system.
10	Implemented ECMs however are not fully operational due to outdated control system.

Based on the information gathered for each facility, the IRFs are grouped into three categories representing top, average and poor performers, as follows:

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[13] Part-load performance represents the performance during partially loaded conditions where the system is not operating a full load.

I. Top performers: IRF site # 2, 4 and 8

Based on the site investigations, it is determined that IRF site # 2 is a top performing facility. Site # 2 has implemented a wide range of ECMs for the major refrigeration system components including compressor, condenser, evaporator and lighting. The control system has also been upgraded which optimizes the operation of the implemented ECMs. Sites # 4 and 8 have also both implemented a number of ECMs including control system upgrades to improve part-load performance. We expect the SEC and BEF values to indicate that sites # 2, 4 and 8 have the highest performance ratings (i.e. lowest SEC and BEF value relative to all other sites).

II. Average performers: IRF site # 6, 7 and 10

The average performing sites were selected due to the fact they have implemented ECMs however the systems have outdated controls. In these facilities, the operators have to manually adjust set points based on load demand changes. We expect the SEC and BEF values to indicate that sites 6, 7 and 10 are average performers relative to all other sites (i.e. higher values than the top performing sites but lower values than the poor performing sites).

III. Poor performers: IRF site # 1, 3, 5 and 9

Site # 1 is an oversized facility which was originally designed and built to operate as a freezer, however, it is operating as a cooler with lower than expected production levels. The refrigeration system has poor part-load performance and an outdated control system with unused refrigerated space.

Site # 3 has an unusual space layout which introduces higher than normal heat loads into the refrigerated space. The refrigerated zone is open to the loading dock where product is loaded via exterior opening roll up doors. Typically, infiltration loads in refrigerated spaces are low enough to be negligible, since the refrigerated space is fully enclosed with a small number of entrance doors that lead into a refrigerated loading dock. The entrances are also typically equipped with air curtains or fast rollup doors to prevent high infiltration loads from non-refrigerated spaces. During the site visit, it was observed that product was being loaded from the exterior door directly to the refrigerated space (i.e. no separate loading dock). This causes an unusually high infiltration load which is considered non-essential (i.e. not essential to the IRF requirements) and thus is a potential efficiency improvement opportunity.

Based on the information gathered for site # 5, the facility underwent an energy efficiency feasibility study where several ECMs were identified with potential savings of over 2.5 GWh/y, if they were all implemented as proposed. However, due to business related matters, the facility did not proceed with any of the proposed ECMs. The refrigeration system is outdated, has poor part-load performance, and limited control capabilities.

Site # 9 is an old facility, however has implemented one ECM: installation of VFDs on evaporator fan motors. The site experienced operational issues with the evaporator fan motors as the motors began failing due to unwanted harmonics on branch circuits feeding the motors. As a result, the VFDs were bypassed and the motors went back to running across the line with no mode for part-load control. The facility has an outdated control system and potentially high infiltration loads due to having manual doors, instead of automatic, between refrigerated spaces. It was also observed that doors were left open during operating shifts.

We expect the SEC and BEF values to indicate that sites # 3, 5 and 9 have the poorest performance (i.e. highest values relative to all other sites).

Table 10 summarises the performance distribution of all 10 sites based on the BEF and SEC values calculated.

Table 10: Summary of SEC and BEF performance representation

Performance Level	**IRF site # based on SEC values**	**IRF site # based on BEF values**
Top performers	1, 6, 7, 10	2, 4, 8
Average performers	2, 4, 8	6, 7, 10
Poor performers	3,5, 9	1, 3, 5, 9

As can be seen, the SEC and BEF values have conflicting representations of performance for the selected IRFs. For example, the SEC indicates that site # 1 is a top performing site while the BEF indicates it is the poorest performing. The onsite investigation revealed that site # 1 has a large amount of unused refrigerated space. This overdesigned space artificially lowers the SEC indicator to a lower value based on Equation (2).

The SEC indicates that sites # 6, 7 and 10 have better performance than sites # 2, 4 and 8 however the BEF indicates the opposite. Facility projects history including energy studies indicate that the sites # 2, 4 and 8 have implemented a wide range of ECMs and are considered as top performers.

The SEC and BEF values for sites # 3, 5 and 9 both indicate that these are the poor performers. This is expected based on the information gathered for each site.

A graphical representation of relative performance based on SEC and BEF values is shown in Figure 19. Alternative SEC values were also calculated using refrigeration energy and essential energy as the numerator in Equation (2) and are also plotted to show relative relationships.

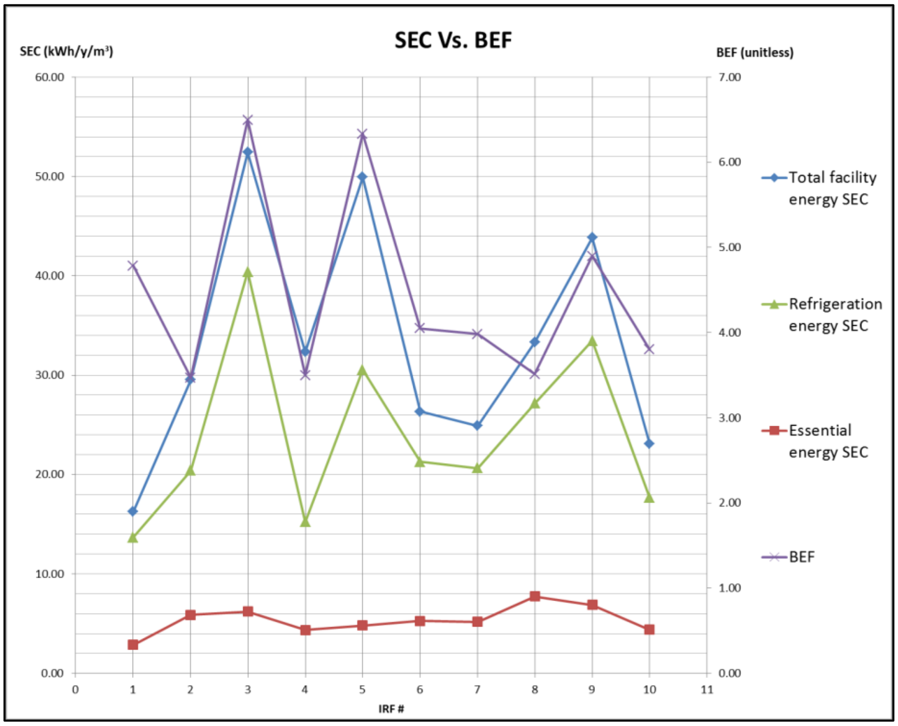


Figure 19: Comparison of alternative SEC values and BEF values

There is a clear pattern with all calculated SEC and BEF values. That is, the performance of each IRF relative to another, as depicted by their corresponding SEC and BEF values, is consistent with the exception to a few outliers which have been identified and explained earlier in this chapter.

It is interesting to note the difference in SEC using total facility consumption and the SEC using refrigeration energy only. For example, the refrigeration SEC value indicates that site # 4 is one of the top performers, which is also consistent with the BEF performance indicator. This observation suggests that the SEC value representing performance can be improved by using refrigeration energy in Equation (2) instead of total facility energy.

