Sustainable Approach to Achieving Energy Efficiency in Manufacturing Operations

by

Kurtis McKenney

S.B. Mechanical Engineering, Massachusetts Institute of Technology, 2001

M.E. Mechanical Engineering, Rensselaer Polytechnic Institute, 2003

Submitted to the MIT Sloan School of Management and the Engineering Systems Division in Partial Fulfillment of the Requirements for the Degrees of

Master of Business Administration
and
Master of Science in Engineering Systems

In conjunction with the Leaders for Global Operations Program at the Massachusetts Institute of Technology

June 2012

Signature of Author ____________________
Engineering Systems Division, MIT Sloan School of Management
May 11, 2012

Certified by ____________________
Sarah Slaughter, Thesis Supervisor
Research Affiliate, Engineering Systems Division

Certified by ____________________
Steven Eppinger, Thesis Supervisor
General Motors LGO Professor of Management, MIT Sloan School of Management

Accepted by ____________________
Olivier de Weck, Chair, Engineering Systems Division Education Committee
Associate Professor of Aeronautics and Astronautics and Engineering Systems

Accepted by ____________________
Maura Herson, Director, MBA Program
MIT Sloan School of Management

This page intentionally left blank.

Sustainable Approach to Achieving Energy Efficiency in Manufacturing Operations

by

Kurtis McKenney

Submitted to the MIT Sloan School of Management and the Engineering Systems Division on May 11, 2012 in Partial Fulfillment of the Requirements for the Degrees of Master of Business Administration and Master of Science in Engineering Systems

Abstract

Energy management in industrial facilities is becoming increasingly popular as firms attempt to become more environmentally responsible and reduce cost by improving operational efficiency. Raytheon is a leader in their industry in energy management, and they view the initiative as a way to become more competitive along with being environmentally responsible. The goal of this project was to develop a framework for achieving sustainable cost reduction in production operations through energy efficiency. The energy efficiency framework will build off the existing lean and six sigma tools and philosophies in an attempt to accelerate acceptance and deployment by using a common language and proven methods in the company and industry.

A 1.6 million square foot manufacturing facility at Raytheon IDS consumed $13 million of energy (90% electric) in 2010, 75% of which was consumed directly by production equipment. The equipment is diffuse, highly specialized, and used in "high mix, low volume" manufacturing. The challenge with improving production energy efficiency in this environment is that it requires a combination of technology improvements, processes modifications, and changes in the way employees conduct their work every day. The project's success relied on cross-functional (i.e., operations, engineering, and facilities) engagement from senior management to front-line operators.

To sustain results, energy performance metrics were designed to keep production area leaders engaged and allow management to set progressive goals over time and reward success. The proposed metrics use a combination of tracked energy use and a "best practice" scorecard that promotes proactive engagement. Lean "Energy Gemba Walks" were initiated to generate and manage best practices and to share knowledge among production areas.

The implementation phase of the pilot project (October and November 2011) resulted in an 18% energy reduction compared with the average for the year. Meanwhile, production output and total labor hours were up 18% and 11%, respectively, during the pilot, while the product mix remained constant throughout the year. The improvements, if sustained, correspond to a $74,000 per year cost savings in the pilot area.

Thesis Supervisor: Sarah Slaughter
Title: Research Affiliate, Engineering Systems Division

Thesis Supervisor: Steven Eppinger
Title: General Motors LGO Professor of Management, MIT Sloan School of Management

This page intentionally left blank.

Acknowledgments

I thank all the individuals and organizations who helped me to complete my research at Raytheon. I thank Steve Fugarazzo, the manager of the Integrated Defense Systems (IDS) Enterprise Energy Team (EET) and the Project Supervisor, and Charlie Mullins, the Project Champion. I also thank the operations and facilities leadership teams for supporting the project and all the individual stakeholders who aided in the project's success. In particular, thanks to Dave Chamberlain and Tracy Fialli of the IDS EET, Kevin Sheehan and Jack Maguire of facilities, and Jeff Stoltz and Vicki Capuzzo of Circuit Card Assembly. Finally, I thank Joe Shepard and his entire team in the Electronic Components Operations production area. Raytheon gave me a practical setting to apply many of the management and leadership skills that I developed over the past two years, and I greatly appreciate the resources provided.

From MIT, I thank my academic advisors, Steve Eppinger and Sarah Slaughter, for their advice and guidance through the course of the thesis project. Also, thanks Don Rosenfield and the Leaders for Global Operations (LGO) program for the incredible education and experience over the past two years.

This page intentionally left blank.

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Motivation: environmental imperative, national security, and operational efficiency

The United States consumed approximately 100 quads[1] of energy in 2011 valued at about $13 trillion. (1) U.S. primary energy consumption is generally broken down into four end-use sectors: residential, commercial, industrial, and transportation, as shown in Figure 1. The industrial sector consumed 31% of the total U.S. energy in 2010, the highest among all end-use sectors, and includes high energy consuming industries such as petroleum and coal, chemicals, paper, primary metals, food, and other manufacturing.

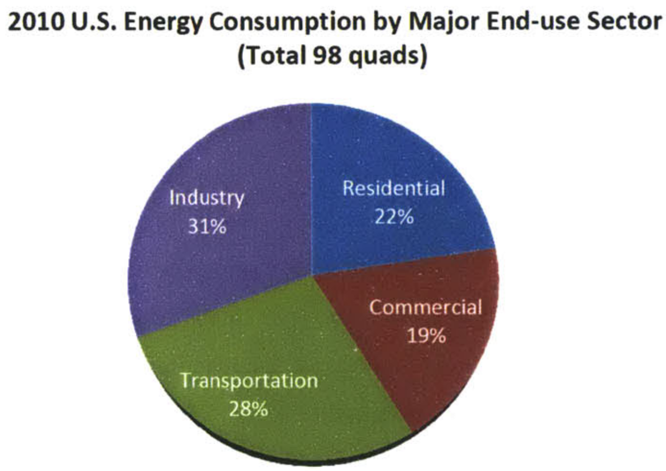


Figure 1: U.S. energy consumption by major end-use sector (2)

Total delivered energy consumption in the industrial sector is projected to grow at the highest rate, 16% between 2010 and 2035 according to the Energy Information Association's Annual Energy Outlook. (3) Part of this expected rise is due to the recovery from the economic downturn over the previous five years, but, nonetheless, there is a large opportunity for energy management in the industrial sector.

The motivation behind energy management can be framed in three main ways: as an environmental imperative, as a national security issue, and/or as a way to improve operational efficiency. Data is mounting on the potential danger of rising greenhouse gas concentration in the Earth's

---

[1] Quadrillion British thermal units

atmosphere. The MIT Joint Program on the Science and Policy of Global Change developed "Greenhouse Gamble" wheels, which are intended to illustrate the probability of different climate change scenarios both with and without significant policy change regarding greenhouse gas emissions. (4) The group projects that without significant policy change, there is a 50% likelihood that the global average surface temperature will increase by 5°C or more in the next 100 years, which will have a significant impact on the global ecosystem and result in a net cost increase to society. (5)

Many government entities, such as the Office of Energy Efficiency and Renewable Energy (EERE), state their mission as not only protecting the environment, but also investing in energy efficiency and alternative energy as a way to strengthen the U.S. economy. Furthermore, the reduction of the U.S. dependence on foreign oil is seen as a way to improve national security. Currently, the U.S. relies on imports for about 60% of its oil demand, and the bulk of the known oil reserves are in the Middle East.

As a part of the community and country, many commercial and industrial firms have taken responsibility for their environmental impact. Since these organizations are held accountable by investors, improving internal operational efficiency or otherwise reducing energy costs through energy efficiency and renewable energy is the most direct motivation for industrial energy management practices. Even though energy may only be 5% of a manufacturer's total cost, energy savings go directly to a firm's bottom line. If the business operates at a 5% net margin, a 10% decrease in energy cost will result in a 10% increase in net profit margin. Said another way, the manufacturer would have needed a 10% increase in revenue to offer a similar increase in profit.

Rising fuel prices and increased energy use over the past several decades have caused all energy end use sectors in the United States to be more conscious of their energy use and costs. Manufacturing companies are finding that there can be an economic benefit to saving energy, either independently or through subsidized government programs. Because of the relatively high cost of electric energy, efficiency projects that reduce electricity consumption are commonly targeted, particularly in industries that consume significant levels of electricity.

Regional and state variation in energy prices can often affect the economics as well. Figure 2 shows the cost of major industrial fuel sources for the U.S as well as the New England region, which has higher electricity prices than the national average.

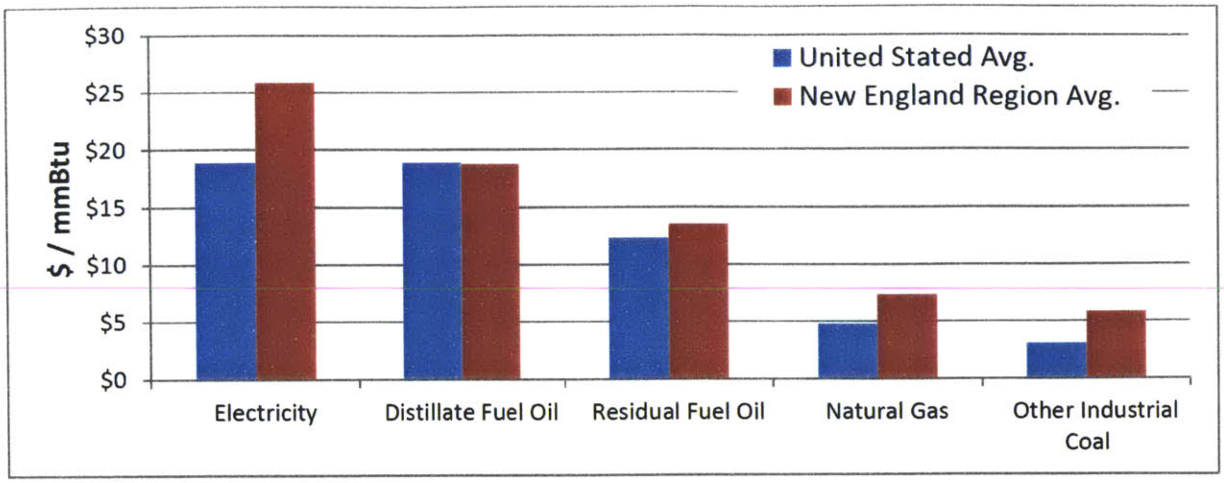


Figure 2: Cost of major industrial fuel sources in 2009 dollars per million btus (primary basis)

Certain states, like Massachusetts, have high electric energy rates even within their relatively high priced regions. On a site, or delivered, energy basis ($/kWh), Massachusetts industrial electricity prices are approximately two times the national average ($0.14/kWh on average in Massachusetts compared with the national average of $0.07/kWh). Facilities operating in high energy cost states and regions have additional motivation to support energy management initiatives.

1.2 Barriers

Despite the presence of NPV positive energy efficiency projects[2] in most industrial settings, there are a number of barriers that prevent achieving energy efficiency improvements in practice. Barriers include those related to employee engagement and awareness, financing energy projects, and having adequate expertise and processes for achieving energy efficiency improvements. More specifically, common barriers include:

- *Low awareness and/or engagement* – Energy typically accounts for less than 5% of the operating costs at industrial facilities, and therefore can easily be overlooked by senior management as an option for improving operational efficiency. (2) Furthermore, energy efficiency opportunities often vary by site, even within the same industry sector, and therefore require technical and economic analysis. In other words, there are few "cookie cutter" solutions, and facilities may not have on-site employees with sufficient training or expertise, engagement, or management support.

- *Elevated hurdle rate* – Industrial sites commonly have tight operational budgets that can drive management to focus on keeping near-term costs low. Over 40% of energy managers indicate that they look for energy projects with a payback of three years or less. (3) McKinsey & Company's commonly referenced report on energy efficiency states that the industry value

[2] Projects offering a positive present value net of the initial investment.

potential for energy efficiency projects is reduced by nearly 50% if a required payback period of 2.5 years is assumed. (2)

- *High perceived transaction cost* – Perceived transaction "costs" here refer to those with uncertain incremental financial cost (i.e., not included in the initial investment cost). These can include the cost of marginal employee time, process disruptions, or potential impact on product quality or safety. Perceptions about product quality risk or employee safety risk are extremely powerful in making decisions that change the current accepted state.

- *Financial accounting for energy* – cost accounting methods can vary widely, but commonly, energy costs are accounted for in site overhead. In a larger manufacturing site with this standard accounting practice, an operations manager who chooses to invest time and resources in an energy efficiency project may not see the direct benefit of the achieved cost savings. Instead, the whole facility might see the reduction in energy cost, meaning the investing manager will only see a small portion of the return. This could prevent an operations manager from selecting and energy efficiency improvement projects when comparing with other options that may more directly impact his or her budget or work area.

- *Diffuse energy loads* – This barrier is relevant to industrial facilities that have a wide range of products and processes. In high energy intensity industries, such as pulp and paper, refining, steel, key energy loads can be well known and centralized. In "high mix, low volume" manufacturing environments, process and test equipment may be spread out across the facility, making focused energy efficiency projects more difficult.

- *Defining efficiency and measuring improvement* – Because energy is not visible, monitoring may be needed to make energy efficiency improvements "seen". Utility bills give an indication of energy consumption, but in large facilities, real energy savings are often confounded by other variables, such as natural weather variations or fluctuations in production volume or product mix. Energy meters can provide the level of data needed, but metering individual equipment can become expensive and requires management. Even with metering, production volume and product mix variations can cloud the results of an energy efficiency project. Analysis may be required to define what energy efficacy means to the facility and/or individual work areas to determine whether a true efficiency improvement in a facility or production area is realized.

1.3 Challenge

The goal of this project is to develop a framework for achieving sustainable cost reduction in production operations through energy efficiency. The research was conducted at the Raytheon Integrated Air Defense Center (IADC) in Andover, Massachusetts. While the Raytheon manufacturing site was used to develop and pilot the energy improvement framework, the general knowledge and process is intended to be relevant for all manufacturing facilities.

Reducing direct production energy is very different than reducing support loads. Support loads can essentially be adjusted or replaced behind the scenes (i.e., without impacting production schedule or processes). On the other hand, reducing production energy requires full engagement of operations personnel to measure, analyze, and implement changes to processes to improve the way they consume energy. Like all organizational changes, there are critical strategic, political, and cultural components that need to be addressed to implement a sustainable change in the way work is conducted by "everybody, every day". In my project, I'm focusing on developing a framework for achieving waste energy reduction in a sustainable way. Three of the project focus areas are:

- *Senior management buy-in* – Bottom line cost savings influence senior managers, who have the ability to set, prioritize, and flow down operations goals to production managers.
- *Employee engagement* – Use existing Raytheon Six Sigma and Lean Manufacturing methods to influence production cell leaders and front-line workers to modify processes and behaviors to reduce energy waste. Performance metrics development will keep cell leaders engaged and allow management to set progressive goals over time and reward success.
- *An iterative, process driven approach* – Develop a data-driven framework that can be used by stakeholders throughout the facility to identify energy waste, improve energy efficiency, and sustain results.

All of the barriers described in Section 1.2 are evident at some level at Raytheon IADC. The current state does not hold mid-level operations managers and cell leaders accountable for the energy that they consume. Furthermore, if they make an energy efficiency improvement, the direct benefit goes to the facilities department, which manages the site-wide overhead budget (including energy).[3] Therefore, currently there is limited incentive for operations managers to improve their production energy efficiency beyond the general plea from senior management to use energy responsibly. Given that improvement projects are often capacity constrained, managers would rather spend time and resources on projects that improve the metrics on which they are evaluated, namely budget, schedule, quality, and safety. The first two focus areas above are designed to have senior managers set goals that will hold production operations accountable for the energy they consume.

The employee engagement piece is particularly critical in this facility because the production equipment is diffuse and specialized and multiple stakeholders are involved. Engineers design processes, operations mangers and cell leads manage them, and operators run them. In order to make a change, you'll need to consider how each stakeholder will view the impact on product quality, schedule, budget, and safety. Without all of the process stakeholders engaged, any one of them could shut down the improvement project for any one of these concerns. In this way, proposed improvements to production energy consumption are far more challenging than building support loads (e.g., air conditioning, lighting,

[3] Note that reducing the site overhead cost does reduce the cost to production areas, but individual production areas do not feel like they can have a significant impact on this site-wide cost, and therefore there is not a strong incentive for them to reduce their energy usage.

ventilation). If it was the air conditioning system you want to improve, you could work with the facilities department to get it done without disturbing the engineers, operations team, operators, and production processes.

Past research efforts focused on energy reduction in manufacturing operations have been conducted at the Raytheon IADC site. The first focused on changing site-wide employee behavior through engagement. (7) The second used Six Sigma methodology to achieve energy reduction in a production work area as well as real-time energy use feedback to support behavior change. (8) These past efforts provide a solid foundation of knowledge, methods, and engaged employees on which to build. The challenge in the current project is to scale the effort to an appropriately sized production area, develop a repeatable process that can be followed and led by the Raytheon Energy Team to achieve sustainable results throughout the IADC facility. The framework is designed to be applicable to production areas with different people, processes, and equipment, making it a useful methodology both internal and external to Raytheon manufacturing operations.

