**AN EVALUATION OF SOLAR AIR HEATING AT UNITED STATES AIR FORCE INSTALLATIONS**

THESIS

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AFIT/GCA/ENV/09-M03

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## Abstract

The purpose of this research was to evaluate the use of solar air heating at U.S. Air Force installations. Specifically, this thesis analyzed Unglazed Transpired Collector (UTC) technology, more commonly known as SolarWalls®. This thesis sought to determine if UTC systems are an economically and environmentally viable technology which Air Force energy managers should include in their portfolio of alternative energy options.

This research question was answered through the use of case studies and life-cycle cost analysis. Case studies were performed at various U.S. military installations which have already utilized UTC systems to provide a consolidated source of lessons learned. A life-cycle cost analysis was performed to quantify the potential cost savings at various Air Force installations to help Air Force energy leaders determine if the technology should be further implemented, and if so, which installations should be considered for future UTC use. The quantitative results of this evaluation determined that the Air Force could realize significant economic and environmental benefits from the use of UTC technology. The information gathered from case studies can help ensure that future users of UTC systems utilize their systems in the most effective manner possible.

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*This work is dedicated to my father.*

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I first want to thank my fiancée for all of her love, support, patience, and understanding throughout my thesis effort. I cannot imagine going through this endeavor without her.

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David S. Brown

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## List of Acronyms

ACC – Air Combat Command
AFB – Air Force Base
AFIT – Air Force Institute of Technology
ASHRAE – American Society of Heating, Refrigerating and Air-Conditioning Engineers
B20 – Biodiesel Fuel (80 percent conventional diesel, 20 percent bio-fuel)
BE – Bioenvironmental Engineering
Btu – British Thermal Unit
BY – Base Year
CDD – Cooling Degree Day
CE – Civil Engineering
CFD – Computational Fluid Dynamics
CFR –Code of Federal Regulations
$CH_4$ - Methane
CO – Carbon Monoxide
$CO_2$ – Carbon Dioxide
COTS – Commercial Off-the-shelf
CSP – Concentrating Solar Power
CST – Concentrating Solar Thermal
CY – Constant-year
DEPPM – Defense Energy Program Policy Memorandum
DESC – Defense Energy Support Center
DoD – Department of Defense
DOE – Department of Energy
DPBP – Discounted Payback Period
DUERS – Defense Utility Energy Reporting System
ECIP – Energy Conservation Investment Program
EO – Executive Order
EPA – Environmental Protection Agency
EPT – Energy Payback Time
ESCO – Energy Service Company
ESPC – Energy Savings Performance Contract
E85 – Ethanol Vehicle Fuel (85 percent denatured ethanol, 15 percent gasoline)
FY – Fiscal Year
GAO – Government Accountability Office
GHG – Greenhouse Gas
HDD – Heating Degree Day
HVAC – Heating, Ventilation, and Air Conditioning
IRR – Internal Rate of Return
LCC – Life Cycle Costs
LEED – Leadership in Energy and Environmental Design
LFGE – Landfill-gas Energy
MAJCOM – Major Command
MBTU – Million Btu (British Thermal Units)

MILCON – Military Construction
NAAQS – National Ambient Air Quality Standards
NASA – National Aeronautics and Space Administration
NIST – National Institute of Standards and Technology
$NO_X$ – Nitrogen Oxides
NPV – Net Present Value
NREL – National Renewable Energy Laboratory
$N_2O$ – Nitrous Oxide
$O_3$ – Ozone
OEH – Occupational and Environmental Health
Pb – Lead
PBC – Performance Based Contracting
$PM_{10}$ and $PM_{2.5}$ – Particulate Matter
PPE – Personal Protective Equipment
PV – Photovoltaic
SAH – Solar Air Heating
SDD – Sustainable Design and Development
SIR – Savings-to-Investment Ratio
$SO_2$ – Sulfur Dioxide
SPBP – Simple Payback Period
$tCO_2$ – Tons of Carbon Dioxide
U.S. – United States
USGBC – United States Green Building Council
UTC – Unglazed Transpired Collector

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AN EVALUATION OF SOLAR AIR HEATING AT
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# I. Introduction

## Background on Alternative Energy in the U.S. Air Force

The Department of Defense (DoD) has played a key role in the establishment, evolution, and sustainment of a variety of industries across the United States (U.S.) and global economy. The U.S. Air Force, a relatively young branch of the DoD at only 60 years old, has already played a significant role in the commercial space, aviation, and defense industries. The development of numerous technologies such as rockets and satellites, advanced jet propulsion, high-speed computing, and wireless communications are all results of Air Force technology development (Delaney, 1999). Another industry that may be even more crucial to both the U.S. and global economy is the energy industry. This industry has received a great deal of attention since the price of oil had recently skyrocketed and the movement to reduce emissions from energy production has steadily gained momentum over the past few years.