Using essential energy in Equation (2) yields the “Essential SEC” value. Since essential energy is the minimum energy required by a facility, the essential SEC represents the minimum SEC value the facility can achieve. This value can be used to estimate the conservation potential of a facility as later described in Chapter 6.3.

Figure 20 shows the variation in magnitudes for alternative SEC values. For facilities with a relatively large incremental difference between total facility energy SEC and refrigeration energy SEC, suggests that the facility has relatively high non-refrigeration energy. For example, this is evident in IRF site # 4 and 5. These sites may have opportunities to explore further on non-refrigeration energy components such as administrative offices or forklifts battery charging. The relatively large incremental difference between refrigeration energy SEC and essential energy SEC suggests that there may be significant opportunities for energy savings on the refrigeration system. However based on the fact that IRF # 2 is one of the top performers, as described earlier in this chapter and also implied by its BEF value, the actual potential for energy savings for some facilities may not be entirely reflected in their corresponding SEC values.

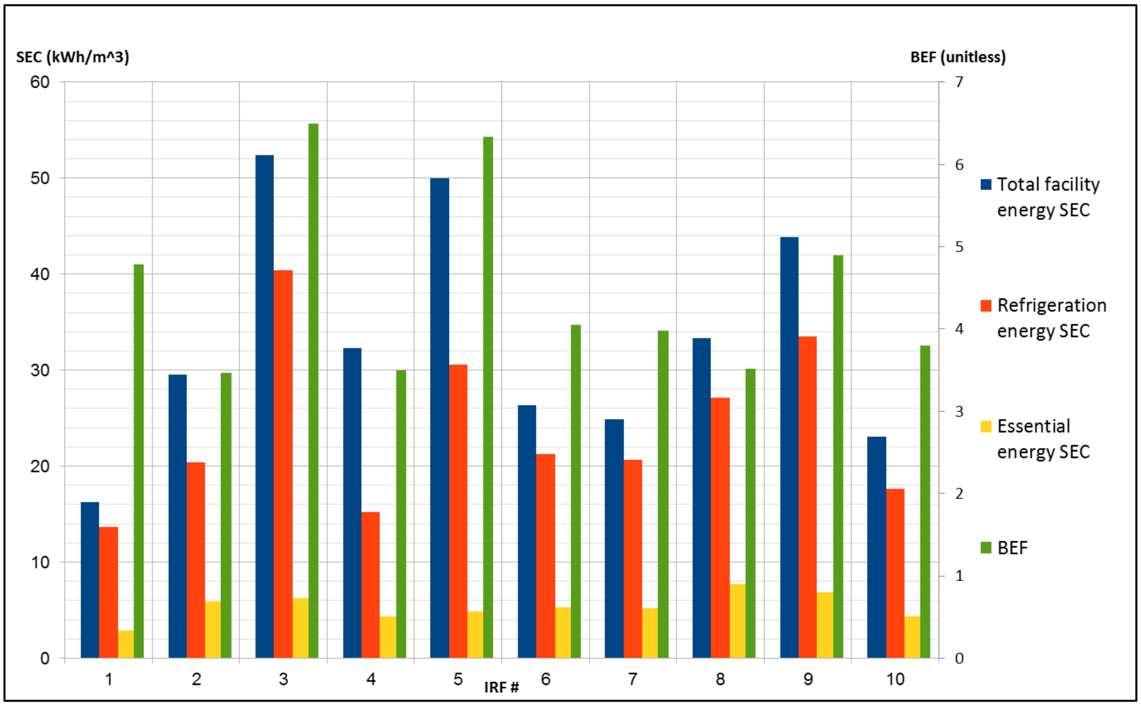


Figure 20: Variation in alternative SEC magnitudes and BEF

6.2.1 Summary of BEF and SEC analyses

The energy components within an IRF were analyzed with variability in refrigeration load and refrigerated space volume. It was found that there is a higher correlation between refrigeration load and refrigeration and essential energies versus the total facility energy. This is due to the fact that the total facility energy includes up to 50% non-refrigeration energy which is not related to the refrigeration process and is not impacted by refrigeration loads. As performance indicators, the SEC and BEF values for each IRF were analyzed. It was demonstrated that the SEC and BEF values represent conflicting performance ratings.

6.3 Estimating Conservation Potential

Benchmarking a facility provides an insight on the potential energy savings that can be achieved. In other words, the wasted energy consumed by the refrigeration system that can be controlled by applying energy conservation measures.

An applicable range of BEF values for a type of facility can represent a powerful tool to determine the maximum and minimum BEF values that can be achieved for a particular type of facility. This can provide insight into the conservation potential for each facility. With respect to the 10 IRFs tested, the following Figure 21 represents the range of BEF values for distribution type facilities:

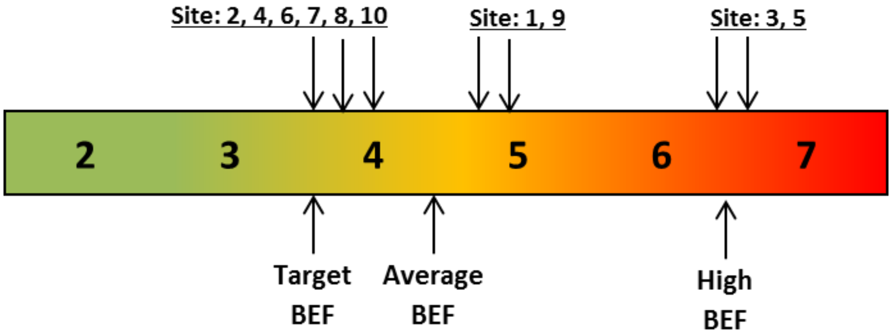


Figure 21: BEF range for 10 distribution type industrial refrigeration facilities

Based on the range of BEF values and the known performances of each of the 10 facilities, a minimum BEF value of 3.47 is set as the target BEF, being the performance of IRF site # 2. Actual performance of each facility is described earlier in Chapter 6.2. Using this target BEF value, the essential energy benchmarking methodology can be used to estimate the conservation potential of each site using the following equation:

$$CP_{BEF} = \left(BEF_{actual} - BEF_{target}\right) \times E_{ess} \tag{19}$$

where;

CP_{BEF}:	Annual conservation potential based on BEF	MWh
BEF_{actual}:	Actual BEF	Unitless
BEF_{target}:	Target BEF value set at 3.47	Unitless
E_{ess}:	Annual essential energy	MWh

Although the wasted energy of each IRF as shown in Table 6 is technically considered the conservation potential, using a target BEF value and Equation (19) provides a more realistic estimate based on a BEF value that has already proven to be achievable.

The conventional SEC metric can also be used to determine conservation potential however needs to be adjusted to account for the actual wasted energy of the facility. The alternative SEC values shown in Figure 19 can be used to determine the “wasted energy” SEC value and is calculated according to Equation (20).

$$SEC_{waste} = SEC_{refrig} - SEC_{ess} \tag{20}$$

where;

SEC_{waste}:	Annual wasted energy SEC	kWh/m^3
SEC_{refrig}:	Annual refrigeration energy SEC	kWh/m^3
SEC_{ess}:	Annual essential energy SEC	kWh/m^3

To determine the conservation potential, similar to using BEF, a target SEC value is selected from the range of SEC values of the 10 facilities. The wasted energy SEC value for site # 2 will be used as the target value since it is known to be a top performer as described in Chapter 6.2. From Table 11, the target annual SEC value is 14.52 kWh/m^3.