1.4 Outline of Document

This research outlines a methodology for achieving energy efficiency in an industrial manufacturing environment, and uses the Raytheon Integrated Air Defense Center (IADC) as a model manufacturing facility. However, while using a specific pilot production area to demonstrate the methodology at IADC, the framework is applicable to other industrial facilities interested in environmental responsibility and operations cost reduction and committed to process improvement.

Chapter 2 provides background information from literature on industrial energy management as well as the current state of energy management at Raytheon IADC in the context of the overall corporation. Chapter 3 describes the methodology, or framework, for achieving energy efficiency in general terms, and Chapter 4 uses an electronic components production area as a pilot project to demonstrate a specific application of the framework. Chapter 5 follows with a discussion of the significance of the results to Raytheon as well as industry in general. The thesis concludes with a summary of the results and recommendations for future research.

2 Background

2.1 Industrial Energy Management

Energy consumption in industry can be broken down into two end use categories: production and support loads. Support energy loads are building loads that support production. Heating, ventilation, and air conditioning (HVAC) for occupant comfort are common industrial support loads along with lighting and water heating. Production loads are the loads that are primarily related to production (i.e., not designed for building comfort). These loads will vary significantly both among industries and within industries, and also can account for a significant portion of the total energy consumption at an industrial facility.

While it is understood that support loads and production loads are not independent from one another, making the distinction is a useful way of thinking about energy usage and energy reduction opportunities in a facility. Reducing production energy is often very different than reducing support loads. Support loads can essentially be adjusted or replaced "behind the scenes" (i.e., without impacting production schedule or processes). An example might be replacing lights or an air conditioning system with more efficient equipment. As long as the new equipment provides an acceptable level of occupant comfort and function, production processes and personnel are unaffected or minimally affected. On the other hand, reducing production energy requires cross-functional engagement of personnel (e.g., operations, engineering, facilities, EH&S[4], labor relations, etc) to measure, analyze, and implement changes to conserve energy while still delivering a quality product on time, on budget, and in a safe way. This is an organizational change that requires an implementation process of its own.

Energy management in production operations requires process management techniques not unlike those developed in lean manufacturing and six sigma. Lean manufacturing, which earned world-wide attention in James Womack's "The Machine that Changed the World" focuses on continuous improvement and the elimination of waste from processes, which inherently means reducing energy in some form or another. The seven standard forms of lean waste in lean thinking are defects, inventory, over-processing, waiting, motion, transportation, and overproduction. While "over-consumption" of utility energy (e.g., electricity, natural gas) is not traditionally discussed in lean literature as operations waste, it could quite logically be included in over-processing or over-production.

A key six sigma reference, "Six Sigma: the Breakthrough Management Strategy Revolutionizing the World's Top Corporations," also does not specifically mention energy efficiency as a potential

[4] Environment, health, and safety (EH&S)

application. (9) However, the six sigma concept places emphasis on using data to drive decisions and using the scientific method, which are extremely useful in energy management since energy use and reduction are not generally visible. Since process improvement methodologies began to gain popularity in the 1980s, corporations have adopted and adjusted lean and six sigma concepts to develop continuous improvement methodologies that meet their needs.

Energy management "activities" are defined by the Energy Information Association's (EIA) Manufacturing Energy Consumption Survey (MECS) as a "practice, procedure, or program designed to reduce an establishment's use of energy in performing normal operations." (4) The Environmental Protection Agency's (EPA) Energy Star Program offers "Guidelines for Energy Management" in which energy management is treated as a continuous improvement initiative, like lean or six sigma. The International Organization for Standardization (ISO) in 2011 released its version of an energy management standard, referred to as ISO 50001. This standard also treats energy management as a continual improvement initiative.

Table 1 lists the key process steps for select energy management and process improvement methods.

Table 1: Comparison of process steps for select energy management and process improvement methodologies

Methodology	**Energy Management**		**General Process Improvement**	
	ISO 50001(5)	EPA Energy Management (6)	Six Sigma DMAIC[5]	Raytheon Six Sigma
Process Steps	Plan	Make Commitment	Define	Visualize
	Do	Assess Performance	Measure	Commit
	Check	Set Goals	Analyze	Prioritize
	Act	Create Action Plan	Improve	Characterize
		Implement Action	Control	Improve
		Evaluate Progress		Achieve
		Recognize Achievements		

It is clear that organizations are beginning to treat energy management as a process improvement challenge. However, many of the improvement principles on their own are, by design, very general. They have to be in order to be applicable across all industries, processes, and equipment types. Much like lean and six sigma, organizations need to adapt these principles to more specifically address their needs.

[5] Define, Measure, Analyze, Improve, Control (DMAIC)

A continuous improvement and data driven approach to energy management will be useful for any commercial or industrial facility, but it is particularly important for improving production energy efficiency in industrial environments. This is because of the highly specialized and/or diffuse energy loads found in industrial settings. In an average commercial building, over 70% of the energy is consumed by "main building loads", or HVAC, lighting, and water heating (which we have defined as support energy loads in an industrial environment). (7) By focusing energy efficiency on these five main loads, the majority of the building energy consumption is addressed. In an average industrial building, direct process end uses account for at least 60% of the total energy,[6] as indicated in Figure 3, and therefore focusing only on "main building loads" generally will not provide the same value as in commercial buildings.

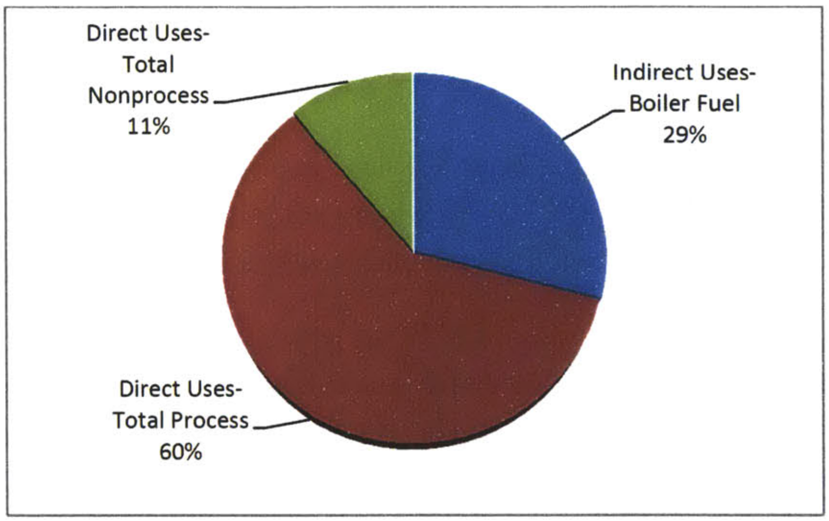


Figure 3: 2006 U.S. Industrial Energy Consumption by End-use (4)

At Raytheon IADC, the focus of this study, as much as 75% of the total building energy is consumed by electric production equipment. This means that by focusing energy management on HVAC and lighting, only 25% of the facility energy consumption is being addressed. Therefore, production energy needs to be specifically addressed in order to continue to achieve aggressive energy reduction goals.

An added benefit of reducing electric equipment energy consumption is that it will indirectly reduce the air conditioning load on the building. During the summer, nearly all of the electric energy

[6] The breakdown of "indirect uses – boiler fuel" between production and support loads is unclear.

consumed by production equipment ends up as heat in the building (unless it is vented[7]), and needs to be removed by the air conditioning system. The extra energy needed to "re-cool" the internal space will depend on the air conditioning system efficiency and the outdoor air conditions, but as a rule-of-thumb, you can estimate that for every kWh of electric energy consumed by unvented production equipment, an additional 0.25 -0.30 kWh (i.e., 25-30%) will be consumed by the air conditioning system to remove the generated heat.[8]

During the heating season, the heat produced by electric production equipment will actually reduce the load on the dedicated building heating system. However, in almost all cases, the dedicated building heating system will be more energy and cost efficient than the resistance heating that production equipment provides. Therefore, it still makes more sense to use the production equipment as efficiently as possible, and let the building heating system handle the heating needs.

2.2 Raytheon Overview

Raytheon Corporation is a manufacturer of defense, aerospace, and homeland security technologies. There are approximately 72,000 employees and 2010 revenues totaled approximately $25 billion. Raytheon markets its products to governments throughout the world, but its biggest customer is the U.S. Department of Defense (DOD).

Raytheon Integrated Defense Systems (IDS) is one of six business units at Raytheon, and the Integrated Air Defense Center (IADC), the focus of this thesis, is one of the Mission Centers within IDS, as depicted in Figure 4.

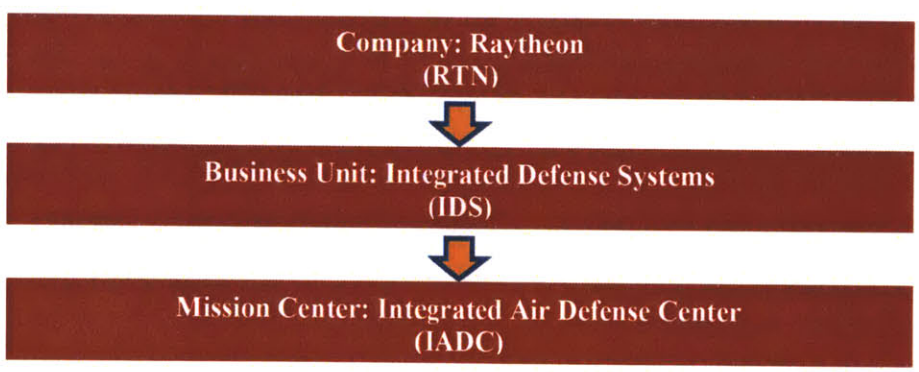


Figure 4: Basic Raytheon organization structure

[7] Note that venting requires makeup air to be pulled from outside, which in turn needs to be re-conditioned and therefore still puts an additional strain on the air conditioning system.

[8] Assumes a typical coefficient of performance (COP) of 3.5 to 4.

IADC is the largest manufacturing facility in IDS, covering 1.6 million square feet. Figure 5 shows that about half (about 800,000 square feet) of the IADC facility is classified as manufacturing floor space. Another 200,000 square feet is classified as lab space, which also contains equipment that, for the purposes of this study, we can classify as production equipment.

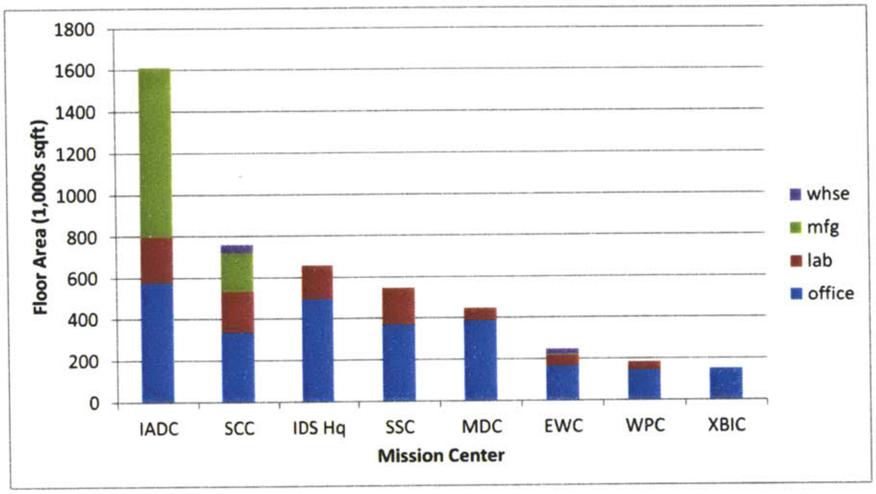


Figure 5: Breakdown of Raytheon IDS floor area by Mission Center[9] and primary function

The IADC, located in Andover, Massachusetts, employs over 4,000 employees, and uses up to three shifts to manufacture various land, sea, and air defense systems. The facility is a "high mix, low volume" manufacturing environment because of the high mix of product types, and the relative low volumes produced.

As a company, Raytheon is an industry leader in energy efficiency. At the corporate level, Raytheon has publicly committed to energy reduction and greenhouse gas reduction goals and has received several awards for their commitment and success. Between 2002 and 2008, Raytheon reduced their revenue normalized greenhouse gas emissions by 38% (mainly from energy reduction) as a participant in the U.S. Environmental Protection Agency's (EPA) Climate Leaders Program. (8) In 2009, they renewed their commitment by setting a goal of achieving 10% absolute GHG emissions reduction between 2008 and 2015. 2011 was the fourth consecutive year that Raytheon has received the Energy Star Sustained Excellence Award, and in 2007, Raytheon earned the Energy Star Partner of the Year honor.

[9] The plot only shows data from the eight largest mission centers.

2.2.1 Energy Usage at IDS

Raytheon's IDS business consumed about $25 million in energy in 2010, 50% of which was consumed at the IADC mission center. This thesis focuses on electric energy consumption because it accounts for the bulk of the facility energy cost and because it is the dominant energy type for production equipment. 70% of the IADC site energy use and 90% of the energy cost is from electricity consumption, while the balance is attributable to natural gas consumption. Figure 6 plots the electric energy consumption and the floor area for the eight largest IDS Mission Centers (MCs). Also plotted is the cumulative percentage of the total electricity and floor area. The figure clearly indicates the importance of IADC's energy performance to the overall energy performance of the IDS business.

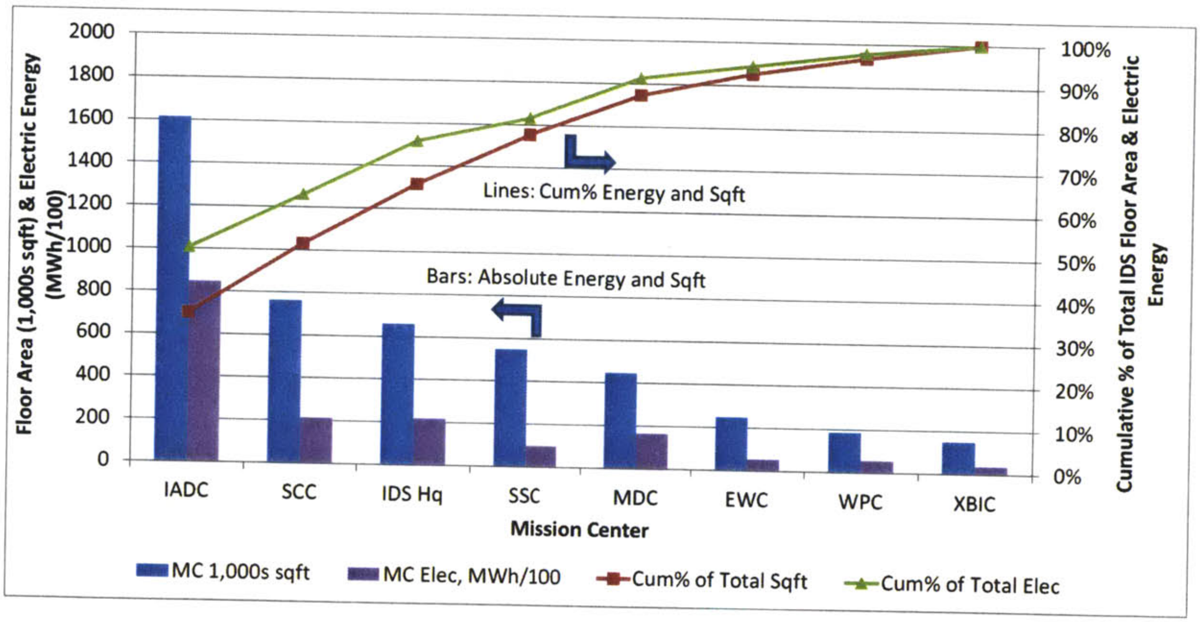


Figure 6: Mission Center floor area and electricity consumption

Like many large industrial sites, IADC negotiates its own electric rates from its provider. For the purposed of this thesis, I have used the average rate of $0.13/kWh, which is the approximate average electric rate for industrial consumers in Massachusetts.

IDS has made significant investments in reducing the consumption of support electric loads, or loads that support production but are not directly used for production. Examples of support loads include building heating, air conditioning, and lighting. These projects are calculated to be positive net present value (NPV) projects, and often offer a quick financial payback and can include utility or government subsidies. In most office buildings, these are the largest energy loads, and therefore improvements in lighting and space conditioning efficiency can significantly reduce the building energy consumption. At IADC, however, 75% of the energy is consumed by direct production loads, and therefore a successful energy management program must also account for these loads. These direct production loads include thermal chambers, large motors, electronic test equipment, hood vents, shop air, process water, and a vast number of other equipment types.

Upper management at Raytheon understands the value of energy management. They understand that it requires about $330 million in annual revenue to pay the $25 million IDS annual energy bill.[10] Energy savings result in higher margins and/or more competitive project bids. They also understand that being a responsible energy consumer goes a long way today towards maintaining a positive public and customer perception, particularly when their primary customer, the U.S. DOD is concerned with the dependence that the U.S. has on foreign fuel sources.