The Air Force has recognized that it has a unique opportunity to make a major impact across the globe by further incorporating alternative energy use in its operations. The Assistant Secretary of the Air Force for Installations, Environment and Logistics, William Anderson, emphasized this point by stating "energy conservation and developing energy technology is a major Department of Defense effort… as the largest consumer of energy in the federal government, the Air Force is in a great position to look for, promote, and utilize alternative energy sources" (Ferrell, 2007).

The Air Force has already made a conscious commitment to incorporate alternative energy in their decision-making process. This strategy was made clear in a 2006 statement made by Dr. Ronald Sega, Undersecretary of the Air Force:

> The Air Force has been working on a strategy to have energy as a consideration in nearly all of its activities, from operations to acquisition. The Air Force is increasing efforts to reduce the demand for energy using good building design, advanced planning tools for operations, more efficient jet engines and better conservation practices. (Buzanowski, 2006).

This strategy has been incorporated into the organizational culture of the Air Force, DoD, and all other U.S. government agencies.

***Balance of Power***

According to the DoD, the basic purpose of the Department is to "provide the military forces needed to deter war and to protect the security of the U.S. Everything we do supports that primary mission. Nothing less is acceptable to us, or the American people" (DoD 101, 2008). Wars are often fought over the obtainment and protection of critical resources, including land, oil, and water. By reducing its own need for oil, the U.S., as the world's leading energy consumer, can curb demand, price, and consumption pressures for the resource. This will in essence provide "defense" for the nation's interests by reducing dependency on other nations for oil. At the present day, all industrialized nations are under pressure to ensure that their demand for oil can be met by their supply. However, it must be accepted that the supply of oil is not unlimited, and U.S. dependency on any particular nation for this resource can lead to a reduction in power and influence over that supplying nation. Conversely, if the U.S. can decrease its dependence on another nation for such a resource, the U.S. would fundamentally decrease the amount of influence the supplying nation possesses.

In 2007, the U.S. imported roughly 67 percent of oil consumed by the nation (GAO, 2008:4). If the Air Force were able to help decrease U.S. dependence of oil imports, then the amount of influence that oil-producing nations have on the U.S. would decline. If the U.S. has an opportunity to create more stability for the government and military by reducing this dependency, and the Air Force can act as a driver in the process, it would make sense for the Air Force do to so. By pursuing and advancing the development of alternative energy technologies, the Air Force can carry out the DoD mission by helping the U.S. reduce dependencies that foster war and threaten security.

***Energy Security***

Security concerns are another fundamental reason why alternative energy is important to Air Force and DoD installations. Increased potential of terrorist activity has caused greater concerns over safeguarding the energy supplied to military installations (Combs, 2005). By producing and utilizing alternative energy within the confines of an installation, the Air Force could decrease the potential impact an adversary could have on base operations by disrupting the external power grid, while also reducing reliance on local power suppliers to provide consistent and reliable levels of electricity.

A fundamental lesson taught in military strategic studies is the concept of "centers of gravity" discussed by Carl von Clausewitz. He emphasized the importance of recognizing and disabling your enemy's centers of gravity, which are defined as "the characteristics, capabilities, or locations from which a military force derives its freedom of action, physical strength, or will to fight" (Iron, 2004). Power plants are a center of gravity for most U.S. Air Force bases across the world. The Air Force is dependent on electricity to perform day-to-day operations and conduct flying missions. This electricity, in most cases, is provided by sources outside the confines and security of the base. Since this flow of electricity from the source to the base typically does not have adequate protection and surveillance, this leaves the Air Force extremely vulnerable to adversaries who would want to disable this center of gravity.