Table 11: Alternative SEC values for 10 IRFs

IRF Site #	Annual refrigeration energy SEC – kWh/m^3	Annual essential energy SEC – kWh/m^3	Annual waste energy SEC – kWh/m^3
1	13.65	2.85	10.80
2	20.40	5.88	14.52
3	40.42	6.22	34.20
4	15.23	4.35	10.88
5	30.53	4.82	25.71
6	21.29	5.26	16.03
7	20.65	5.18	15.46
8	27.15	7.72	19.42
9	33.46	6.88	26.59
10	17.66	4.38	13.28

Estimating conservation potential using the SEC values can be calculated using the following equation:

$$CP_{SEC} = \left(SEC_{waste} - SEC_{target}\right) \times V \tag{21}$$

where;

CP_{SEC}:	Annual conservation potential based on SEC	kWh
SEC_{waste}:	Annual wasted energy SEC	kWh/m^3
SEC_{target}:	Annual target SEC value set at 14.52	kWh/m^3
V:	Cold storage volume	m^3

A summary of the calculated conservation potentials using SEC and BEF for each of the 10 IRFs is shown in Table 12.

Table 12: Summary of calculated conservation potentials for 10 IRFs using BEF and SEC

IRF Site #	Annual CP_{BEF} (MWh)	Annual CP_{SEC} (MWh)
1	493	Negative
2	0	0
3	393	411
4	15	Negative
5	1,998	1,620
6	340	169
7	218	77
8	23	327
9	1,101	1,352
10	170	Negative
Total Annual CP (MWh)	**4,751**	**3,956**

As can be seen in Table 12, the conservation potential using SEC results in negative values for a few of the sites. This is because the SEC value for site # 2 was not the lowest value as we would expect it to be, for the reasons described in Chapter 6.2.

However, in an overall comparison of total conservation potential estimated using BEF and SEC, the BEF estimated conservation potential is approximately 17% higher than the SEC method for all 10 facilities.

6.3.1 Summary of conservation potential analysis

One of the primary purposes of a performance metric is to provide insight on the conservation potential of a facility. Using the BEF and SEC values of the 10 IRFs, the conservation potential was calculated based on Equations (19), (20) and (21). Using alternative SEC values, such as refrigeration energy SEC and essential energy SEC, a more accurate conservation potential can be calculated.

The ICE-E model and Evans' work as mentioned in Chapter 3.3, involves a comprehensive assessment of a facility in order to determine actual energy conservation measures and potential energy savings that can be achieved, from implementing those measures. This approach is commonly used in energy efficiency feasibility studies which can be costly and time consuming. From the research conducted on the IRFs presented in this dissertation, history of energy efficiency initiatives for each facility revealed that in some cases, time and effort is spent on an energy study resulting in little to no opportunities for energy savings. This can be avoided by first benchmarking the facility using a performance metric that clearly shows the potential for energy savings.

With an essential energy model developed for a particular type of ISP, the BEF metric can be easily calculated. The BEF range and target BEF values for a type of facility can then be used to truly gauge the potential for energy savings that can be achieved. Once a facility is benchmarked, one can then decide if a comprehensive energy study is worth doing in order to identify actual energy conservation measures.

6.4 BEF vs. M&V

This chapter will analyze a select number of IRFs which have implemented ECMs, and that have gone through M&V activities for verification of actual energy savings achieved. The DSM activities are sponsored by the local utility via DSM programs. The programs rely on energy efficiency feasibility studies, third party engineering reviews and M&V activities to recommend ECMs and verify the actual energy savings achieved. The M&V period is typically between 6 to 12 months pre- and post-ECM.

Table 13: Summary of implemented ECMs for selected IRFs

IRF site #	Implemented ECMs
2	• VFD on evaporator fan motors
4	• Fast roll up doors • Controls upgrade • LED Lighting • VFD on evaporator fan motors
6	• LED Lighting • VFD on evaporator fan motors
8	• LED Lighting • VFD on evaporator fan motors
10	• LED Lighting • VFD on evaporator fan motors

Using the EEB methodology, the essential and the refrigeration energy are calculated for each of the selected IRFs before and after implementation of ECMs. The following graphs are the output of the essential energy model showing annual energy profiles during the M&V period.

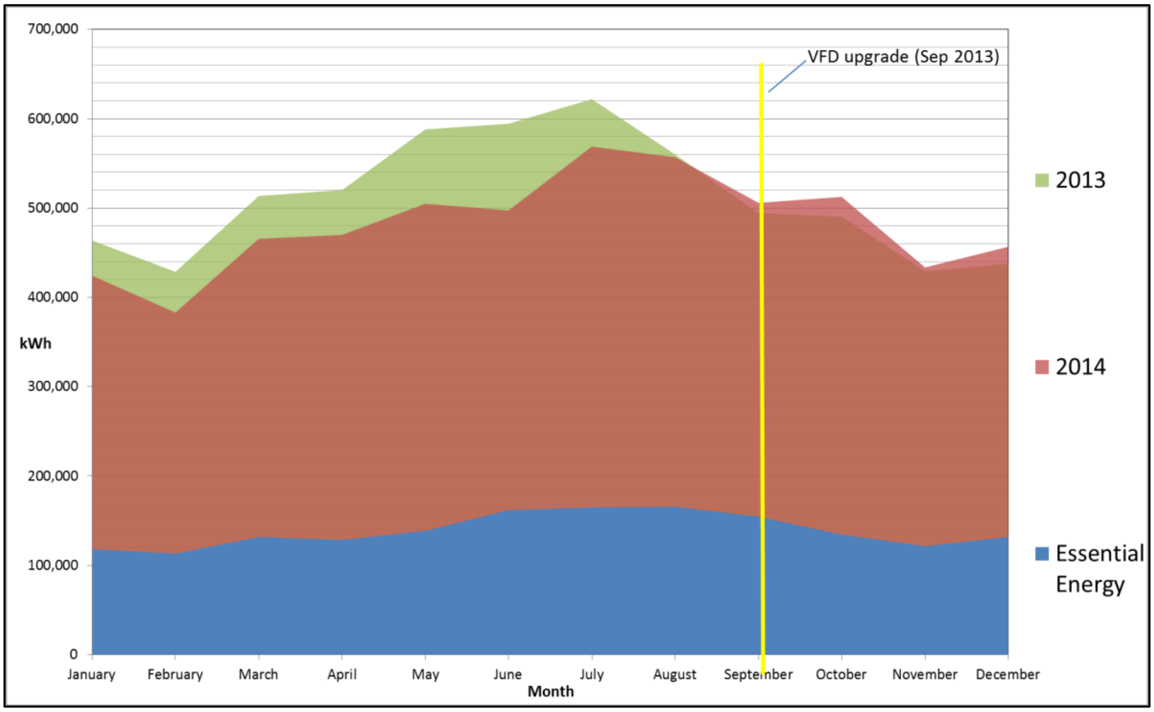


Figure 22: IRF site # 2 annual energy profile

The VFD upgrade ECM was implemented around September 2013. The reduction in wasted energy can be seen in the following year 2014 between January and August, in Figure 22. It is worth noting that the essential energy remains relatively constant throughout both periods with minimal variation. This is also true for the other selected IRFs. For distribution type facilities, production patterns are relatively constant throughout the year so the variation in essential energy is mainly due to the change in ambient temperatures, which is evident during the summer months.