2.2.2 Energy Management at Raytheon IDS

The energy management initiative at IDS is the responsibility of the Enterprise Energy Team (EET), which falls under the facilities department within operations. The primary function of the EET is to develop and implement programs and projects to help reduce the business's energy use. The EET is also inherently involved with the company's greenhouse gas (GHG) emissions goals, although environmental goals are technically managed by the Environmental, Health, and Safety (EHS) team.

All the energy consumed at IADC is allocated to the facilities overhead budget, and the IDS EET commits to annual energy goals for IADC as well as the other IDS mission centers. During review periods, the current status relative to an operations goal is highlighted with the colors green, yellow, or red. In a nutshell, green is good, red is bad, and yellow is borderline performance relative to targets. During review periods, management reviews mission center and business wide goals, and the "stop light" color system allows management to quickly visualize where targets are not being achieved.

While obviously the company would prefer to be "green" against all of their operations performance goals, there may be other important factors to consider when analyzing "red" energy performance. Namely, if production output in the facility goes up, which is obviously a good thing for business, the energy consumption will almost certainly also increase. The current energy goals are set on an absolute basis and do not account for variations in production output. Additionally, there may be uncontrollable weather fluctuations which can have an impact on energy performance.

Nonetheless, even with reasonable justification for a rise in energy use over a review period, IDS's energy performance goals engage senior leadership in the energy management initiative and allow

[10] Assuming the corporate net profit margin of 7.6%.

the EET to track their progress and introduce new efforts, if necessary. Senior management engagement is a critical component of any successful continuous improvement initiative.

IADC strives for "total employee engagement" (TEE) in its continuous engagement initiatives, not just senior management engagement. A past research project at IADC investigated methods for achieving total employee engagement. (7) The goal was to achieve responsible consumption of energy through awareness and behavior change. The past effort used the IDS "Energy Citizen" campaign as the foundation for his effort. By creating a tracking tool in the IADC Virtual Business System (VBS), a network tool used to track and share a number of performance metrics, the project team was able to track individual work areas' participation in the campaign, and set goals. While employee engagement is particularly important in industrial settings with many diffuse and unique process loads, it is difficult to directly correlate engagement to real energy savings.

As I mentioned above, 75% of the energy at IADC is consumed by direct production equipment. Production area managers and operators have control over this equipment. However, the energy goals are set and tracked at a facility level, and production managers are not accountable for their energy bills, nor do they generally know how much energy their individual areas are consuming. Moreover, if an individual production area manager spends time and resources to reduce energy consumption, the benefit is spread across the entire facility in the form of a lower energy bill. Since it is hard to track and reward improvements in individual work areas, the incentive to focus on these types of improvements is low.

2.2.3 Energy monitoring

Raytheon IADC has invested in a significant amount of energy monitoring equipment. The facility electric system is divided into ten substations, each of which is monitored for energy use. Further sub-metering is installed at many of the substations, and the data can be accessed from a SQL database. The 2010 energy consumption at each substation, broken down by production, air conditioning, and lighting, is plotted in Figure 7.

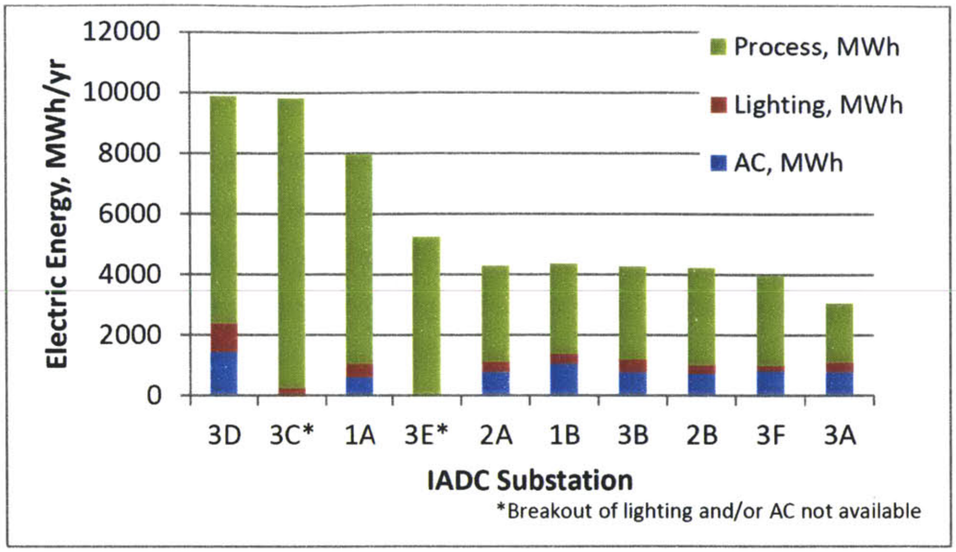


Figure 7: 2010 energy consumption at each IADC substation as recorded by the building monitoring system

The challenge with energy monitoring is providing "the right data, to the right decision maker, at the right time, and in the right context." (15) Building monitoring systems can provide a large amount of data, but as the monitoring system becomes more complex, trained people are required to maintain the system and deliver the data to the right people at the right time. A big challenge at the IADC facility is that the electrical system and the production areas do not match up in a simple way. A production area might be in serviced by more than one substation or more than one main line, so it is a difficult task to determine precisely how much energy a particular production area or cell is consuming. Adding more and more metering becomes prohibitively costly and difficult to management and maintain.

Past research efforts have investigated the data delivery method and timing. Espindle used the Virtual Business System (VBS), which is used to deliver other operations performance metrics, to deliver energy data to production areas. (8) In the same research, Espindle was able to show significant energy reduction in high energy consuming equipment by providing real-time energy data to the equipment operators and area managers.

2.2.4 Lean Manufacturing and Six Sigma at IADC

The IADC has a dedicated lean manufacturing office, called the Operations Excellence Research Center (OERC), which was established in 2001. In 2008, IADC won the North American Shingo Silver Medallion award for operational excellence. These awards are referred to as the "nobel prizes for operational excellence" and provide evidence of the dedication and success that Raytheon has had with its lean transformation. One of the OERC's activities is the coordination of the "Lean Games," for which work areas compete against each other for the best lean projects. In general, energy management has not been a focus area for the OERC, but recent rounds of Lean Games have included energy as part of the scoring criteria for projects.

Raytheon Six Sigma (R6σ) is a corporate wide process improvement program initiated in 1998. The program is designed specifically for Raytheon, but builds off of other corporate six sigma programs. Six steps are followed to guide improvement project to completion: visualize, commit, prioritize, characterize, improve, and achieve. Raytheon Six Sigma provides an avenue for employees to receive process improvement training, and work cross-functionally on site improvement projects.

Raytheon IADC makes use of lean, six sigma, and energy management philosophies and teams. Interestingly, these groups tend to operate somewhat independently from one another. As the energy team focuses more on energy management in production operations, there is a significant opportunity to find synergies among these teams and methodologies. Lean and Raytheon Six Sigma offer tools and a common language with which to engage stakeholders and management energy improvement projects and initiatives.

2.2.5 Cultural Dynamics

The culture at IADC is extremely important when attempting to manage an organizational change. With 4,400 people and 1.6 million square feet, there are sub-cultures in different production areas, in different functions (e.g., engineering, operations, facilities), as well as among the represented employees (unions) and non-represented employees. It's important to be cognizant of these different sub-cultures when attempting to influence and obtain buy-in for a "global" change initiative.

The cornerstone continuous improvement slogan at Raytheon is "everybody, every day." There's evidence of this in email signatures, in presentations, on the building walls, and on signs as you exit the campus. This phrase is referenced in all existing change initiatives, including lean manufacturing, six sigma, and safety. Senior management is committed to the concept of total employee engagement (TEE), and this mentality is an important part of the IADC culture and appetite for change.

Safety and quality are paramount in IADC operations, and can be self-reinforcing values. Commitment to safe working conditions demonstrates respect for employees, which in turn motivates employees to focus on adhering to standards and creating quality products.[11] On the other hand, this mentality also can result in resistance to proposals to change existing processes or equipment run rules. Proposed changes that are perceived to have a potential impact on product quality or safety will impact

[11] Note that respect for employees and continuous improvement are the hallmark principles of the Toyota Production System (TPS), which is often credited for giving Toyota a competitive advantage in its industry.

decisions. This was previously referred to as a high transaction cost, and speaks to the need for relying on data to influence stakeholders when suggesting a change in the way a piece of equipment is used (whether for energy efficiency or any other waste reduction effort).

3 Methodology Using R6σ and Lean Principles

A critical aspect of this thesis project is developing a methodology for achieving and sustaining results. The objective is to create a framework that is general enough that it can be applied across a broad set of different production areas within Raytheon (and potentially across different industries), but specific enough to provide prescriptive guidance on how to achieve results. Raytheon, like many organizations, has existing tools and methodologies in place for continuous improvement (e.g., Six Sigma, Lean Manufacturing, ISO). The energy efficiency framework will build off the existing tools and philosophies in an attempt to accelerate acceptance and deployment by using a common language and proven methods in the company and industry.

There are many frameworks for managing change in general and, more specifically, energy efficiency in an organization. These methods were described in the background section and are listed again in Table 2 along with their corresponding process steps.

Table 2: Change management frameworks and processes

Framework	Six Sigma DMAIC	ISO 50001	EPA Energy Management	Raytheon Six Sigma
Process Steps	Define	Plan	Make Commitment	Visualize
	Measure	Do	Assess Performance	Commit
	Analyze	Check	Set Goals	Prioritize
	Improve	Act	Create Action Plan	Characterize
	Control		Implement Action	Improve
			Evaluate Progress	Achieve
			Recognize Achievements	

I selected to use the Raytheon Six Sigma process as a basis for the energy efficiency framework. Not only does six sigma provide a scientific, data-driven approach to managing change, but the language of Raytheon Six Sigma is already understood and respected among Raytheon management. There are six process steps, or phases, to the R6σ approach. The steps are designed to be carried out in serial fashion, but I found that some phases (e.g., commit) required continuous attention throughout the project as new stakeholders became involved. I found that the characterize, improve, and achieve phases may be best carried out in an iterative fashion, with each iteration covering a manageable "chunk" of work and offering the opportunity to achieve success more quickly while the team has commitment from the key stakeholders. Sections 3.1 to 3.6 provide a more detailed discussion of the R6σ process steps as they apply to the energy efficiency framework. Specific examples of the application of the methodology in the pilot area are given in Section 4.

3.1 Visualize

The project vision identifies the main goal, and ideally creates a link between the energy efficiency efforts and the overall operations strategy. Discussions with senior management gave a clear indication that improving competitiveness and affordability was a key part of the IADC operations strategy. This strategy influences the goals and targets that are set and flowed down to production areas. Energy efficiency and the accompanying cost savings are well aligned with this operations strategy, and explicitly drawing this parallel in the project vision will help with achieving buy-in for the proposed project. As such, our vision is to drive improvement in competiveness and affordability through energy efficiency in production operations.

The vision should create a top-level understanding of savings potential to enable management to prioritize the importance of energy efficiency efforts relative to other initiatives in terms of how much time and resources to commit. The vision should also create an expectation for success, both in the short term and long term.

3.2 Commit

In the commit phase of the project, we identify who needs to "buy in" to the project goals and objectives in order to achieve success. As a part of corporate continuous improvement initiatives, organizations strive for "total employee engagement", and ideally commitment from everyone in an organization would be the best way to achieve results. However, in this phase of the project I have tried to identify critical stakeholders without whose commitment would result in a breakdown in the project's success. Critical stakeholders become evident as you learn the decision making process for making changes to the current state.

3.2.1 Identifying Key Stakeholders

Figure 8 displays the cross-functional stakeholders at IADC that are key to changing the way a production area uses energy.

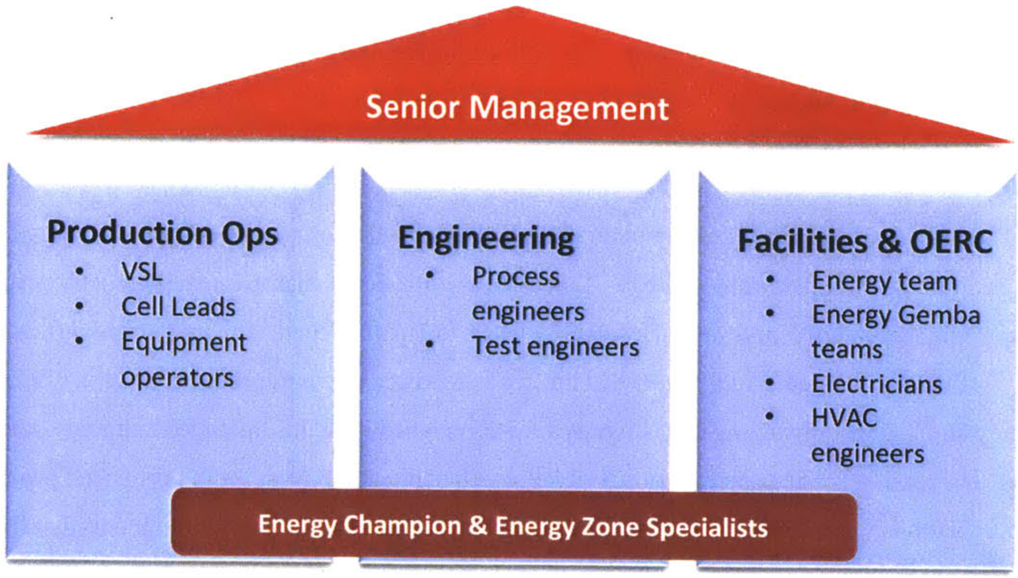


Figure 8: Key stakeholders in production area energy efficiency projects

Additional details on how the key stakeholders are involved in the process of production energy efficiency improvement at IADC are given in section 4.2. The general approach is to learn and understand the various functions and roles involved, and how they interact. The team needs to understand how decisions get made, and who is involved in the process.

3.2.2 Earning Buy-in

This task is a critical phase of the "commit" step and the overall success of the project. It is difficult mainly because there isn't a concrete set of steps that will result in successfully achieving buy-in. Different functions, employment levels, and personalities will respond differently to tactics of influence. What I can do is share some principles that I found useful in engaging stakeholders. Also, it's important to note that although the "commit" phase is the second step of the R6σ process, the process of engaging stakeholders will continue throughout the project, and someone (e.g., Energy Champions, Enterprise Energy Team, Energy Gemba Teams, Energy Zone Specialists) will have to be responsible for sustaining and developing the level of engagement even after all the process steps are complete.

- *Understand the chain of command and performance metrics and incentives* - If the key stakeholders have been identified, as in 3.2.1, then you should have a good handle on this principle. It's critical to understand how each stakeholder is connected to one another, and to understand the decision making unit (DMU) and the decision making process (DMP). For example, if you want to modify the run rules for a piece of equipment, who has the authority to make that decision, and who will he/she/they consult with during the decision making process.

- *Respect people, build relationships, find champions* - This may sound obvious, but building relationships with stakeholders will help support engagement in your project. The fundamental principles of the Toyota Production System (TPS) are continuous improvement and respect for people. These are self-reinforcing principles in that people that are treated with respect are more likely to feel loyalty and be motivated to contribute the continuous improvement of an organization. (16) Learn about people, the processes and equipment with which they are involved, and what drives them at work. Not only will you get a better understanding of which tactics to use to try to influence them, but "liking" is a fundamental Cialdini principal (i.e., people are more likely to want to help people that they like). If you rush into a production area and try to start suggesting that people change the way people do their work, you will run into resistance, and it will be hard to recover. Take the time to learn about the people and show them that you are interested in the current processes. Also, in the process of learning about people, you are likely to find a couple people who are already excited about energy efficiency, and who can help "champion" your project and help to influence others.

- *Answer the question, "what's in it for them?"* - Although it's nice to think that saving the planet is sufficient to answer this question, and it may be for some, many will not see a significant connection and you will have to go "deeper" to find a way to influence them. After building relationships and understanding what the drives the DMP, you will be able to more effectively answer this question for the different members of the DMU.

Remember, it is likely not the specific task of any of the stakeholders to be more energy efficient (if it is, congratulations, you're working within an advanced EMS), but at the top level the energy efficiency vision is (or should be) aligned with everyone else's, and that is to create and capture value for the organization. As you answer the question, "what's in it for them," try to frame energy efficiency in terms that are more directly related to specific goals and objectives the stakeholders may have. A few examples are given in Table 3.

Table 3: Examples of framing energy efficiency to match stakeholders' primary performance goals

Stakeholder	Examples of framing energy efficiency to fit stakeholder's primary performance goals
Senior management	• NPV+ project, bottom line cost savings, facility overhead budget goals, corporate energy goals
Value Stream Lead (middle manager), process engineers, and cell leads	• Lean projects for Lean Games (think of energy as over-processing or other lean waste) • Six sigma project requirements
Equipment operators	• Relate to home energy efficiency • Frame improved competitiveness and affordable as job security.