Alternative energy can allow the Air Force to rely substantially on energy produced within the confines of the base, which helps provide protection to this center of gravity. Adoption of alternative energy technologies would bring value to more austere and deployable environments as well. Diesel generators, in addition to relying on oil, are loud and create large heat signatures. Fuel cells, a form of alternative energy, can produce electricity in a much more concealed manner. This technology could pay great dividends in such environments. These two scenarios provide an excellent example of how the Air Force would benefit by being energy self-sufficient from alternative forms of energy production.

***Air Force Dependency on Oil***

Since its inception as an independent department in 1947, the Air Force has been heavily dependent upon oil. For this reason, the Air Force needs to place a strong emphasis on the pursuit of alternative energies. It has been speculated by some that the "last drop of oil will be burned in a U.S. Air Force jet." This statement is rooted in the perspective that there are no foreseeable alternatives for military aircraft propulsion systems other than using liquid fuel, namely fuel oil. While this statement will likely remain unconfirmed for a long time, it paints a bleak picture for the Air Force. If that statement were to hold true, it would likely be because the Air Force was never able to create an alternative fuel source to replace the petroleum used today, while other users of oil were able to adapt. This dependence is a major cause for concern because the "U.S. military is powered, fueled and transported by petroleum-derived commodities. A significant oil disruption not only threatens our nation's economic security, it endangers the national security machinery itself" (Eggers, 2008:12). The reliance on energy by the DoD cannot be understated. In FY 2007, the DoD consumed over 90 percent of the petroleum used by the federal government (Energy Strategy, 2008).

Alternative energy has provided some incredible opportunities to power vehicles. This has been demonstrated through the use of wind by sailboats and the use of electricity, biodiesel, solar, and hydrogen fuel cells for automobiles. The airplane industry, in terms of developing alternative forms of energy use, still has a long and arduous road ahead. Airplanes simply are not as fuel-flexible as ground vehicles (Daggett, 2006).

A recent report published by the National Aeronautics and Space Administration (NASA) in October, 2006, discussed the challenges involved in using alternative forms of fuel for airplanes. Some of the different alternatives that have been studied for airplanes include bio-derived fuels, methanol, ethanol, liquid natural gas, liquid hydrogen, and synthetic fuels. All of these fuels present serious safety, logistical, and performance challenges. The report stated that these alternative fuel sources cannot reach equivalent amounts of energy created by conventional jet fuel without requiring a substantial increase in: volume and weight; production, infrastructure, and design costs; and carbon dioxide ($CO_2$) emissions.  While synthetic fuels have provided some promise, further research and development is necessary (Daggett, 2006).

Overall, aircraft in the commercial sector have experienced dramatic improvements in fuel efficiency since the 1960s.  The NASA report predicts that a 15 to 20 percent improvement in efficiency will occur in the future, which will make flying with commercial airlines the "most efficient means of transportation."  Figure 1 illustrates Boeing's prediction of air travel growth (Daggett, 2006).