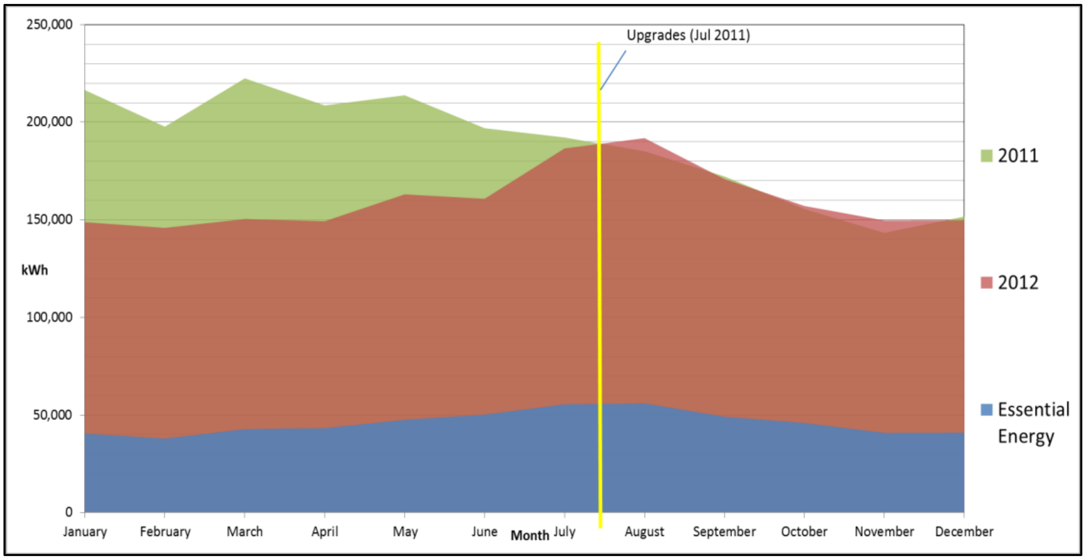


Figure 23: IRF site # 4 annual energy profile

Figure 23 shows the annual energy profiles for site # 4. The ECM upgrades were installed around July 2011 and the energy savings can be seen in the reduction in wasted energy in 2012 compared to 2011.

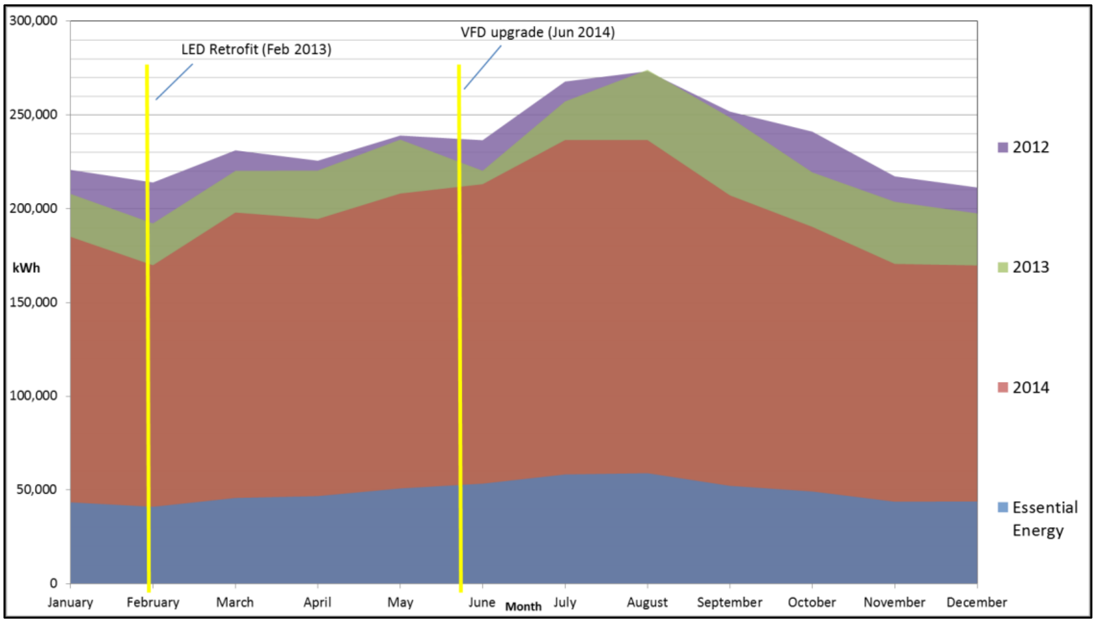


Figure 24: IRF site # 6 annual energy profile

Site # 6 implemented ECMs in different years as shown in Figure 24. The reduction in wasted energy, which is the difference between the refrigeration energy and the essential energy during the same period, can be clearly seen from 2012 to the final reporting year of 2014.

The following Figure 25 and Figure 26 show the energy profiles for site # 8 and site # 10, respectively. ECMs for both sites were implemented at different times however within the same year. Energy savings are shown as a reduction in wasted energy from 2013 to 2014.