Setting performance goals and incentives that directly influence behavior regarding energy efficiency would also be an excellent way to gain stakeholder engagement. Specific energy goals and incentives for mid-level production managers at IADC did not exist during this thesis project, and will be discussed in the "achieve" phase. As discussed in Section 2.2.3, measuring energy consumption at the level necessary to enable goal setting for mid-level operations managers is a big challenge for any large manufacturing facility. Another challenge with setting energy goals is that, in general, production volume and production energy consumption are directly related to each other (i.e., as production goes up, energy consumption goes up). Increased production from increased product demand is good for the company, and so energy performance goals should be set so that production areas are not punished for increased production. For example, formulating an energy efficiency metric (e.g., production output per energy input) is one way of normalizing energy consumption for production output.

Also, employees will quickly become frustrated by metrics that they cannot control, or that they perceive that they cannot control. For example, mid-level operations managers at IADC cannot control the weather, and a hot summer should not destroy an engaged middle manager's ability to achieve his or her energy performance goal. Therefore, air conditioning (or heating) loads should not be included in production energy performance metrics.[12] Nonetheless, performance metrics can be a great way to incentivize and quantify performance as well as enable a reward structure.

3.3 Prioritize

In the prioritize phase, the goal is to break down the problem into more specific objectives. Often organizations focus on finding opportunities where the greatest impact can be made towards achieving the vision with the least amount of effort and resources, commonly referred to as "finding the low hanging fruit." A simple representation of this prioritization strategy is illustrated in Figure 9.

[12] Air condition (and heating) energy data can also be normalized for season variations using cooling-degree-days (and heating-degree-days) and humidity data, but the metrics will be simpler and more transparent to production managers if weather dependent support building loads are removed from metrics.

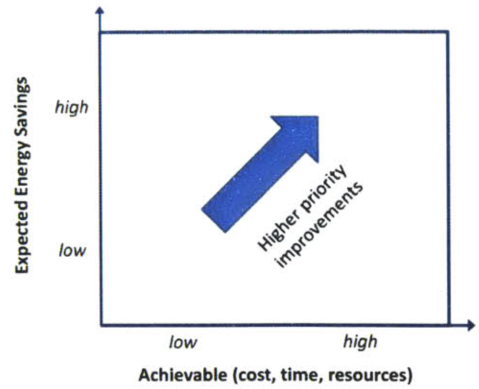


Figure 9: Simple project prioritization strategy

How achievable an activity is will vary from site to site, but generally can be evaluated in terms of how much it will cost, how long it will take, and how many resources will be needed. Data should be used to the extent practical to make decisions about project priorities. Decisions can be made about:

- Where to start
- How large an area to focus on at one time
- What types of loads to focus on (support loads, production loads, a sub-set of production loads, etc)
- Capital intensive vs. low or no-cost projects

Raytheon's building management system (BMS) is sophisticated enough to provide top-level energy data that allows the team to make these decisions. Facilities with less sophisticated BMS's will need to gather data and/or rely more heavily on intuition and analysis.

Given the challenge and the time required to build a case for financing of new equipment, no or low-cost efficiency improvements often prove to be the "low hanging fruit". This was the case for this thesis, which focuses on using existing equipment more efficiently. These types of improvements are generally less capital intensive, but require employee engagement to capture real energy savings in practice.

3.4 Characterize

This step in the six sigma process is an assessment of the current state and an evaluation of improvement opportunities. The Raytheon Six Sigma process, like many change management frameworks, relies heavily on data. Data is required to baseline the current state, understand and quantify opportunities, and to quantify and sustain results. This process is often referred to as "data driven decision making". Data can also be instrumental is earning buy-in from management and key stakeholders.

Along with a characterization of the current equipment in the production area, we also want to evaluate the current state of the processes in place for identifying problems, swarming to problems, and sharing knowledge around the production area and throughout the facility. Furthermore, we want to determine how well management is driving these processes. These are the "four capabilities" described by Steven Spear in his influential book, The High-Velocity Edge, on how organizations achieve exceptional performance. (9)

3.4.1 Identifying Equipment with Energy Waste

There are hundreds (and potentially thousands) of individual pieces of electric equipment in the pilot area alone. Given the limits on metering equipment and the level of cross-functional personnel coordination needed for data collection, described in 3.7, measuring the energy consumption of every load is not practical. However, even with more monitoring equipment and an improved coordination process, blindly measuring every load would not be a good use of time or resources. With a few basic steps and some intuition, load characterization can be simplified without a significant loss of accuracy. In general, I wanted to measure equipment that:

1. Consume a significant amount of energy, and
2. Have opportunities for energy savings.

In other words, I want to measure equipment that wastes the most energy. As mentioned, lean manufacturing is the practice of improving operational efficiency by eliminating waste, or *muda*. Lean manufacturing literature also categorizes two types of waste. (10) Type I *muda* are tasks that do not directly add value to a product (i.e., non-value-add (NVA)), but are unavoidable under current conditions. An example of this type of waste in an energy context would be energy needed to preheat an oven to the proper operating temperature. Type II *muda* are NVA tasks that are immediately avoidable. An energy waste example would be leaving an oven on without product inside or leaving a product in an oven for longer than is required.

Equipment with addressable energy waste can be filtered out by walking the production floor with cell leads (or someone knowledgeable of the equipment and processes) and looking for higher voltage equipment (e.g., 208 V, 480 V, or 575 V) that is on for long periods of time (i.e., hours per shift). Large motors, ovens, chambers, and test equipment are common candidates to meet these criteria.

Devices that have opportunities for no or low-cost energy savings are generally those that are commonly left on (or in an idle state) during periods when they are not interacting with product.

Equipment can be aggregated into logical functional groups. For example, the pilot area has four medium sized ovens used for potting (i.e., baking) electronic components. These ovens are approximately the same size and are used for the same mix of products. Although the operating temperature and run time may vary for each oven on a daily basis, these devices likely use a similar amount of energy, on average during the year, and have similar savings opportunities.

It is also important to consider the level of accuracy that is required for decision making. For example, if $1,000 in energy savings is assumed to be significant and worth the investment of time, there is no need to put in extra effort to determine if the exact savings for a particular improvement idea will be $8,000 or $10,000. Either way this is a good project, and efforts should be shifted to focus on more marginal projects.

Small energy loads, while they do may not be key savings opportunities, should not necessarily be disregarded as unimportant to the energy management project. While turning off task lights and computer monitors individually will not save a significant amount of energy, miscellaneous loads in aggregate can make up a significant amount of energy. Furthermore, good energy practices for small energy loads will carry over to larger loads, and the importance of supporting engagement and instilling good habits should not go overlooked.

3.4.2 Improvement Opportunity Categorization

A simple "who, what, when, why, and how" approach was taken to characterize improvement opportunities:

- *What* is the equipment?
- *How* can the equipment be used more efficiently?
- *Why* does the change make good business sense (i.e., what are the energy savings)
- *Who* will be accountable for implementing the change
- *When* is the deadline for the implementation of the change

To answer the "how can the equipment be used more efficiently," question, a three-lens analysis was applied to categorize energy improvements, as shown in Figure 10. The three categories are as follows:

- *Technology* – These improvement opportunities use technology hardware or software to improve energy efficiency. Examples include insulation, equipment replacement, or automation technology such as timers and sensors

- *Process* – Improvement opportunities that involve adjusting how production work gets accomplished. For example, modifying the run-rules for what, when, and how equipment can get shut down partially or completely. Visible signs and other lean *poka-yoke* (mistake proofing) tactics can be used to improve processes.

- *People* – Improvement opportunities that involve training or behavior changes that result in energy efficiency improvements.

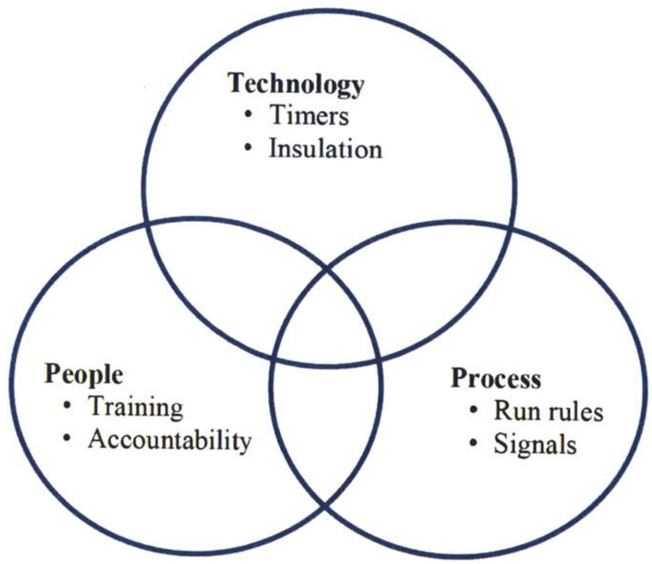


Figure 10: Three-lens approach to categorize energy efficiency improvement opportunities

As Figure 10 illustrates, each of the three lenses intersect the others, indicating that improvement opportunities can be (and likely are) a combination of two or all three of the improvement categories. Changes in behavior are reinforced with changes in process and then further improved, simplified, or automated with changes in technology. For example, the installation of a timer (a technology change) on a piece of equipment would also require a run-rule change to specify when and how the timer should be used. Additionally, one would need to engage the operator in the process and provide training so that the timer gets used properly to give the intended result.

Some might argue that if you use automation technology, you can remove the "people" aspect of improvements. This may be true in manufacturing environments where equipment automation makes economic sense. In high mix, low volume manufacturing environments like the IADC, process automation often does not make good business sense, and therefore, the behavioral side of process improvements is critically important.

Table 4 gives an example of how an improvement opportunity can be tracked. Responsibility can be given to the mid-level operations manager, cell lead, energy champion, energy team, or other stakeholder who can understands the opportunity and has access to the appropriate resources. The due date, not listed in Table 4, is a good way to prioritize opportunities, and maintain a schedule. A complete table of opportunities is given in 4.4.2.

Table 4: Example of improvement opportunity tracking table

Process Equipment	Opportunity			Expected Savings/yr	Responsibility	Due Date
	People	Process	Technology			
Vacuum Bake Chambers	Training on shut down procedures and run-rules	Shut down heating elements whenever possible	Add timers to heating elements	$20,000-$40,000	Cell lead 1	
	Training on timers	Shut off circulation fan and vent fans when empty always				
	Assign accountability on 1st and 2nd shift	Add shutdown process signs				

3.5 Improve

After the current state has been characterized and improvement opportunities identified, the next phase of the project involves implementing countermeasures to improve energy efficiency. The actual improvements pursued will depend on the opportunities identified, and the focus in this methodology section is not to provide details about the specific improvements made at the IADC facility, but rather to provide insights about common opportunities and improvement processes.

During this step, it was important to provide only guidance on implementing proposed changes, but to allow the production area stakeholders to be responsible for the actual implementation. This plays on the Cialdini principal of commitment, described in his book "Influence: The Psychology of Persuasion". (9) The objective is to give ownership and accountability to the production area personnel. The expectation is that the improvement is more likely to be sustained if the people who manage and execute the day-to-day work feel accountable. Furthermore, by allowing the stakeholders to discover solutions, they are learning to "see" energy waste and implement solutions.

3.5.1 Changing equipment run-rules

Equipment run-rules here are defined as the process for turning equipment on an off. Changing the run-rules does not necessarily mean changing the manufacturing process for a product, which generally will be more difficult to implement. For example, a product may need to be baked in an oven for an hour at 100°F. A change to the manufacturing process might be only baking the product for a half hour at 200°F. This sort of change would require approval from the process engineer and likely testing to prove that the change does not affect the product quality. A change to the run-rules might be to turn off the oven after baking the product for an hour at 100°F. This change does not affect the manufacturing process, and while energy savings can be achieved in both cases, equipment run-rule changes should be much easier to implement.

However, changing run-rules still requires some careful thought and coordination. You'll need work with the process engineers to consider the impact on the life of the equipment of turning the equipment on and off. At times, equipment has a simple on/off switch, while other times there are separate switches for various sub-systems which may or may not need to be switched on/off in the proper sequence. For example, large vacuum bake ovens at IADC have separate power switches for the heating elements, circulation fan, vent fan, and vacuum pump. The process engineer did not want the vacuum pumps to be switched off, but significant energy savings were still obtainable by switching off the other powered sub-systems, particularly the heating elements.

With some equipment, there may be perceptions about startup and shutdown that will need to be addressed before the required stakeholders will buy-in to new run rules. Continuing with the oven example, a few common misconceptions were:

- *"It takes "too long" for the ovens to warm back up to operating temperature"* – Operators and cell leads are very concerned about having equipment available whenever they need it. By measuring start-up times, I was able to show that ovens would pre-heat in 15 to 25 minutes (depending on the oven), which was manageable considering that parts were often baked for 12, 36, or even 72 hours. Furthermore, cell leads often had some advanced notice about which equipment would be needed, allowing them to plan for the pre-heat time.
- *"Ovens consume more energy during preheat than they do maintaining the operating temperature"* – While it is true that the average power draw during the preheat time is typically higher than during steady state operation for typical electric ovens, it is not true that they will use more energy if they are turned off and then brought back up to temperature compared with being held at a constant temperature. This is simply because the ovens consume zero energy while they are off, which more than offsets the extra energy during the preheat time. This was also easily verified with measurement data.

- *"These ovens can't be turned off"* – Referring again to the vacuum ovens, there may be significant energy savings achieved by switching certain sub-systems off during down time without shutting down the entire system.

When attempting to alter these perceptions, it was critical to utilize the "5 why" method and to use data. The "5 why" method is a lean technique for getting to the root cause of a problem, like asking the question "why" multiple times in sequence.

3.5.2 Installing new technology

New equipment installation can mean replacing existing equipment with more efficient or more appropriately sized equipment, or it can mean installing an add-on automation technology (e.g., sensor, timer, or insulation). In any case, the team needs to think about what new processes and run-rules need to be created and posted, and what people need to be trained to use the technology efficiently.

All of the technology improvements addressed in this research project were add-on technologies. It is often difficult to financially justify the replacement of functional equipment purely on the benefit of energy savings, although these opportunities do sometimes exist. However, when equipment reaches the end of its useful life, it is important to consider operating costs (including energy costs) in the buying decision. This can mean both looking for efficient equipment, and also looking for equipment that is "right-sized." For example, a larger volume oven will use more energy than a similarly designed smaller oven. If the smaller oven meets the capacity needs of the operations, energy savings can be achieved.

3.5.3 Signage

Signs provide constant visual reminders about processes, run-rules, or equipment instructions. Much of this information is written in detail in large process or equipment manuals, but signs posted on the equipment can provide critical information in a much more accessible form. I found that signs work best when they:

- Answer the questions who, when, and how – For example, John Doe should shut down a piece of equipment at the end of first shift by following the given shutdown procedure.
- Adhere to document control procedures – If the sign has names and procedures on it, it is important to make it a controlled document so that revisions can be easily made and so that it conforms to standard quality practices.
- Assign accountability – Use real names so that people take ownership and can be held accountable.
- Use visuals and poka-yoke – The signs should be easy and quick to read and leave as little room for confusion or mistakes as possible. Pictures or visual cues can be helpful.

Signs can also be useful for knowledge transfer. Cell leads and operators commonly rotate among production areas or temporarily fill a position, and signs provide reminders and tips to new or temporary operators.

3.6 Achieve

The final phase of the project focuses on sustaining improvements and putting measures in place that will facilitate continuous improvement. Success will require dedication to an iterative process, and methods need to be put in place to incentivize learning form mistakes and sharing knowledge across the production areas and the entire facility.

While we focus on sustainability in the achieve phase of the process, all of the steps in the process are designed to create sustainable improvements, from creating the vision and earning buy-in from senior management, to measuring improvement opportunities and assigning accountability. The initial pilot project size (and recommended subsequent projects) was set such that the production area of interest was managed by a single operations manager with decision making power. The employee level below would not have had the ability to make decisions about changing run-rules and the employee level above would neither have physically been situated in the production area nor have had day-to-day oversight of the area's operations.

During the pilot project, the Enterprise Energy Team (EET) and I led the process, but tried to establish ownership with the key stakeholders in the production area. The improvement process is an iterative one, and the EET and I were only in the area for a single iteration. It is critical to teach the area stakeholders to see energy waste and the process for fixing the problems.

3.6.1 Performance metrics

Another potential method for achieving sustainable results is developing performance metrics. Production managers and cell leaders are commonly incentivized by operations goals and metrics. Energy metrics will keep operations personnel engaged and allow management to set progressive goals over time and reward success. As was mentioned previously in Section 3.2.2 on earning buy-in, careful thought needs to be given to how these metrics are designed. Increased production demand, which is good for the company, will generally increase energy usage. The energy metrics should not punish a production manager for an increase in demand. Likewise, in a high mix environment like Raytheon, shifts in the product mix can affect the energy usage, and metrics need to be robust to these sorts of variation. Managers should also not be held accountable for a metric that can be influenced by an unseasonably hot summer, since managers obviously cannot control the weather. With appropriate measurement, weather and production volumes and mixes can be taken out of the metric or otherwise normalized.