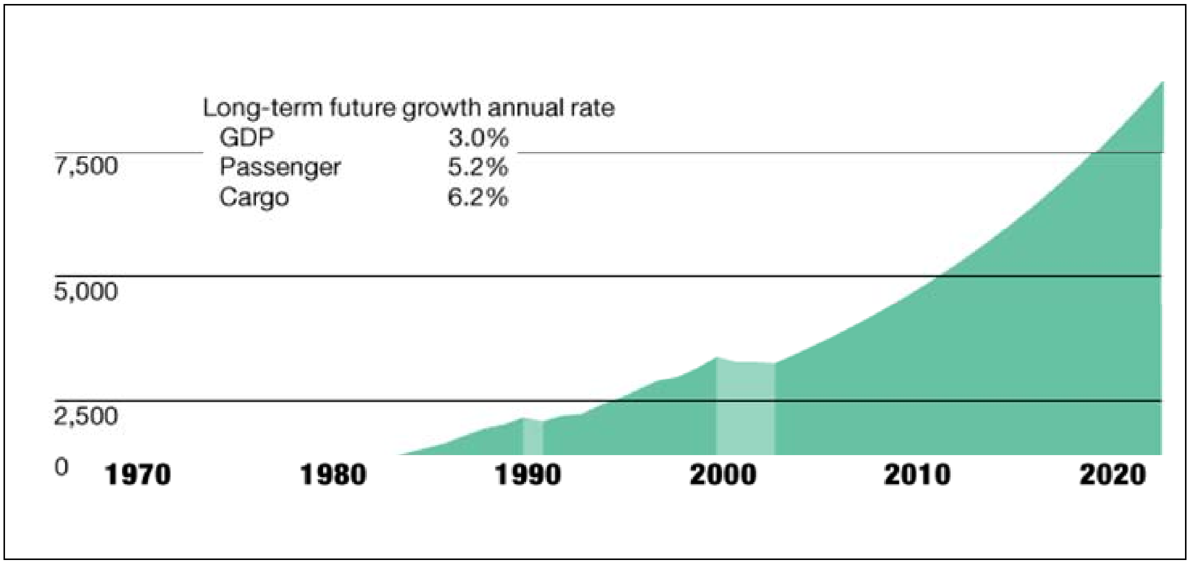



**Figure 1:  Revenue Passenger Kilometers by Year (Billions)**
(Source: Daggett, 2006)

It is evident that projected growth in air traffic will outpace these future gains in fuel efficiency, which means that demand for fuel in the aircraft industry will continue to increase in the future (Daggett, 2006).  This increase in demand can lead to a corresponding increase in the cost of jet fuel for the Air Force in the future.  Therefore, we find that cost is another major reason why alternative energy is so crucial to the Air Force.

***Energy Costs***

Jet fuel only represents six percent of global oil consumption (Daggett, 2006). However, it represents the one of the largest single line-items in the Air Force's annual budget from year to year. As discussed previously, Air Force planes require much higher performance fuels than other common consumers of oil such as ground vehicles. Since the use of alternative energy in airplanes is currently much more limited than that of the ground transportation and electrical power industry, it is in the Air Force's interest that alternative energy develops considerably to reduce consumption of oil across these two industries. Unfortunately, the current outlook in energy consumption by fuel type does not look promising for aircraft, which use petroleum as the predominate source of fuel. The data from Figure 2 illustrate that anticipated petroleum and coal consumption will likely continue to rise in the next 20 years. Not only will this consumption rate rise, but it will do so at a higher rate than that of renewable and hydropower consumption.

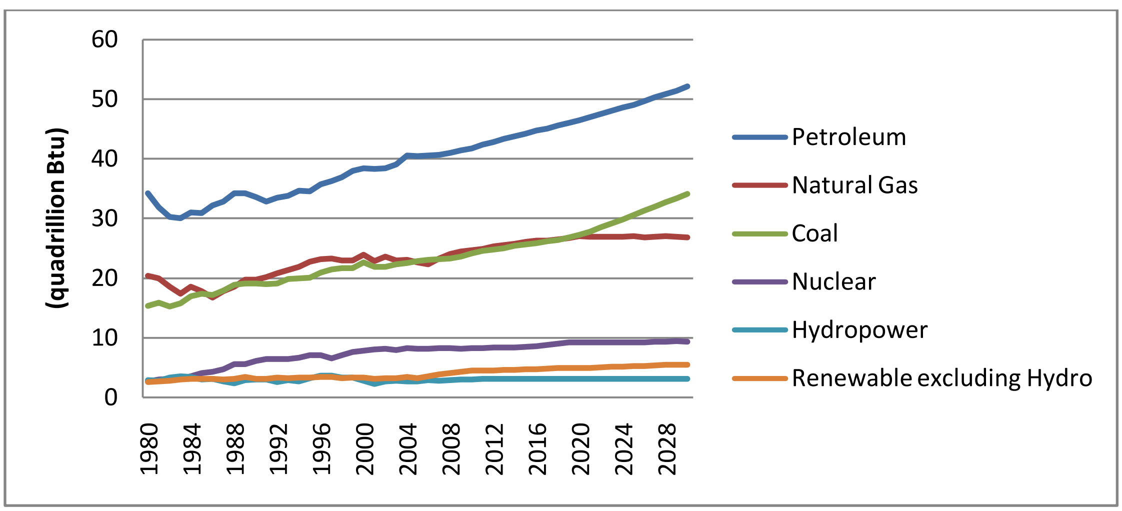



**Figure 2: U.S. Energy Consumption by Fuel, 1980 - 2030**
(Source: U.S. Department of Energy, 2007)

This trend will likely coincide with a continued rise in the price per barrel of oil. For every increase of $10 per barrel of oil, DoD operating costs for that year of execution increases by roughly $1.3 billion (Department of Defense, 2007). Figure 3 illustrates the historical inflation-adjusted price per barrel of oil during the past 60 years. Inflation adjustments reflect November 2008 prices (Inflationdata, 2009).