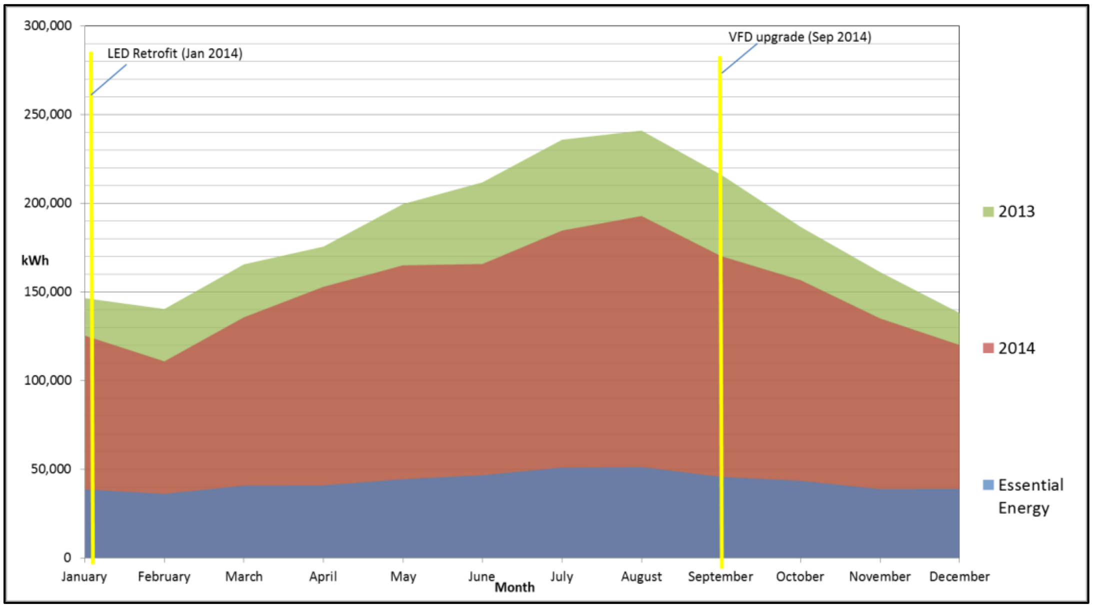


Figure 25: IRF site # 8 annual energy profile

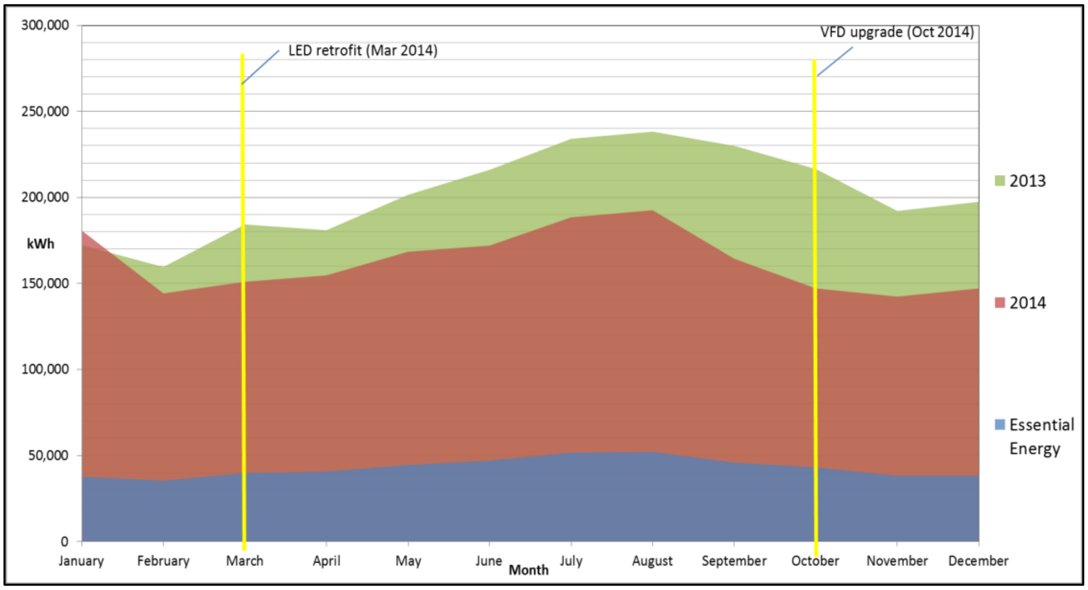


Figure 26: IRF site # 10 annual energy profile

The essential energy model output graphically represents the variability in essential and waste energy throughout an operating year. As stated in Chapter 4.1 and graphically represented in Figure 7, energy savings can only be achieved by a reduction in wasted energy.

To estimate the energy savings (E_s) based on the EEB methodology, the following Equation (22) is used.

$$E_s = [E_w]_{pre} - [E_w]_{post} \tag{22a}$$

$$E_s = [E_R - E_{ess}]_{pre} - [E_R - E_{ess}]_{post} \tag{22b}$$

where;

E_s:	Energy savings	MWh
E_R:	Refrigeration energy	MWh
E_w:	Wasted energy	MWh
E_{ess}:	Essential energy	MWh

The energy savings is represented by the reduction in wasted energy (E_w) between pre- and post-ECM conditions. Subtracting the essential energy from the refrigeration energy (E_R) automatically normalizes the wasted energy value for the same period. Table 14 provides a summary of the final recorded M&V energy savings and the calculated energy savings using the EEB methodology.

Table 14: Summary of energy savings for selected IRFs

IRF Site #	Annual M&V recorded savings (MWh)	Annual EEB calculated savings (MWh)	Difference (%)
2	667	667	-0.02
4	827	676	-18
6	676	556	-18
8	482	360	-25
10	648	675	+4

The percent difference values represents the percent change in EEB calculated savings relative to the M&V recorded savings. The data shows a wide range of difference in savings estimates. Based on the information gathered from the site investigations and the history of DSM activities including details on M&V methods used, the reasons for the difference in savings estimates are as follows:

- Site # 2 is by far the closest match with actual M&V data analysis. The energy savings were measured using IPMVP Option B which involves continuous measurements of baseline and post-retrofit energy use [4]. For this particular site, total refrigeration energy consumption (including compressors, evaporators, condensers and lighting) was logged from 2013 through to 2015.

- Site # 4 underwent M&V Option C which does not involve metering, instead utility billing data for the whole building is analyzed to determine total energy savings of all applied ECMs [4]. This particular site has a large office space and also a large amount of dry storage areas which are not served by the refrigeration system. In fact, the non-refrigeration energy for this site was estimated at 53% of the total facility consumption. Essentially the M&V analysis attempted to estimate energy savings of an ECM related to the refrigeration system by analysing the total facility consumption, which over half is made up of non-refrigeration energy. Any variation in non-refrigeration energy during the M&V period is reflected in the energy savings estimate value.

- Energy savings for sites # 6 and # 8 were also verified based on utility billing analysis. These facilities have a unique system whereby they allow refrigerated delivery trucks to plug into the buildings main power supply to charge their batteries overnight. This consumption is obviously not related to the facility's refrigeration process; however, it is considered as highly variable and production dependant as refrigeration energy. This unpredictable variability is believed to impact the M&V analysis resulting in inaccurate savings estimates.

- Finally, site # 10 savings were also verified using utility billing analysis; however, this site does not share the same non-refrigeration energy variability characteristics as the other facilities. In this case, the EEB estimated savings is closely matched with the M&V verified savings with a less than 5% difference.

6.4.1 Summary of BEF and M&V analysis

The BEF vs. M&V analysis demonstrated how the EEB methodology can be used to estimate energy savings of implemented energy conservation measures. Verified energy savings of select IRFs using M&V options were compared against calculated savings using EEB. The difference in savings observed triggered a deeper investigation into the actual operating characteristics of the IRFs relating to both refrigeration and non-refrigeration energy components. The investigation revealed valuable insights into how energy is consumed within each IRF and how DSM activities impact a facility's total consumption.

The findings suggest that even using strict IPMVP guidelines for M&V, estimating energy savings can be challenging due to the uncertain and highly variable operating conditions of a facility as in its entirety.

6.5 Further Analysis on IRF Site # 2

Further analysis was conducted on IRF site # 2 and is summarised in this chapter. As explained in Chapter 6.2 and 6.4, IRF site # 2 is considered as a top performer with implemented energy conservation measures and verified energy savings via a comprehensive measurement and verification analysis, based on IPMVP Option B. The analysis presented in this chapter reveals the variability in energy and refrigeration load components over a full year.

Figure 27 shows the variability in essential energy components over a full year as calculated by the essential energy model. As can be seen, the most prominent variation is exhibited by the compressor essential energy being the highest energy consumer. As the total essential heat load varies over the year, peaking during the summer months due to high ambient temperatures increasing the envelope load, the essential energy required by the compressor also increases proportionally.