There are a couple of options for creating an energy metric that normalizes for production volume. One would be to create an efficiency metric in which some measure of output is combined with energy input. At IADC, for example, production output is tracked with "earned standards," or just "standards." Standards are measured in units of time, and essentially track how much progress, or value, has been created. IADC also tracks total labor hours for production operators. A linear regression model can be created for the monthly production energy consumption over the last 24 months, using standards and labor hours as regressors. The intent is to develop a correlation between the level of production output and the total time spent by operators in the facility and the production energy consumed. Such a correlation might be as follows:

$$\boldsymbol{Energy = A + B \times Standards + C \times Labor\ hours,} \qquad \textbf{(Equation 1)}$$

Where production energy is the output; A, B, and C are constants determined by the regression model, and standards and labor hours are variable inputs to the equation. Other relevant factors should be considered in the regression model, allowing the model to determine with factors are statistically significant.

A second way to normalize energy consumption for production is to look at off-shift periods when production is not happening (e.g., a time period during the night or weekend). The idea here is that if equipment is not being used during off-periods, it should be getting shut down. If the metric influences production areas to shut down equipment before they leave for these off-times, this mentality will likely carry over to on-shift periods.

There are various reasons why the above methods for creating a performance metric won't work in a production environment (e.g., lack of energy data, lack of statistically significant correlations, etc). There still may be other options to develop a quantitative performance metric. For example, a set of "best practices" related to energy can be developed, weighted, and rolled into a performance score. Best practices give production areas specific pro-active tasks that they can use to improve their energy performance. The downside, of course, is that the best practice score is not directly tied to measured energy consumption. Furthermore, this method requires leadership and a process to calibrate and verify the scores among production areas.

3.6.2 Rewarding outstanding performance

Once performance metrics are in place, exceptional performance can be rewarded. We previously discussed the fact that production areas at IADC do not see the direct benefit of energy cost reductions because energy cost is lumped into a site-wide overhead pool. Performance metrics provide an opportunity to provide a direct benefit to incentivize improvement. Incentives can be offered in the form of monetary rewards to individuals or teams or in the form of celebrations or prizes (which often can be valued by employees beyond their monetary cost). Other options include offering a portion of the energy savings in the form of a discretionary overhead budget to the production area, which can be reinvested in tooling, training, or additional improvement projects in the area.

3.7 Data Collection Methods

Raytheon IADC has a number of systems and technologies for collecting energy data.

- AEMC 8335 Power Quality Analyzer – Four portable units were available to support extended data logging on production equipment. These systems have the ability to measure both current and voltage on three-phase high voltage industrial equipment, and log real power draw at time intervals as small as one second. These meters required an on-site union electrician for installation and removal, and required the metered equipment to be shut down at the breaker level prior to installation and removal. The installation process required the coordination of process engineers, operations cell leads, and facilities electricians to properly shut down equipment and schedule a time when production could be interrupted and the electricians were available. The coordination effort proved to be the bottleneck, as the installation process itself generally took about 30 minutes.

- Schneider Electric CM5000 – These are the permanently installed circuit monitors that are installed on switchgear throughout the IADC. These meters provide real power draw data every 15 minutes to a SQL Server database that can be accessed via the internet. Most of the lighting and air conditioning equipment is monitored with these meters, but production equipment is generally only captured in aggregate at certain distribution nodes within the substation. This makes these meters good for providing high level or top down energy consumption data, but poor for providing data on individual equipment or production energy efficiency projects.

- Watts Up Pro Wattmeter – One portable unit was available to measure instantaneous real power draw for 120V equipment. This equipment includes computer equipment, workbench equipment, such as solder irons and baths, and did not require an electrician to operate.

4 Applying the Energy Efficiency Framework to a Pilot Production Area

The energy efficiency framework is designed to provide a methodology for any production area in the Raytheon IADC facility to achieve more energy efficient production operations. The methodology is also intended to be applicable at other sites and other organizations. Like any organization change, using a pilot project to develop and test an initiative is a great way to obtain practical feedback and address many of the risks on a small scale before rolling the initiative out to the entire facility or company. At IADC, the project team selected an electronic components manufacturing and testing area as a pilot area to test the benefits and challenges of the energy efficiency methodology in practice.

4.1 Visualize

The vision creates a link between the energy efficiency efforts and the overall facilities operations strategy. For Raytheon, our vision is to drive improvement in competiveness and affordability through energy efficiency in production operations.

Focusing on electricity, which accounts for 90% of the energy cost at IADC, we estimated the potential site energy savings to be in the range of $500,000 to $2 million annually, corresponding to a 5% to 15% electric energy savings, respectively.[13] This top level understanding of savings potential allows management to prioritize the importance of energy efficiency efforts relative to other initiatives in terms of how much time and resources to commit. Note that there is a significant range in savings potential because the outcome is highly dependent on successfully engaging stakeholders in the process, as depicted in Figure 11. The vision also creates an expectation for success.

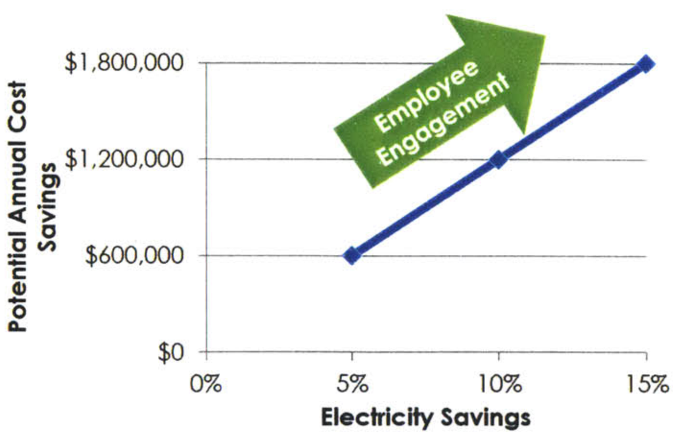


Figure 11: Potential IADC annual cost savings as a function of electricity savings

[13] EnerNOC, an supplier of energy management services and technology offers to reduce total addressable energy spend by 15% by identifying low-cost or no-cost opportunities. (11)

4.2 Commit

By followed the methodology outlined in 3.2 for earning buy-in in the pilot area, I was able to identify critical stakeholders, as shown in Figure 12, as well as the decision making unit and the decision making process.

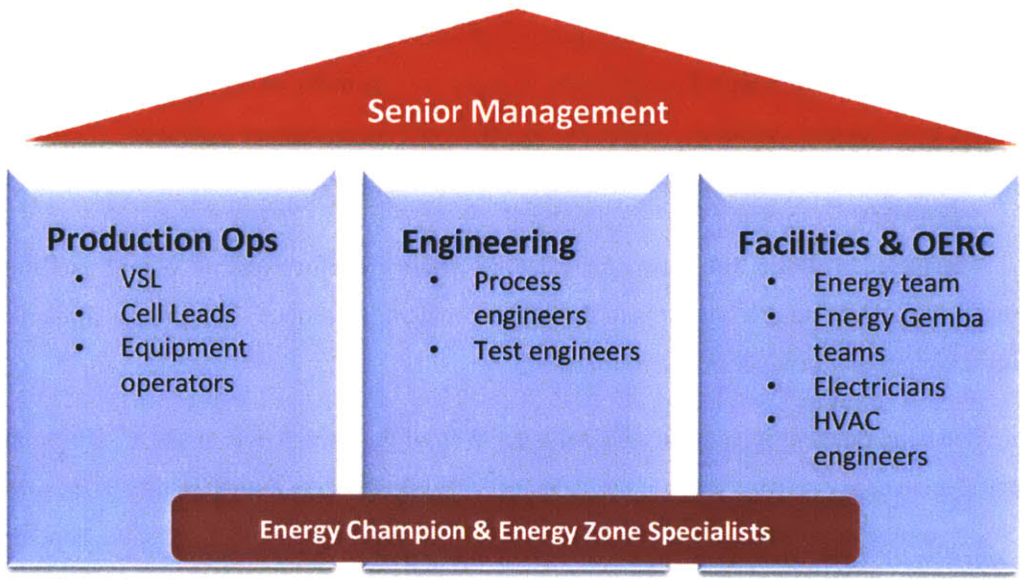


Figure 12: Key stakeholders in the IADC pilot production area energy efficiency project

Additional details on how the key stakeholders are involved in the process of production energy efficiency improvement are as follows:

- *Senior management* – Managers, directors, and VP of operations, engineering, and facilities are influenced by bottom line cost savings. Energy in the IADC facility is aggregated in an overhead budget. The group of senior managers has direct responsibility over these costs and has the ability to set, prioritize and flow down operations performance goals.

- *Value stream leaders* – Production areas at IADC are divided into "value streams", each of which is managed by a "value stream leader" (VSL). The VSL is a middle manager who generally physically sits in the production area he or she is responsible for, oversees day to day operations, and reports up to senior management. VSLs have decision making authority in their production areas regarding interruptions to production or changes in equipment run rules. They directly manage cell leads in their areas.

- *Cell leads* – There are generally several cell leads per value stream, depending on the number of operations and people in the area. Cell leads manage equipment operators and are well in tune with the production processes and schedules. While cell leads do not have authority to make decisions about process changes, they have tactical responsibility over production processes, and are critical in the implementation and sustainment of new or modified processes.

- *Equipment operators* – Operators are the front-line workers, who generally have very good knowledge of equipment and processes. The operators are union represented employees and are ultimately the ones turning the equipment on and off during regular operation.

- *Engineering stakeholders* – Process and test engineers in a value stream directly report to engineering senior managers, but have dotted line responsibility to the area VSL. As the designers of processes, tests, and much of the equipment involved, the engineers are consulted by the VSL regarding changes to processes or equipment run rules. The engineers generally have insight into whether a proposed modification will affect the product quality, the longevity of the equipment, or the safety of the operators.

- *Facilities* – As mentioned in 2.2.2, much of the energy management responsibility resides with the Enterprise Energy Team (EET), which is a part of facilities. The electrician trade union, required for the installation and removal of metering equipment, also fall under the facilities organization. Facilities personnel also manage building air condition, lighting, compressed air, and process water along with installed energy meters. Facilities management overseas the site energy budget.

- *OERC* - The Operations Excellence Research Center (OERC), as mentioned, is the group driving the lean initiative at IADC. They interact with all production operations areas through kaizen events and the Lean Games. They are leading the Energy Gemba Walk initiative, which will be discussed in the "achieve" phase of this thesis.

- *Energy Champions and Energy Zone Specialists* – Energy Champions are an existing group of employees from operations and engineering functions around the facility who are given responsibility to lead energy efficiency efforts in their production areas. Energy Zone Specialists do not exist in the current state at IADC, but are intended to be individuals who are knowledgeable of and responsible for particularly high energy intensive equipment (e.g., a group of thermal chambers), and who interact with the equipment on a daily basis. The term comes from the role of Safety Zone Specialist, which does exist at IADC, and performs a similar duty with a focus on safety.

4.3 Prioritize

Raytheon's building management system (BMS) is sophisticated enough to provide top-level data on how energy is consumed in the plant. As mentioned, there are ten electric sub-stations in the plant, each of which is monitored by Schneider Electric energy meters. Furthermore, the air conditioning (A/C) and lighting loads are independently monitored, allowing the main building support loads to be separated from production loads. The pilot project consisted of production area in a single electric substation. The 2010 electric energy consumption breakdown in the pilot area is given in Figure 13. About 85% of the electric energy in the substation was consumed in 2010 by production energy, and in 2011 the pilot area production equipment was on pace to exceed a half a million dollars in electric energy.

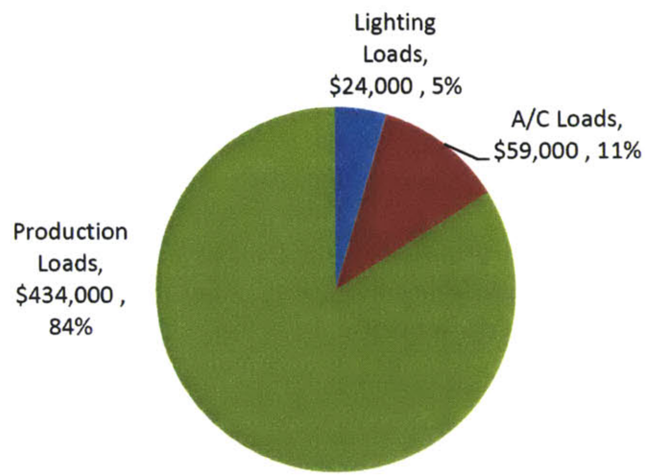


Figure 13: Pilot area 2011 electric energy consumption

Air conditioning and lighting consume the remaining 15% of the electric energy, and therefore were not the priority for this thesis. However, air conditioning and lighting combined still costs $83,000 per year, and if improvement opportunities presented themselves, they should not be overlooked. As mentioned above, improvements to building support loads can be easier to implement because they generally do not impact production processes.

The pilot area heating system is fueled by natural gas, and the annual heating bill is approximately $5,000. Because the natural gas bill is less than 1% of the total energy bill, the heating system, and natural gas use in general, was not a priority for this thesis.

Given the potential timing and hurdle rate barriers associated with capital intensive projects, this thesis project focuses on finding no or low-cost energy efficiency improvement opportunities.

4.4 Characterize

4.4.1 Mapping Energy Waste

Following the methodology for identifying equipment with significant electric energy waste, a select set of loads were identified to measure. Other loads were measured in previous efforts or are continuously monitored on the IADC energy monitoring system. The estimated energy consumption of these loads was plotted in a Pareto chart, as shown in Figure 14.

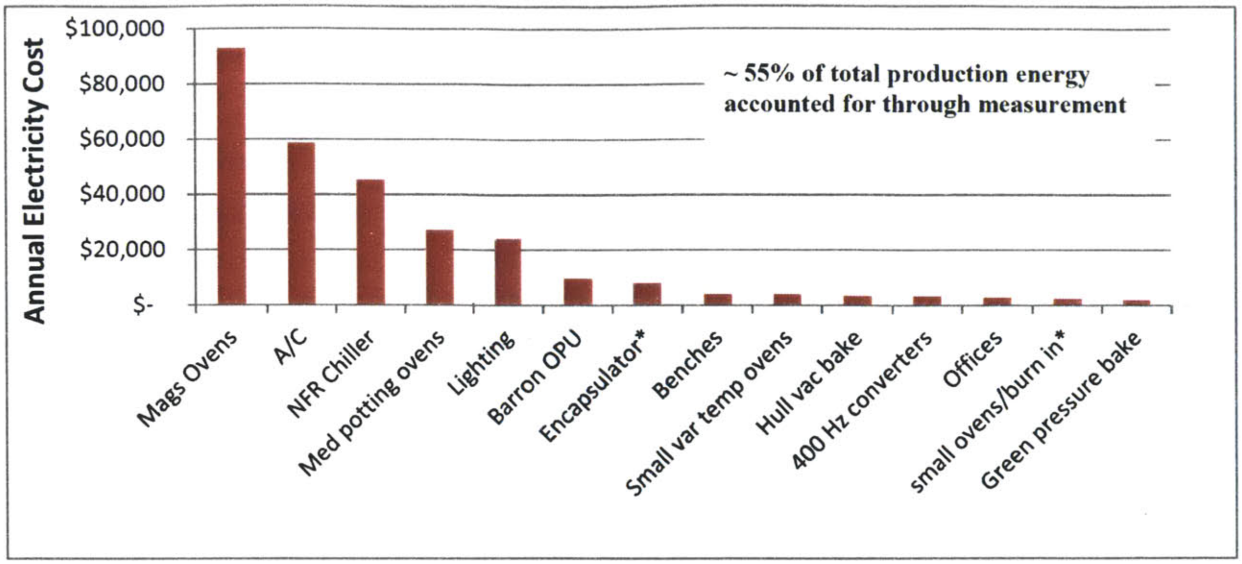


Figure 14: Pareto chart of major electric loads in the pilot production area.

The 14 loads or load groups in the pareto plot account for approximately 55% of the total energy consumed in the pilot area, highlighting the benefit of strategically selecting which equipment (of the hundreds of devices) to take the time to measure. Also of note is that approximately 30% of the total energy is consumed by thermal chambers, as shown in Figure 15, and therefore thermal equipment was a focus for the improvement effort.

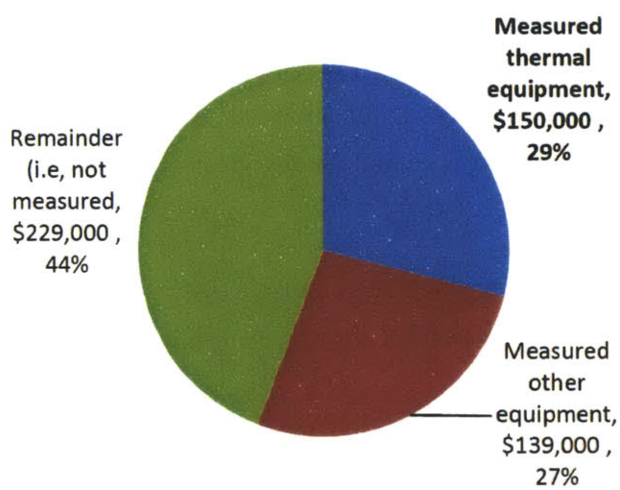


Figure 15: Thermal equipment accounts for about 30% of the energy consumption in the pilot area

4.4.2 Improvement Opportunity Characterization

A simple "who, what, when, why, and how" approach was taken to characterize improvement opportunities, as was described in 3.4.2. Figure 16 again shows the three lens approach to analyzing energy efficiency improvement opportunities, described in 3.4.2.