We can see this similar pattern in the evaporator and condenser essential energy since, according to Equations (15) and (16), the condenser and evaporator essential energy are calculated based on total essential load.

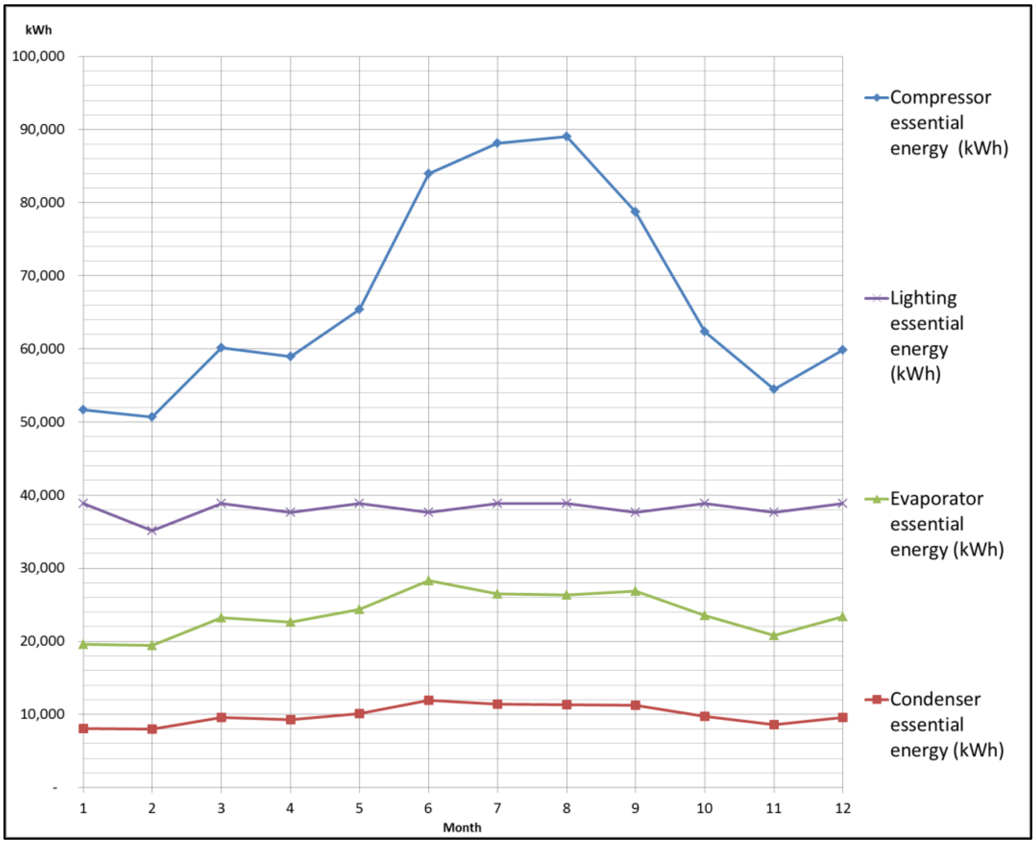


Figure 27: Variability in essential energy components for IRF site # 2

Figure 28 shows the variability in essential refrigeration load components over a full year for IRF site # 2, during the same reporting period as in Figure 27. As can be seen, the most prominent variation is in the essential envelope load. The variation in envelope load is directly proportional to the variation in ambient temperature, which is expected according to Equation (4).

However, the highest essential load with a more sporadic and unpredictable variability is due to the product load. As production patterns vary throughout the year (i.e. product quantity and product entering temperatures) the product essential load varies accordingly.

The evaporator fan motor load varies according to Equation (11) and is based on the variability in total load. The fan motor load variation is not as clearly visible at this scale due to the evaporator's EPM factor being a small value. However it can be seen that the fan motor load peaks at month 6 which corresponds to the peak in product load.

The lighting load on the other hand has the least variability since it is not impacted by any other variation except for the facility's operating hours, as expected according to Equation (6). For this facility, the daily operating hours are constant throughout the year therefore the only variation in lighting heat load per month is due to the actual number of days in each month.

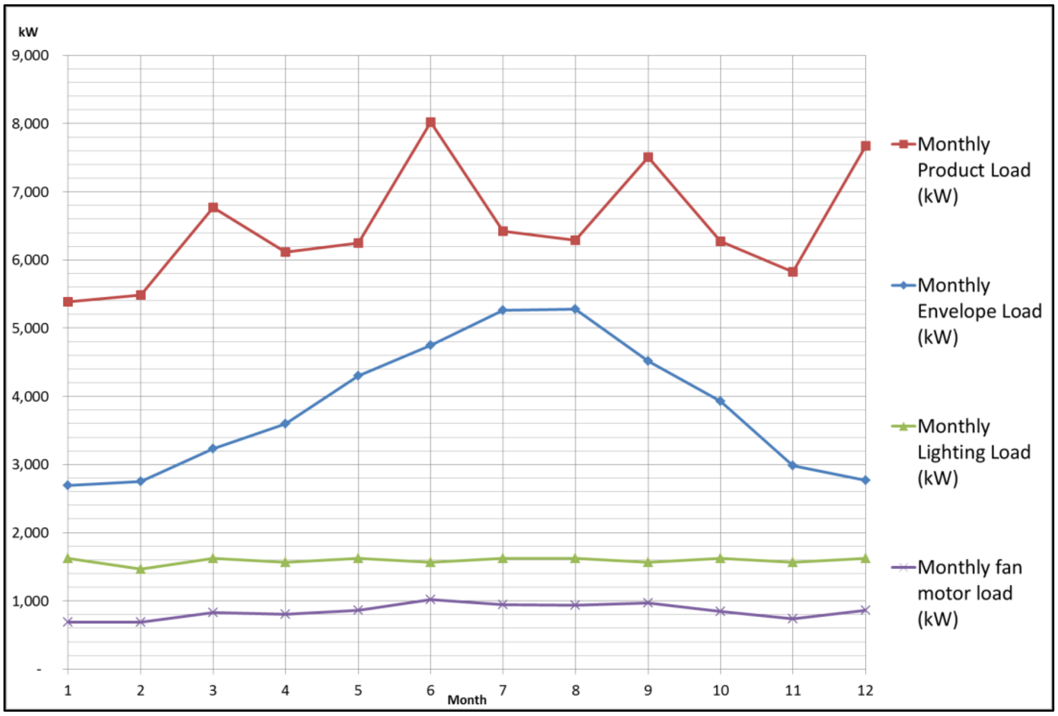


Figure 28: Variability in essential refrigeration load (in kW) for IRF site # 2

6.6 Essential Energy Model Sensitivity Test

In Chapter 6.4, actual measurement and verification data gathered for the purpose of verifying energy savings for DSM programs was used to help validate the essential energy model in estimating energy savings. For further verification of the model, a sensitivity test was run to analyze variability in essential energy with changes in input parameters.

Select parameters including zone temperature, product entering temperature, product rate of loading and zone occupancy hours were changed by +/-25% and +/-50% while monitoring changes in total essential energy calculated by the model. For each parameter, the base case value was multiplied by 1.25 and 1.50 for +25% and +50% change, respectively. For the negative change, the base case value was multiplied by 0.75 and 0.50 for -25% and -50% change, respectively. For each change in value, all other parameters were kept at the base case value. The percent difference (% Diff.) is the difference in the total essential energy with respect to the base case. Summary of the results are shown in Table 15.

As can be seen, all negative percent changes resulted in negative percent difference in essential energy proportional to the positive percent changes, as expected. With exception to the 50% negative change in product entering temperature where the essential energy resulted in a -64.6% difference compared to the 9.6% difference in the positive change. This is due to the fact that as the product temperature approaches its freezing point, according to Equations (7), (8), (9) and (10), the product latent and above freezing heat loads are zero and therefore the essential energy is significantly reduced.

Table 15: Model sensitivity test results

+ % Change								
	Base Case		**+25% Change**			**+50% Change**		
Parameters	Parameter Value	Essential Energy (kWh)	Parameter Value	Essential Energy (kWh)	% Diff.	Parameter Value	Essential Energy (kWh)	% Diff.
Zone Temperature (F)	-5	151,705	-6.25	155,806	2.7%	-7.5	159,988	5.5%
Product Entering Temperature (F)	45	151,705	56.25	158,971	4.8%	67.5	166,236	9.6%
Product Rate of Loading (lbs/day)	100,000	151,705	125,000	178,471	17.6%	150,000	205,236	35.3%
Zone Occupancy (hrs/yr)	1,036	151,705	1,295	152,342	0.4%	1,554	152,977	0.8%

- % Change								
	Base Case		**-25% Change**			**-50% Change**		
Parameters	Parameter Value	Essential Energy (kWh)	Parameter Value	Essential Energy (kWh)	% Diff.	Parameter Value	Essential Energy (kWh)	% Diff.
Zone Temperature (F)	-5	151,705	-3.75	147,687	-2.7%	-2.5	143,753	-5.5%
Product Entering Temperature (F)	45	151,705	33.75	144,440	-4.8%	22.5	53,710	-64.6%
Product Rate of Loading (lbs/day)	100,000	151,705	75,000	124,940	-17.6%	50,000	98,174	-35.3%
Zone Occupancy (hrs/yr)	1,036	151,705	777	151,069	-0.4%	518	150,429	-0.8%

Based on the sensitivity test results and the validation of energy savings estimates for the select IRFs with the measurement and verification data as presented in Chapter 6.4, the proposed essential energy model has been verified and validated. Changes in inputs to the model are reflected in the model's output of essential energy and essential refrigeration load as expected.

Chapter 7: Conclusion, Contributions, Further Work

The idea of comparing the performance of an ISP to its ideal conditions, given its unique operating specifications, rather than to another facility, is what distinguishes the BEF concept from traditional benchmarking.

Just as there are no two human beings alike on our planet, there are no two systems or processes that are alike in every possible way. Every ISP operates under its own unique conditions based on its inputs and the task it is intended to accomplish. It can then clearly be seen that comparing the performance of an ISP to its ideal conditions, given its unique independent variable parameters, will avoid the limitations of traditional benchmarking, as follows:

- **The benchmarking process** becomes less tedious and less costly than the traditional benchmarking process since normalization is automatically taken into account in the reference (or essential energy) value.

- **The reference (essential energy)** is solid and reliable and takes into account the variable independent parameters to allow for effective benchmarking. BEF values as benchmarks are reliable and accurate since there is no need to disclose proprietary trade secrets and confidential information.

- **Measurement & Verification process** and the BEF concept can, in some cases, offer a synergetic value through continuous monitoring of the BEF and allow accurate verification of energy savings. Routine adjustments are not required since the normalization process is already embedded in the mathematical model used to calculate the essential energy.

- **Ethical and legal issues** are diminished since any proprietary information, such as production details, are entered directly into the mathematical model used to calculate the essential energy. Sharing of sensitive information is not required with essential energy benchmarking.

BEF is based on the essential energy model and can:

a) Describe what did happen with higher comparability due to normalization of all major independent parameters that impact energy use.
b) Allow better estimates of what would have happened (M&V and baseline adjustments).
c) Predict what should happen with energy conservation measures being implemented (explain variance).
d) Evaluate what could happen with best practice (conservation potential).
e) Enable innovation of best practices technologies.
f) Develop automated feed forward energy control strategies based on the independent parameters and their impact on energy use.
g) Measure of market trends over time and indirect measure of market transformation.
h) Real-time M&V that can be automated and is consistent, concise and compelling.

i) Based on a dynamic baseline that can describe all major conditions at any time (re-baselining or back-casting is not required).

The BEF as an indicator of energy efficiency can:

a) Initiate immediate repair or drive corrective action.
b) Predict energy loss reduction.
c) Optimize (continuous improvement to target potential savings).
d) Manage dashboards.
e) Track performance.
f) Data control and diagnostic check of measurement error.

7.1 Recommendations for Using EEB

As part of essential energy benchmarking, the BEF metric for benchmarking can be used by government and utilities for conservation and energy efficiency programs. Consultants and designers can also use the metric for retrofits and when designing energy efficient systems and processes.

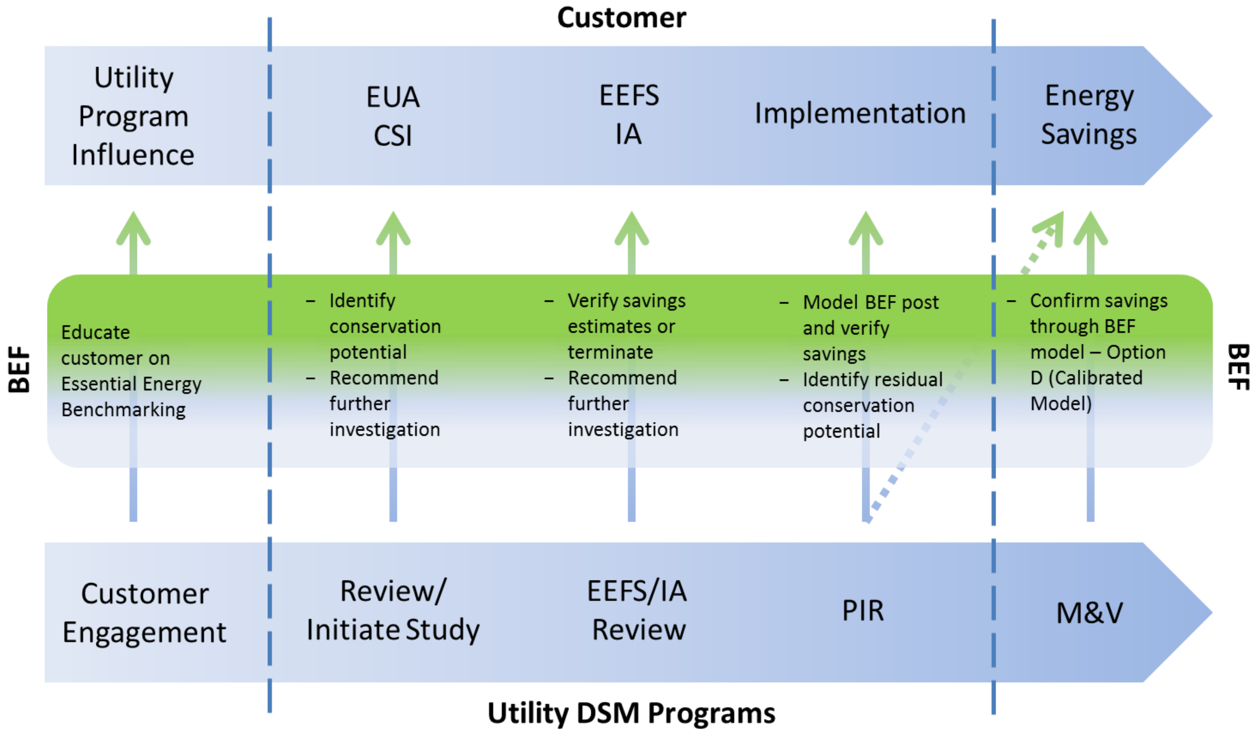
New plant design programs are much more likely to meet energy efficiency goals if quantitative metrics and targets are specified in program documents, and are tracked during the course of the delivery process. If efficiency targets are not properly defined, any additional capital costs associated with attaining higher efficiencies can be difficult to justify.