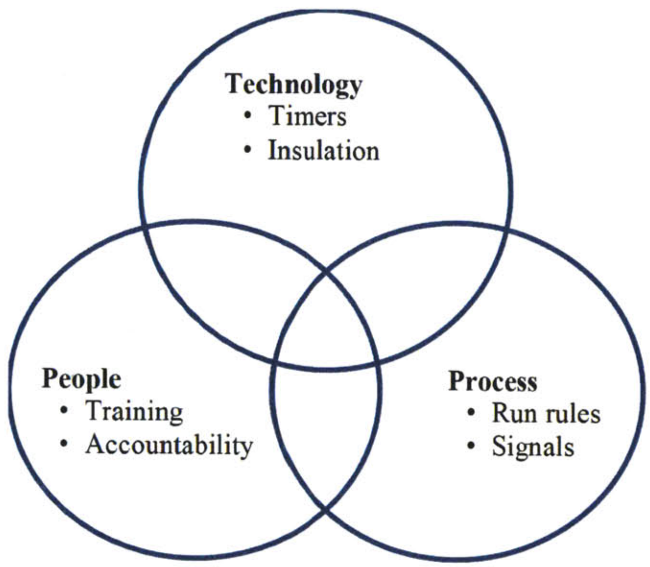


Figure 16: Three-lens approach to characterizing improvement opportunities

Table 5 lists the improvement opportunities that were identified in the pilot production area. Progress towards completion of opportunities is also given in Table 5. A simple numerical tracking system is shown where:

- 0 - the opportunity has not been addressed
- 1 – Progress made with a positive outlook, completion needed
- 2 – Implementation complete, sustainment needed

An 'x' indicates that the opportunity was explored but the attempt was not successful or infeasible

Table 5: Improvement characterization and tracking for a select set of production equipment

Process Equipment	Opportunity						Expected Savings/yr
	People	Completion Level	Process	Completion Level	Technology	Completion Level	
	Training on shut down procedures and run-rules	1	Shut down heating elements whenever possible	1	Add timers to heating elements	2	
	Training on timers	1	Shut off circulation fan and vent fans when empty always	1			
Vacuum Bake Chambers	Assign accountability on 1^{st} and 2^{nd} shift	2	Add shutdown process signs	2			$40,000
Barron Oil Processing Unit	Add hose split to remove filling bottleneck	0	Turn off or down on weekends	0	Insulate hot surfaces	2	$7,500
	Assign responsibility		Turn off after testing				
	Shutdown training						
400 Hz Frequency Converters	Grant access to generator room	x		x			$2,700
	Train operators on use of timers	1	Use timers that are currently installed	1			
Potting Ovens and Variable Temp Assembly Ovens	Assign 1st and 2nd shift responsibility for shutting down at the end of shifts and for weekends	2	Use smaller variable temp assembly ovens first	0			$1,500
Green Pressure Cure Tanks	Assign 1st and 2nd shift responsibility for shutting down at the end of shifts and for weekends	2	Can heat be turned off or reduced when not in use	2	Insulate hot surfaces	2	$1,250
Hull Vacuum Bake Chamber			Turn off or down on weekends	1	Insulate hot surfaces	2	$750
CWI Test	Train operators on use of dampers	0			Add dampers to vents	1	Gas energy
Air Conditioners			Adjust startup and shutdown times to correspond with production	2			$6,000
Assembly Exhaust			Close hoods and bench exhaust valves	0	VFD on vent fan on roof	0	A/C and vent fan energy

4.5 Improve

The purpose of this section is to provide specific results for improvement projects identified in the pilot area to demonstrate the energy management framework. As has been discussed, the pilot area is different from each of the other production areas in the IADC facility in terms equipment types and processes, not to mention other facilities and other industries. Therefore, these results can be considered as cases for how the general methodology can be applied to manufacturing environments, but cannot be applied universally.

4.5.1 Technology Improvements

4.5.1.1 Insulation

An oil processing unit (OPU), shown in Figure 17, maintains the level of oil quality needed for products and operates essentially 24 hours per day, seven days per week. The outer surfaces of the equipment were measured to be between 125°F to 150°F. This indicates that there is a significant amount of heat loss to the environment, which is about 70°F. Furthermore, as mentioned, this adds an additional burden on the air condition system during the cooling season in order to keep the indoor building condition at a comfortable level. Insulation could significantly reduce the heat loss, and therefore, the energy consumption of the OPU, but in order to justify the capital expense (material and labor), an economic case was developed.

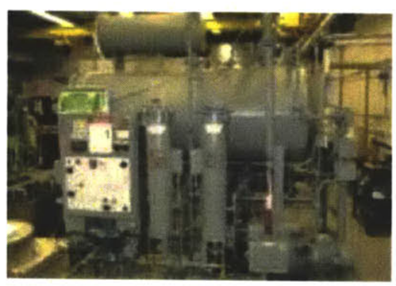


Figure 17: Oil processing unit (OPU) in the pilot area was identified as an opportunity for insulation

The energy consuming components of the OPU are heaters, which cycle to maintain the oil at the proper temperature, and pumps and controls, which operate continuously while the equipment is on. The real energy consumption of the OPU was monitored for about a week. One data point every five seconds was enough to accurate capture the cycling of the heaters.

Nearly all of the electric energy consumed by the OPU is lost as heat to the environment since there is no ventilation. Complex heat transfer equations and modeling would be needed to accurately model the heat transfer to the environment, but using a few simple calculations, we can get a quick estimate of whether or not a business case can be made for insulation. The simplified equation for convection heat transfer is as follows:

$$Q = hA(T_s - T_a) \ , \qquad \textbf{(Equation 2)}$$

Where Q is the heat loss to the environment, h is the effective heat transfer coefficient, A is the surface area of the OPU, T_s is the surface temperature of the OPU, and T_a is the ambient temperature of the work area. Given the measured heat loss, an estimated surface area of 12 square meters, an average surface temperature of 130°F (54°C), and a measured ambient temperature of 70°F (21°C), the effective heat transfer coefficient was calculated to be about 22 W/m^2-K.

By adding an inch of Armacell Armaflex insulation, it was approximated that the average surface temperature can be reduced to approximately 90°F (32°C).[14] Assuming that the heat transfer coefficient has not changed significantly, the expected heat transfer rate (energy loss) can be estimated for the insulated OPU to be 2 kW on average, or a 75% reduction from the uninsulated state.

Given an installation cost of $4,500 and the expected energy savings of $7,500, this project offers a payback period of eight months and a net present value (NPV) of approximately $35,000 over 10 years.[15] The application of insulation to the hot surfaces of other equipment also offers attractive payback periods and potentially safety and/or operator comfort benefits.

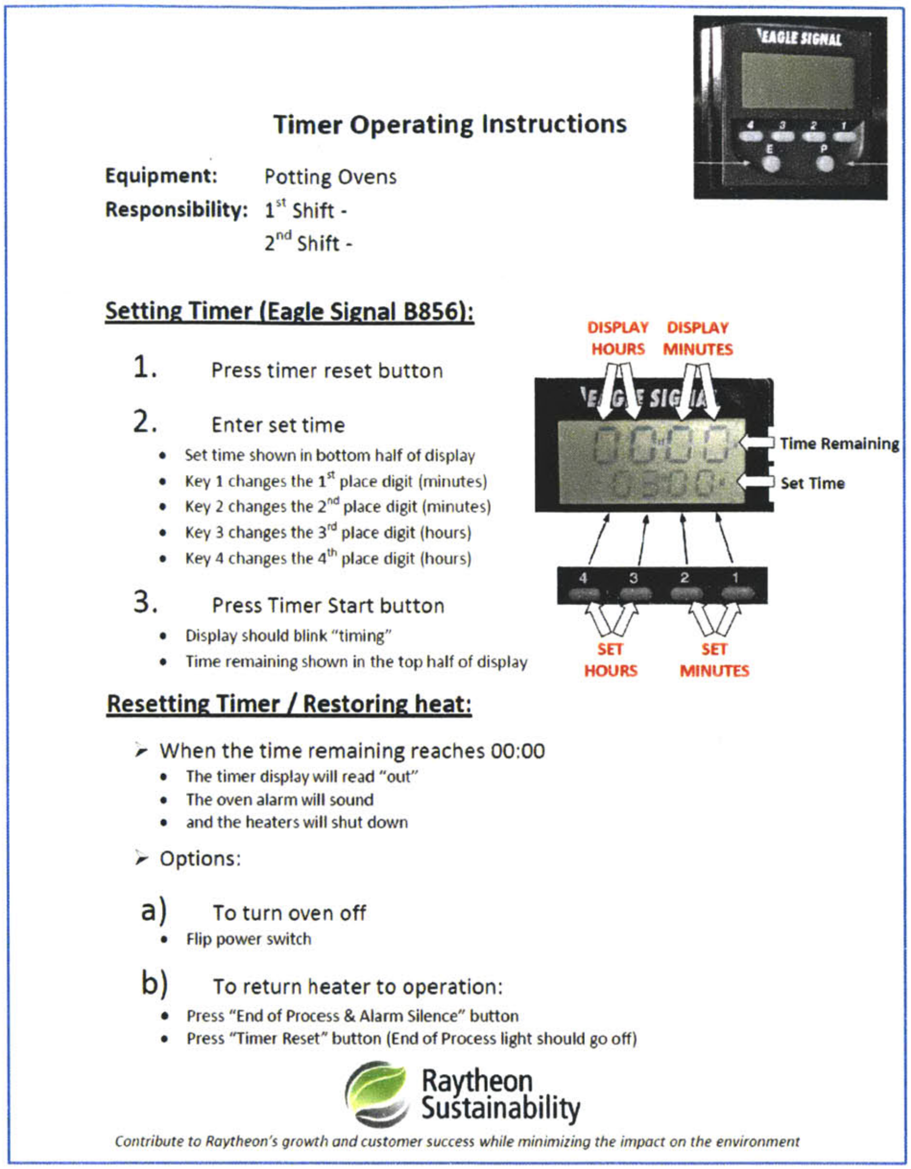
The economic case was very sound for this project. However, there was not currently a standard process for funding this type of project at IADC. The facilities department funds building infrastructure projects (e.g., walls, air-conditioning, plumping, etc), but they generally do not fund equipment related projects. It is up to the production area to manage the burden of equipment costs. However, in this case, the insulation was purely an energy savings project (i.e., it didn't affect production at all) and energy cost falls under the facilities overhead budget. So it is understandable that the production area did not want to cover the cost when the direct benefit was being captured in the facilities budget. The solution was to communicate this issue to the facilities and production area managers and recommend that the benefits be matched with the burden or risk, or in this case, that facilities cover the cost of the insulation project.

An advantage of insulation improvements under the "technology, process, and people" categorization is that they generally do not require the process and people components. Once the insulation has been installed, it is essentially "hands-off" and will generate energy savings year after year.

[14] Based on surface temperature measurements of insulated equipment with similar operating conditions.
[15] Discount rate of 15% assumed.

4.5.1.2 Timers

An example of a technology improvement that does require accompanying process and people components is the installation of timers on ovens. Oven timers can be used to automate the shutdown process on equipment. This can save significant energy when product oven cycles end during periods when operators are not present to shut the ovens off. For example, many products in the pilot area have specified minimum bake times, which means the quality of the products is not affected if they are left in the oven for longer than the specified time. Therefore, to increase productivity, products will be put in ovens at the end of the day or on Fridays, and will not be removed until the following day or week, after which they have been in the oven (and consumed more energy) than necessary. Instruction sheets were created and given to cell leaders to post on equipment and with which to train operators (as illustrated in Figure 18).



Timer Operating Instructions

Equipment: Potting Ovens
Responsibility: 1st Shift -
2nd Shift -

Setting Timer (Eagle Signal B856):

1. Press timer reset button
2. Enter set time
   - Set time shown in bottom half of display
   - Key 1 changes the 1st place digit (minutes)
   - Key 2 changes the 2nd place digit (minutes)
   - Key 3 changes the 3rd place digit (hours)
   - Key 4 changes the 4th place digit (hours)
3. Press Timer Start button
   - Display should blink "timing"
   - Time remaining shown in the top half of display

Resetting Timer / Restoring heat:

- When the time remaining reaches 00:00
  - The timer display will read "out"
  - The oven alarm will sound
  - and the heaters will shut down
- Options:

a) To turn oven off
   - Flip power switch

b) To return heater to operation:
   - Press "End of Process & Alarm Silence" button
   - Press "Timer Reset" button (End of Process light should go off)

Raytheon Sustainability

Contribute to Raytheon's growth and customer success while minimizing the impact on the environment

Figure 18: Example of an operating instruction sign for a new technology

Certain products at IADC need to be held at a certain temperature until they are moved to the next step in the process. For these products, timers for which the start time and the stop time can be set (not just the duration) will be most effective.

4.5.2 Process Improvements

4.5.2.1 Modifying equipment run-rules

Many of the opportunities identified involved modifying the run-rules for equipment, namely, when and how particularly energy intensive equipment can be shut down (or put in a reduced energy mode). Note that changing run-rules does not necessarily mean changing the production process, as mentioned in the methodology section. A change of a production process is generally much more complicated because it needs to be determined whether the change will impact the output or quality. Equipment run-rules can be modified without affecting the production process, and therefore generally can be achieved much more readily.

There are five large vacuum-bake chambers, called magnetics ovens, in the pilot area which, in aggregate, consume approximately $100,000 per year in electric energy. These chambers, pictured in Figure 19, have electric heating elements, vacuum pumps, fans for circulating air within the chamber, and fans for exhausting air out of the building.

Figure 19: Walk –in vacuum-bake chamber, five of which are located in the pilot area

These ovens have permanent energy monitors installed from past energy management projects, although at the time of this thesis the data was not being monitored or used. (12) The power draws of the ovens range from 30-40 kW, of which the heating elements, the vacuum pump, and the fans account for approximately 82%, 14%, and 4%, respectively.[16] At the time of the thesis project, there was not a standard practice for shutting down the chambers. The chamber vacuum pumps were intentionally left running continuously because of issues during restart in the past.[17] Even though each of the major system components (heat, pumps, fans) can be shut off independently, anecdotal and frequent visual inspections

[16] Electronic controls are assumed to be a negligible contribution to energy consumption.
[17] Based on discussions with pilot area engineers.

indicated that the entire system remained on most of the time, regardless of whether or not product is in the chamber.

The most obvious opportunity for energy savings is shutting down these chambers, or at least the heaters and fans, when they are not in use. Barriers to achieving energy savings in practice as well as countermeasures are given in Table 6.

Table 6: Causes of and countermeasures for the vacuum bake chambers not being shut down when not in use

Barriers: why are vacuum chambers not being shut down when not in use?	Countermeasures
1. There was a general lack of awareness about how much the equipment costs to operate (since no one in the production area ever sees the energy bill) and the perception that the cost of energy is cheap relative to the cost of the product	• Measurement and communication to VSL, cell leads, and operators
2. Lack of accountability and/or fear that someone has it on for a reason	• Signage with designated equipment owners (see Figure 20)
3. Perception that it takes a long time to preheat	• Measurement (25 mins) and comparison to product cycle times (12-72 hours) and typical advanced notice and required prep times
4. Perception that it takes more energy to reheat than to sustain the operating temperature	• Measurement clearly showing that this is not the case and communication
5. Perception that the vacuum pump needed to be kept on at all time to avoid equipment failure	• Unclear whether this perception is true, but it more important to communicate that the heat, which consumes 82% of the energy, and the fans can be shut off independently
6. No one on second shift felt that they had the authority to shut down the ovens	• Established a second shift equipment owner and provided training on equipment run rules

IADC already had a practice of using green "equipment up" signs that provide a visual signal that a piece of equipment is operational (note that the flip side of the sign is a red "equipment down" sign). Previous energy conservation efforts have incorporated information about when the equipment should be shut down into these signs, as shown in Figure 20. These "energy up signs" were posted on much, but not all, of the equipment in the pilot area. Notably, all of the large ovens lacked this signage.

In addition to posting "energy up signs," we addressed barriers 2 and 6 (accountability) from Table 6 by added the "Equipment Responsibility" box to the signs, allowing production areas to assign equipment owners for each of the relevant production shifts. Responsibility for updating, maintaining, and posting these signs was given to the cell leads and the area energy champion.

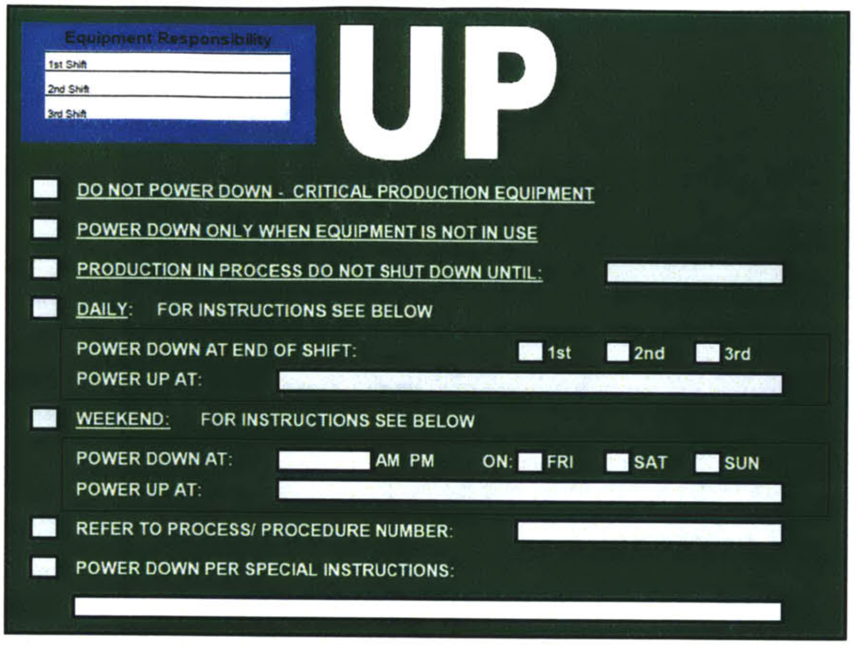


Figure 20: Standard IADC energy "equipment up" signs were modified to include equipment responsibility

The green energy up signs provide information about who and when equipment should be shut down, but does not provide information on how to shut the equipment off. In some cases, like the vacuum bake chambers, the procedure is more than simply flipping an on/off switch, since it was decided that the vacuum pumps needed to remain on. We generated signs to provide the information to switch the equipment into an "idle" mode, as illustrated in Figure 21. The sign gives ownership to the process, provides simple process steps, and also provides information on how long it will take the equipment to come back to operating condition. The sign as a control document number in the upper left corner so that the electronic version of the document can be tracked and maintained. Finally, in an effort to mistake-proof the process, green circles with numbers corresponding to the process step were posted on the appropriate system controls on the equipment.

<Document control number>

Equipment Idle Procedure[i]

Equipment: Vacuum Bake Chamber (Oven A)

Responsibility: 1st Shift:
2nd Shift:

Switch to Idle: (when oven is empty)

1. Switch off "heat enable"
2. Switch off "exhaust" fan
3. Switch off "circulation" fan

Reheat: (requires 25 minutes from room temperature to 212°F)

3. Switch on "circulation" fan
2. Switch on "exhaust" fan
1. Switch on "heat enable"

[i] Does not replace full shutdown procedure; see full shutdown documentation for instructions

Raytheon Sustainability

Contribute to Raytheon's growth and customer success, while minimizing the impact on the environment

Figure 21: Example of an idle procedure created and posted on equipment for the purpose of saving energy

4.5.2.2 Matching air-conditioning and production schedules

While the focus of the thesis was on production loads, one opportunity that was identified involved the air-conditioning system (a building support load). During the cooling season, building air conditioning systems typically come on prior to the building being occupied so that the indoor air can be brought to a comfortable condition when the building occupants arrive. From an energy perspective, you want the air-conditioning system to come on only early enough so that comfortable conditions are achieved just as the "typical" work day begins.[18] At IADC the "typical" work day varies depending on how many production shifts are run. In the pilot area, the typical production schedule is two shifts, five days per week.

It was found that the air-conditioning schedule was matched fairly well with the two-shift production schedule during the work week, but that the A/C was coming on about 12 hours before the 6:00 am start time on Monday morning. Only about three hours were needed to pre-cool the building, and by shifting the air-conditioning schedule to better match the production schedule on Monday morning, about 10% of the A/C energy was saved. This will amount to about $6,000 saved annually based on 2011 operating and weather conditions.

4.6 Achieve

4.6.1 Summary of results

The implementation, or improvement, phase of the pilot project occurred during October and November of 2011. During the improvement phase, the production energy was 18% lower than the average monthly production energy from January through September. These savings were measured at the aggregate level in the pilot area, and therefore include savings from all production equipment in the production area, including the equipment specified in Table 5. Since production levels vary in this environment, it's also important to note that the production output (called "earned standards") was up 18% during the improvement phase, and the total labor hours was up 11%. The product mix could also impact the results, but during 2011, the mix of product output in the pilot area was relatively constant.

In summary, output and value created was up during the two month improvement phase while energy consumption was down, providing strong evidence that the energy efficiency of the production processes has been improved. If sustained, these pilot area improvements will save $74,000 per year. This includes projected savings of $6,000 in air-conditioning, which will be realized in the summer months, and $8,000 in savings from insulation of thermal equipment, which was completed at the very end of the thesis project.

[18] Note that in some cases pre-cooling can make economic sense if the outdoor temperature and humidity changes substantially during the pre-cool period, since air-conditioning systems become less efficient as the outdoor temperature and humidity rises.

4.6.2 Performance metrics

As described in the methodology section, the achieve phase is focused on sustaining results and facilitating continuous improvement. The implementation of energy performance metrics will be a key factor in sustaining energy efficiency improvements and driving continuous improvement. The behavior of production leaders (VSLs and cell leads) is already driven by performance metrics that influence production schedule, budget, quality, and safety. Metrics allow management to rate and rank performance, provide incentives, and set progressive goals over time. The energy team has proposed and begun to implement an energy performance metric that compiles performance scores from:

- energy efficiency metric based on energy data (i.e., Sunday off-hour energy)
- Best practice scorecard
- Self-assessments
- Energy Citizens

A dashboard tool is being set up using the existing Virtual Business System (VBS) toolbox, which will allow production areas to see their performance, track opportunities, and share best practices.

4.6.2.1 Energy efficiency metric based on energy data

As discussed in 3.6.1, energy consumption metrics may need to be normalized for production volumes to provide the right incentive. For example, you don't want an energy metric that can't be met because production volume, which is good for the business, increases. I ran a linear regression model on the monthly production energy consumption over the last 24 months, using standards and labor hours as regressors. The intention was to develop a correlation between the level of production output and the total time spent by operators in the facility and the production energy consumed. Such a correlation might be as follows:

$$\boldsymbol{Energy = A + B \times Standards + C \times Labor\ hours,} \qquad \textbf{(Equation 3)}$$

Where production energy is the output; A, B, and C are constants determined by the regression model, and standards and labor hours are variable inputs to the equation.

The results of the regression modeling, described in Appendix A, show that there is not a statistically significant correlation between standards and production energy. The correlation between labor hours and production energy was stronger, but still was not a great predictor of how much production energy will be consumed. Particularly, when the goal is relatively low percentage improvements in energy consumption (e.g., about 10%), the uncertainty of the correlation is too high to use as a performance metric.

A second way to normalize energy consumption for production is to look at off-shift periods when production is not happening. For example, for many areas including the pilot areas, production is down on Sundays. The idea here is that if equipment is not being used on Sundays, it should be getting shut down. If the metric influences production areas to shut down equipment before they leave for weekends, this mentality would likely carry over to weekdays. The Sunday energy consumption for the pilot area is plotted in Figure 22. Notice that during the improvement phase of the pilot project (October and November) the average energy consumption on Sundays was down 25%.

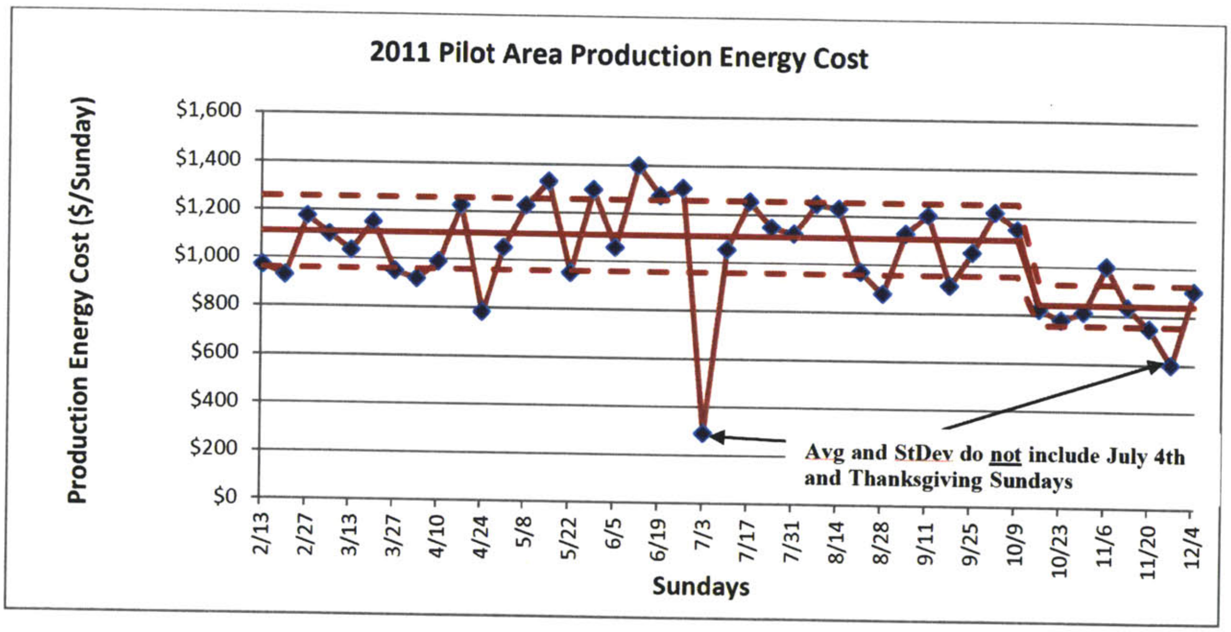


Figure 22: Sunday production energy consumption for the pilot area

Unfortunately, this is not a perfect metric either because production areas like the pilot area may, for example, have product in long vacuum bake cycles over the weekends even though operators are not on-site.

There is another issue with efficiency metrics in production environments like that of the pilot area, and common throughout the IADC facility. In the pilot area, there are a significant number of batch processes (e.g., ovens that can hold a number of products at once). Therefore, if production volumes increase, the ovens may be more full, but use the same amount of energy as they would with a single product. While filling ovens is a more efficient use of energy, if it is production volumes alone, and not operator discretion or process standards, that drives oven batching, then the energy efficiency will not be sustained. As soon as production volumes go down, the efficiency will go down. Therefore, a simple efficiency metric may give a false impression of sustainable efficiency improvement during periods of increasing production.

To counter this phenomenon, a series of energy "best practices" were developed to measure proactive involvement in energy improvement.

4.6.2.2 Best practices

We developed best practices to support the energy metric to counter some of the deficiencies discussed above. Best practices also give production specific pro-active tasks that they can use to improve their energy performance. The best practices are developed by the energy gemba teams as they carry out gemba walks throughout the facility, and are intended to be general enough that they are applicable to many of the production areas at IADC. Specific criteria are given for how to achieve the best practices, and are given in Table 7.

Table 7: Energy best practices, scoring criteria, and example scoring

Best Practices	Score (1-5)	Criteria
Engaged energy champion	4	Maintains current projects or initiatives, assigns energy zone specialists, tracks opportunities, leads energy Kaizens
Equipment energy signage and power down documentation	4	Shutdown processes in place (when, how, who)
Automation of equipment shutdown and startup	3	Timers, sensors installed and used on equipment where feasible
Energy efficient process related ventilation and exhaust	2	VFD, hoodless vents, process in place for closing hoods and bench exhaust, responsibility assigned
Lighting and HVAC schedule matched to production schedule	5	Communicate work schedule to facilities
Process for energy in new/replacement equipment purchases	1	Process for evaluating Insulation, right sizing, automatic shut-off
Efficient use of compressed air	n/a	Process for leak detection and repair
Insulation of equipment and infrastructure	4	Minimal uninsulated hot and cold surfaces
Engaged workforce	3	Leadership Standard Work, assigned equipment responsibility, self-assessments, idea generation
Engage VSL and Cell Leads	3	VSL and cell leads participate in Gemba walks, conduct self-assessments, are energy zone specialists, report progress, manage energy projects, update process signs
Perform process analysis	2	Batching, Lean pull processes, right sizing equipment and capacity
Average Score	3	Green >= 4, 4 > Yellow >= 3, Red < 3
% of total points possible	62%	Green >= 80%, 80% > Yellow >= 60%, Red < 60%

Figure 23: Energy best practices list with scoring criteria and example scoring

A "stop light" color scheme (red is bad, yellow is borderline, and green is good) is used for the other operations performance metrics, and therefore is recommended for use with the energy metrics as well. The color code provides a simple visual indication of performance, even without a perfect understanding of the specifics of the targets.

4.6.2.3 Self-assessments and Energy Citizens

The IADC VBS currently offers an energy audit tool as well as a tool for tracking Energy Citizens. The energy audit tool allows production areas to assess their work spaces and record instances of equipment being left on. However, the audit tool is currently self-initiated and self-regulated, and is only routinely used by one production area. It is not currently used to set performance goals. The Energy Citizens is a current awareness program in which VBS tracks the percent of employees from each production area who have completed the Energy Citizens questionnaire. This tool is a simple method of showing employees that IADC is serious about energy conservation, and for employees to make a public commitment to joining the effort, but it is difficult to say how it has impacted actual energy use.

The new energy dashboard will integrate the existing tools that have been developed into a single location. Also, the energy audits tool will be transitioned into a best practice self-assessment tool. Production areas will be incentivized to continuously review and improve their performance on the best-practices, which are what will be used in the performance metrics and reviewed during energy gemba walks (discussed in Section 4.6.4). You could equate this to studying the material that you know is going to show up on an exam.

4.6.2.4 Rolling up performance into a single metric

The VBS dashboard will be used to track the performance of each of the above parameters and will be used to roll-up the scores into a single performance metric. Having a single energy performance metric is a good way for management to get easy insight into how the many production areas are doing against their operations performance goals. They can then drill down into the details in areas where there might be issues or exceptional performance. An example of how the performance scores can be rolled up into a single performance metric is given in Table 8. The combined energy score is a weighted average of the four described energy components.

Table 8: Performance metric roll-up

Metric	Weight	ECO Score	Notes	Subtotal
Off-hours Energy	20%	100%	Assumes goal set at 10% reduction and 25% achieved	20%
Best Practices	40%	62%	Calculated in Table 7	25%
Self Assessments	30%	75%	Assumed 75% completion of assigned assessments	23%
Energy Citizens	10%	75%	Assumed 75% completion of Energy Citizens questionnaire among employees	8%
Performance Score	Green >= 80%, 80% > Yellow >= 60%, Red < 60%			**74%**

The weights are assigned subjectively based on the level of influence the metric would have on achieving energy savings. The Energy Citizens program has been active at IADC for several years, and while it does inspire some level of commitment, it has not generated measureable energy savings and therefore is given a lower weight. The off-hours energy metric is weighted at 20% because there may be production related reasons why the energy consumption varies on Sundays, for example. If more specific monitoring is installed or a valid energy efficiency term is developed, then the weight for the monitored energy portion of the metric could increase.

4.6.3 Incentives

Performance metrics enable incentives to be put in place upon achievement of certain levels of performance. Incentives can take the form of either rewards or punishment (commonly referred to as "carrots" or "sticks", respectively). Both can incentivize a certain type of behavior, but for a new initiative, I believe that to create an environment of learning from failure, it is better to focus on rewarding good performance rather than punishing poor performance. At IADC, the stigma of having a "red" performance metric offers a form of punishment anyway.

I discussed how the cost accounting at IADC steers production managers away from investing time and resources (i.e., taking on risk) to save energy cost. Energy is an overhead cost, and therefore is not directly "seen" by production area managers. However, NPV positive projects exist with no or low upfront cost. In order to capture this value for the company, incentives should be offered at a level that will drive action.

There is an existing channel for rewarding outstanding performance. Individual cash rewards can be given for outstanding performance. I would recommend adding another channel for rewards in which production area managers (i.e., VSLs) receive rewards in the form of discretionary overhead budget. This reward can be used to fund tooling, training, or follow-on process or energy improvement projects. In this way, the rewards are being reinvested back into the company. These rewards are also targeted at the VSL level, where the decision making power lies regarding process changes in production areas.

The incentives should also be aimed at sustaining past results. For example the incentive structure might be set up as displayed in Table 9.

Table 9: Example incentive structure for sustained energy efficiency achievement

Parameter	2012	2013
Criteria 1: Energy Efficiency (Standard / Energy)	≥ 2011 Achieve Phase	≥ 2011 Achieve Phase
Criteria 2: Energy Best Practices Score	≥ 80%	≥ 90%
Recognition to production area	• Discretionary overhead award • Individual monetary awards	

4.6.4 Energy gemba walks

Gemba walks are a lean manufacturing tactic, discussed at length in Womack's book, "Gemba Walks", in which senior management dedicates time to walk the production floor, follow the value stream, and see what is going on. (13) This is a knowledge sharing tactic, and requires that senior management see first-hand how value flows through the production facility that they manage.