There are various initiatives that are supported by US and Canadian government actions in setting future goals for new plant design. As an example, the University of California Regents Policy requires all new construction to exceed California Title 24 by at least 20 percent.

It is well documented that wide spectrums of laboratory owners, ranging from universities to federal agencies, have explicit goals for energy efficiency in their facilities. For example, the Energy Policy Act of 2005 requires all new federal buildings to exceed ASHRAE 90.1-2004 by at least 30 percent**.**

Essential energy benchmarking using BEF can significantly reduce the costs associated with verifying energy savings of energy conservation measures when compared to conventional M&V activities. Furthermore, the BEF concept provides a tool to more accurately assess the conservation potential of industrial systems before or after an energy conservation measure is implemented.

Figure 29 shows how the BEF concept can be integrated within the utility-customer relationship adding value across a typical DSM program chain.



Legend;

CSI:	Customer site investigation
EUA:	End-use assessment
EEFS:	Energy efficiency feasibility study
IA:	Incentive application
PIR:	Post implementation review
M&V:	Measurement and verification

Figure 29: Essential energy benchmarking utility value chain

Industrial facilities certified to ISO 50001/6 Energy Management Systems:

Essential energy benchmarking enables organizations to establish a systematic approach on Energy Management Information Systems at the facility level, to achieve continual improvement of energy performance with benefits like:

- Customer engagement opportunity
- Energy savings opportunities
- Controlled persistence of energy conservation measures
- Market transformation and spill over

The proposed concept of essential energy benchmarking has some salient features that are highlighted throughout this dissertation and are summarized as follows:

a) Allows normalized comparison of energy performance (embedded in the mathematical model) by taking into account the energy consumption in relation to the independent parameters, input and output materials, and their variation over time.
b) Enables the identification of the wasted energy, i.e. the energy that does not add value within a given process.
c) Enables the identification of energy savings potential by using a benchmarking approach that accounts for the complexity of a given production process.
d) Enables accurate performance rating of ISPs.
e) It can be used to predict and target energy savings more accurately based on its potential for wasted energy reduction rather than a percentage of total consumption.
f) Enables a more transparent and consistent approach to verifying and tracking energy savings.
g) It can provide plant management and operators an assessment of their current energy performance improvement opportunities.
h) It offers a reliable tool for energy management.
i) It has the potential to assist government and utilities in meeting energy efficiency and DSM program objectives.

Besides the technical features presented above, essential energy benchmarking has business orientated features making it financially attractive to the different segments of audience.

a) Low cost of implementation and maintenance.
b) Easy to use, not requiring special qualification.
c) Reduces Utility program costs at different levels:
    I. Energy study proposals
    II. Estimating simulated baselines for new plant designs
    III. Estimates conservation potential and supplementary energy savings
    IV. Reduces the M&V costs
    V. Enables reliable metrics for benchmarking
    VI. Enables reliable assessment of ECM persistence
d) Enhance customer participation (mutual interest) on DSM programs
e) Enables new types of customer orientated standards that may also change:
    I. The landscape configuration of energy efficiency standards
    II. Configuration and content of internal process of energy efficiency standards
f) Offer a scientifically based leverage tool to DSM partners:
    I. Government and utility programs
    II. Quality management systems at customer level
g) Stimulates technical progress (market evolution):
    I. New conceptual designs of ISP
    II. Enhanced performance of equipment and power converters at the manufacturer level
h) Offers a reliable tool for implementation of ISO 50001 energy management standard.

As discussed in Chapters 3.1 and 6.3.1, The ICE-E model for cold stores benchmarks a facility based on specific energy consumption and can also estimate potential energy savings for specific energy conservation measures. As proposed in this dissertation, essential energy benchmarking can be used to determine the overall conservation potential of a facility without the need of comprehensive data gathering and analysis.

The ICE-E model calculates the total heat load of a facility based on assumptions and compares it to the actual energy used by the facility, which is essentially the coefficient of performance of the facility. The essential energy mode on the other hand calculates the essential heat loads and also the essential energy required to satisfy the heat loads, which is then compared to the actual energy used. The challenge in this approach is determining the essentials of the facility and the essential performance metrics for each load and energy components.

7.2 Further Work

The research and data analysis presented in this dissertation demonstrated how essential energy benchmarking can be applied to industrial refrigeration facilities. The 10 facilities tested were distribution type facilities which have unique characteristics that impact energy use and performance and therefore, their corresponding BEF values fall within a range specific to that type of facility.

When benchmarking the performance of facilities using the BEF value, the facility being benchmarked against must be of the same type in order to ensure an accurate and meaningful comparison. Therefore in order to benchmark other facility types such as storage warehouses or processing facilities with similar types, reference BEF values for each type are required. Ultimately, a range of BEF values can be developed for each type of facility. The range of BEF values will also provide the minimum BEF value that can be achieved for each facility type. This minimum value can be used as a target BEF value that a facility can aim to achieve. The difference between the actual and the target BEF values can be used to estimate the technical conservation potential for a particular facility.

Further development of the essential energy benchmarking concept can also include developing essential energy models for different systems or processes. Currently, the Canadian Standards Association Group is developing standards for benchmarking other systems based on essential energy benchmarking. Besides the benchmarking standard for industrial refrigeration facilities being in its final stages of development, two other standards are currently being developed. These standards are: benchmarking the performance of slurry pumps used in mining sites and benchmarking the performance of data centres. In both cases, an essential energy model is currently being developed to calculate the minimum energy required to accomplish the task of the system or process. Similar to the standard for refrigeration, the minimum energy is calculated based on user entered data that define the non-controllable operating conditions and requirements of the system or process. The BEF values are then calculated based on Equation (3) and, similar to refrigeration facilities, the type of facility will impact the range of BEF values.

Other systems or process that can also benefit from essential energy benchmarking include gas compression systems, mechanical pulping, wastewater treatment, thermal drying processes for wood or coal, and also commercial buildings.

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