IADC derived its "safety gemba walks" from this concept, and senior operations managers walk the production floor to see with their own eyes the current state of safety in production. During the thesis project, the OERC kicked off "energy gemba walks," during which members from the OERC and the energy team walked around production areas (value streams) with the area value stream lead (VSL) and energy champion. The goal is to engage value stream leads and cell leads in assessing how their processes consume energy and work with them to identify energy waste and improvement opportunities. Figure 24 illustrates the energy gemba walk cycle.

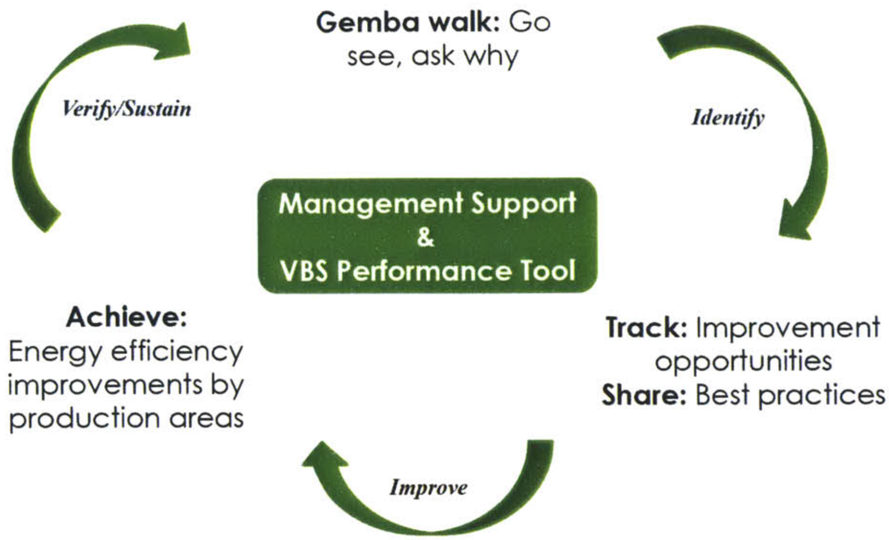


Figure 24: The energy gemba walk cycle

At the core of the energy gemba walk initiative is senior management support. While the gemba walks are targeted at the day-to-day managers of the production areas (the VSLs), senior management support for the effort will help keep the VSLs engaged in the practice. The energy gemba team presented the vision of energy gemba walks to the operations directors, who in term rolled out the practice to the production VSLs.

The vision for the gemba walks is that they will not only provide a method of sharing knowledge and identifying opportunities, but they will feed best practices and best practice scores into the energy performance metric. Since energy gemba teams will be engaged throughout the facility, they will be well suited for calibrating the best practice scores among production areas.

5 Discussion

This thesis presents a framework for achieving sustainable energy efficiency in manufacturing operations. The methodology was developed and tested in a pilot production area (or value stream) to provide validation in an appropriately sized environment as well as to discover barriers to achieving sustainable results.

Reducing direct production energy is very different than reducing support loads. Support loads can often be adjusted or replaced behind the scenes (i.e., without impacting production schedule or processes). On the other hand, reducing production energy requires full engagement of operations personnel to measure, analyze, and implement changes to processes to improve the way they consume energy. Like all organizational changes, there are critical strategic, political, and cultural components that need to be addressed to implement a sustainable change in the way work is conducted by "everybody, every day". The project focuses on developing a framework for achieving waste energy reduction in a sustainable way.

Common barriers to achieving energy efficiency in manufacturing operations are described in detail in Section 1.2, which were derived from literature as well as from observation during the pilot project. Again, the barriers identified are:

- Low awareness and/or engagement
- Elevated hurdle rate
- High perceived transaction cost
- Financial accounting for energy
- Diffuse energy loads
- Defining efficiency and measuring improvement

The framework for achieving energy efficiency follows the Raytheon Six Sigma method of process improvement, which is built on general process improvement and six sigma concepts and therefore is applicable to other industrial environments that are committed to achieving environmental responsibility and operations cost savings.

5.1 Applicability to Raytheon IADC

The goal of this project was to develop a framework for achieving sustainable cost reduction in production operations through energy efficiency. The project objective aligns with the vision that energy efficiency becomes part of the continuous improvement mentality at Raytheon to improve competitiveness and affordability.

The pilot area achieved savings that are projected to equate to $74,000 in annual energy cost savings, or about 15% of the addressed production energy. The energy savings potential throughout the IADC production facility may vary, but 10% energy savings would equate to approximately $1 million dollars in annual cost savings. This is analogous to achieving an increase of $13 million per year in revenue.[19] Also, since IADC accounts for about 50% of the IDS business energy consumption, reducing production energy consumption will go a long way towards achieving the Raytheon corporate goal of achieving 10% greenhouse gas reduction by 2015.

5.1.1 Execution Strategy

IADC is an industry leader in both energy management and environmental responsibility. Not only have they set and achieved aggressive energy reduction goals, they are also working towards a zero waste goal at the facility. However, despite past success, IADC will continue to face challenges and barriers to achieving continuous improvement in energy efficiency. The barriers identified in Section 1.2 are all evident to some degree in the IADC facility, particularly with respect to achieving energy reduction of production equipment.

As discussed, the production loads at IADC are diffuse, meaning there are many unique pieces of equipment spread out across the facility. In general, this means that IADC can't simply focus on a few high energy intensity loads, nor can they afford to ignore the importance of total employee engagement.

Specific next steps for Raytheon IADC are as follows:

- I recommend that the IDS energy team applies the framework to each of the IADC production areas, with the ultimate goal of achieving 5% to 15% energy savings, or $0.6 - $1.8 million annually, within a 1-2 year time frame.
- The energy and lean teams incorporate the energy metrics into the existing operations performance metrics system and test them on the pilot production area. Discretionary overhead and individual rewards can be offered to incentivize sustained achievement.

To support these near-term activities as well as to ensure long-term success of this initiative, IADC will need continued senior management support, to build employee engagement and accountability, and to continue to use the framework developed to support sustainable success.

5.1.2 Senior management support

The importance of senior management support is not a novel discovery in this project. Literature on continuous improvement shows consensus that the efforts and initiatives in which senior leaders are

[19] Assuming the corporate net profit margin of 7.6%

engaged will obtain better engagement at lower employee levels. Energy costs are commonly buried in facility overhead costs, which are not directly visible to mid-level production managers, but directly impact the net income of the facility. Bottom line cost savings influence senior managers, who have the ability to set, prioritize, and flow down operations goals to production managers.

Senior leaders also shape the culture of an organization. Large and mature organizations run the risk of creating a shared mentality of not disrupting the "way things have always been done." This type of mentality creates an organization that avoids change, and can create a significant barrier to any continuous improvement initiative. Senior managers at IADC support continuous improvement and commonly refer to the shared mentality of "everybody, every day." This mantra promotes a culture of total employee engagement and a relentless pursuit of improvement. This same philosophy needs to be applied to the energy efficiency initiative.

5.1.3 Promote engagement, accountability, and a culture accepting of change

Senior management support, described above, will provide the foundation for total employee engagement. Ideally, IADC would like all its employees to understand how their work consumes energy and to create a mindset of energy efficiency. If energy efficiency becomes part of the everyday mindset, it will not be a burden, it will simply be the way work is done. The energy efficiency framework is designed to help stakeholders learn to identify energy waste in their work areas, and give them a process for improvement. Beyond engagement, the framework is also designed to assign accountability so that all stakeholders know what their objectives are and are responsible for achieving those objectives.

5.1.4 An iterative, process driven approach

With a facility of engaged and accountable stakeholders who are supported and monitored by senior leaders, a set of data-driven processes and an iterative approach will provide a standard set of tools with which to make improvements and share knowledge.

Like lean and other continuous improvement methodologies, the energy efficiency framework is intended to provide a set of processes for achieving results. Furthermore, an iterative approach needs to be taken in order to sustain results and realize continuous improvement. Since the Enterprise Energy Team at IDS has limited capacity, the team will need to lead the process in production areas that have been divided into manageable pieces. "Value streams" are production areas at IADC that are managed by a "value stream leader." This is a mid-level operations manager who oversees the day-to-day operations in the value stream, and has the decision making power over process changes and equipment usage. Therefore, I recommend that the facility be broken up at the value stream level. Beyond the process iterations around the facility led by the EET, value stream stakeholders need to be following an iterative process in their own work areas. I recommend that energy gemba walks be used to facilitate this iterative approach, score production area performance against a best practice scorecard, and create and share best practices among production areas.

5.2 Application to Industry in General

The United States consumed approximately 100 quads[20] of energy in 2011 valued at about $13 trillion. (1) The industrial sector consumed 31% of the total U.S. energy in 2010, and is the sector that is targeted in this thesis project.

The motivation behind industrial energy management can be framed in three main ways: as an environmental imperative, as a national security issue, and/or as a way to improve operational efficiency. Each provides valid support for developing an energy management initiative, but I would recommend that the energy management vision be created such that it most resonates with the business or operations strategy of the facility or facilities of interest.

The framework methodology described in Section 3 is intended to be general enough that it can be applied across a broad set of different production areas across different industries, but specific enough to provide prescriptive guidance and examples on how to achieve results. The methodology was developed in the context of the manufacturing environment at IADC, which is a "high mix, low volume" production environment that consumes mostly electric energy. I have observed that the product flow in this environment makes it difficult to establish simple, transparent energy efficiency metrics. Similar manufacturing environments can use the same process to design performance metrics, but the metrics should be customized for the unique production environment. High-volume production and environments with single-piece flow may lend themselves to more simple energy efficiency metrics. The addition of a best practice score-card provides day-to-day operations managers with specific pro-active actions that they can take to improve their energy performance.

Facilities with highly centralized energy use or facilities that consume energy in other forms (e.g., gas, fuel) can still benefit from the methodology presented in this thesis. The energy efficiency framework provides guidance on creating a vision, earning stakeholder commitment, prioritizing and characterizing opportunities using data, making improvements (to technologies, processes, and behaviors), and sustaining results. Furthermore, the methodology provides insights on identifying and mitigating key barriers to success. While the specific examples may be most relevant to manufacturing

[20] Quadrillion British thermal units

facilities similar to Raytheon IADC, general approach and methods are applicable in any industrial environment.

6 Appendix A: Regression modeling for performance metrics

Multi-linear regression modeling was used in an effort to create an energy efficiency performance metric that correlated energy consumption to production output. The goal was to be able to set target energy consumption levels for production areas that do not depend on the production level, which can vary significantly at IADC.

In the end, production energy consumption was found to be correlated to a production parameter (labor hours). However, the approach was not implemented in practice for two key reasons:

1. The energy reduction goals at IDS are generally in the range of 0-5%, and the uncertainty in the regression model is greater than this target range. The model is not accurate enough to set targets that could be used to fairly hold production managers accountable.
2. Resources are not available to further develop and maintain a regression modeling tool.

The regression analysis can be conducted with either JMP software or with the Data Analysis Toolpack add-in for Microsoft Excel. I looked at daily (or weekly) data for both production energy consumption as well as a number of available production parameters. It was important to use daily or weekly data to eliminate the variation caused by the different number of fiscal days and weeks per month. The production parameters available were:

- Actual hours – the number of total labor hours charged
- Tracked hours – the number of budgeted labor hours allocated
- Earned standards – a metric (measured in hours) which directly relates to the value earned on products

I also broke down the above parameters by major product type (of which there were two) to try to capture the impact of product mix on energy consumption. The linear normal probability plot indicated that the data set was normally distributed. The linear regression indicates that the only statistically significant parameter in the model (95% confidence) is the total actual labor hours. After removing the other parameters from the model, the resulting model F-value is 0.01, indicating the model is significant with 99% confidence. The output of the model is shown graphically in Figure 25. The adjusted R^2 for the model is 27%, indicating that the accuracy of the model is not that good.

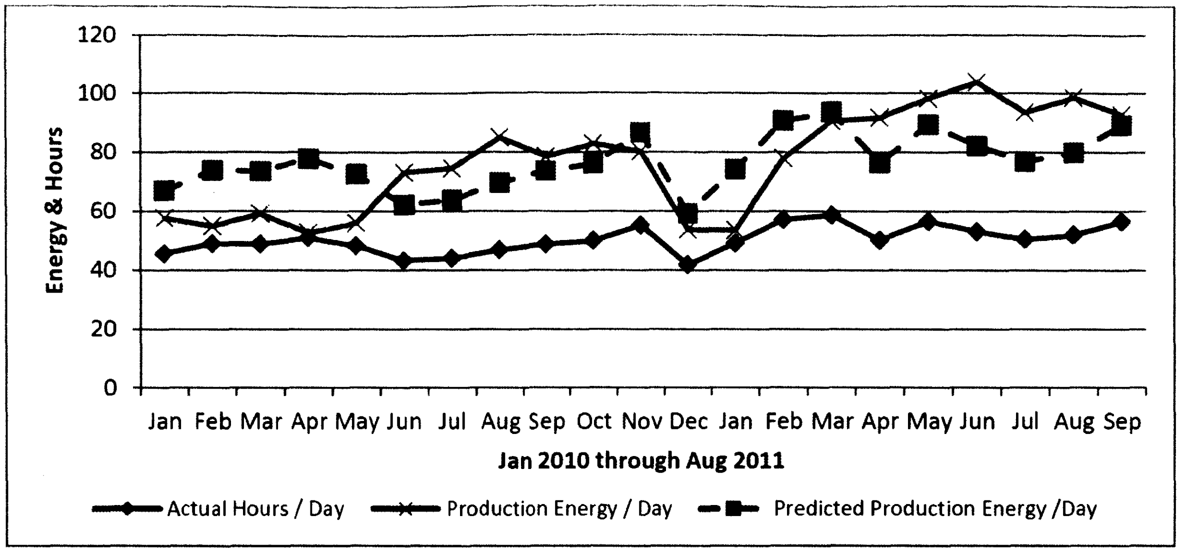


Figure 25: Regression model for production energy based on total labor hours

Intuitively, it makes sense that labor hours alone would not accurately explain production energy consumption because much of the equipment (e.g., ovens) runs overnight and on weekends even when workers are not charging hours.

Nonetheless, regression analysis can be a useful tool for creating performance metrics if the appropriate explanatory variables exist and data is available.

7 References

1. **Energy Information Association.** Energy Consumption by Sector and Source, United States. [Online] 2012.

2. **Energy Efficiency and Renewable Energy (EERE).** *Buildings Energy Data Book, Section 1.1.1.* March 2011. available at http://buildingsdatabook.eren.doe.gov/DataBooks.aspx.

3. **Energy Information Association (EIA).** *Annual Energy Outlook.* 2011.

4. **MIT Joint Program on the Science and Policy of Global Change.** [Online] http://globalchange.mit.edu/resources/gamble/.

5. **IPCC.** *Summary for Policymakers, in Climate Change 2007: Impacts, Adaptation and Vulnerability.* s.l. : Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmenetal Panel on Climate Change, 2007.

6. **McKinsey & Company.** *Unlocking Energy Efficiency in the U.S. Economy.* July 2009.

7. **Johnson Controls and the International Facility Management Association.** *Johnson Controls Energy Efficiency Indicator, North America.* 2008.

8. **Norelli, Michael.** *Reducing Energy Usage in a Manufacturing Facility through a Behavior Change Based Approach.* s.l. : MIT , 2010.

9. **Espindle, Leo.** *Process Management Principles for Increasing the Energy Efficiency of Manufacturing Operations.* June, 2011. Master's thesis, MIT.

10. **Schroeder, Mikel Harry and Richard.** *Six Sigma: The Breakthrough Management Strategy Revolutionizing The World's Top Corporations.* 2000.

11. **Energy Information Association.** *2006 Manufacturing Energy Consumption Survey.* 2009. Available at http://38.96.246.204/emeu/mecs/contents.html.

12. **International Organization for Standardization (ISO).** *ISO 50001: Energy Managment Standard.* 2011. available at http://www.iso.org/iso/iso_50001_energy.pdf. ISBN 978-92-67-10552-9.

13. **U.S. Environmental Protection Agency (EPA).** *Energy Star Guidelines for Energy Management .*

14. **U.S. Energy Efficiency and Renewable Energy (EERE).** *2010 Buildings Energy Data Book.* March, 2011.

15. **Raytheon.** *2010, Corporate Responsibility Report.*

16. **Littlefield, Mehul Shah and Mathew.** *Energy Intelligence: Creating Data Driven Efficiency.* s.l. : Aberdeen Group, 2010.

17. **Fine, Charles.** *Toyota Supplier Relations (A): Fixing the Suprima Chassis.* s.l. : MIT Sloan School of Management, February, 2008.

18. **Spear, Steven.** *The High-velocity Edge.* s.l. : McGraw Hill, 2009.

19. **Womack, J and Jones, D.** *Lean Thinking.* s.l. : Simon and Schuster, 1996.

20. **Ciadini, Robert.** *Influence: The Psychology of Persuasion.* 1993.

21. **Womack, James.** *Gemba Walks.* s.l. : Lean Enterprise Institute, 2011.

22. **EnerNOC.** http://www.enernoc.com/solutions/. [Online] January 2012. http://www.enernoc.com/solutions/.