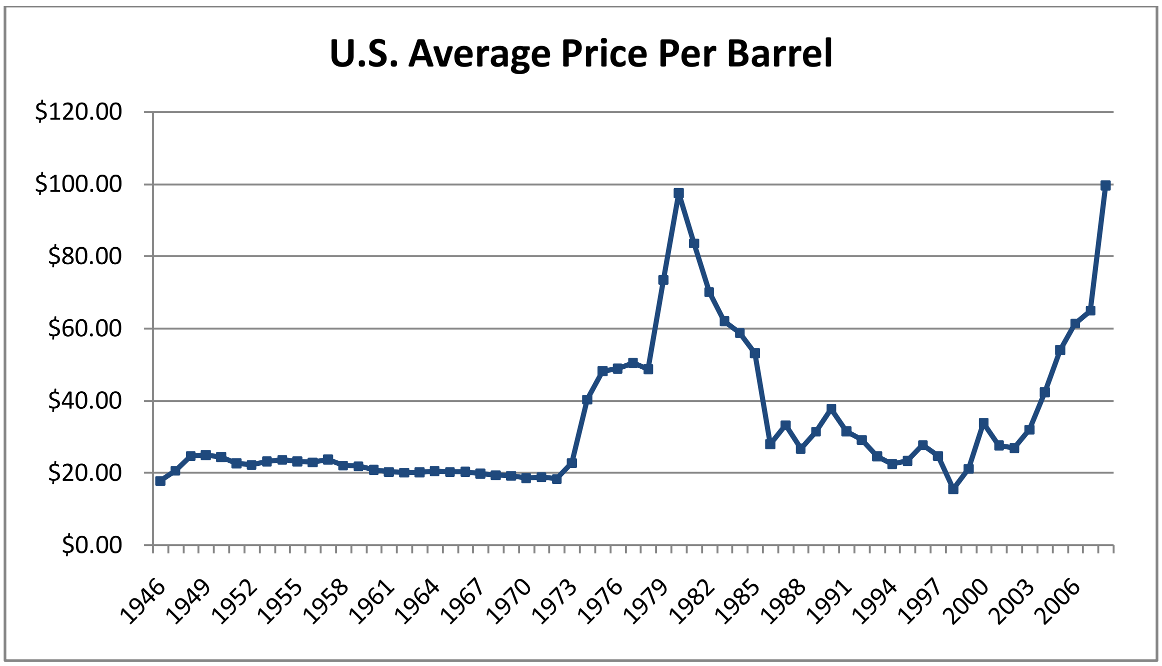



**Figure 3: Inflation Adjusted Average Price of a Barrel of Oil (BY08$)**
(Source: Inflationdata, 2009)

If the upward trend in oil prices continues, it will put fiscal stressors on the Air Force and reduce the available budget for replacement of its aging fleet of aircraft. This will also lead to increased pressure on the acquisitions community to develop lighter and more fuel efficient aircraft in the future; this provides justification for the Air Force to pursue alternative energy in all fields, not just jet fuel. In the other case, where oil prices may revert to historically lower prices, it is still justifiable that these courses of action be made. President-elect Obama addressed this exact scenario in a television interview with Steve Kroft on 14 November 2008. In the interview, Kroft asked if doing something about energy was less important as oil prices decrease to lower levels. In his response, President-elect Obama stated:

> It's more important. It may be a little harder politically, but it's more important… because this has been our problem. You know, oil prices go up, gas prices at the pump go up, everybody goes into a flurry of activity. And then the prices go back down and suddenly we act like it's not important, and we start, you know filling up our SUVs again. And, as a consequence, we never make any progress. It's part of the addiction, all right. That has to be broken. Now is the time to break it. (60 Minutes, 16 November 2008).

Aside from energy costs incurred by the Air Force due to jet fuel, there are also substantial energy costs incurred by Air Force installations to power the infrastructure and equipment needed to carry on its mission. From Figure 4, we can see that almost 20 percent of FY 2007 energy costs were associated with powering facilities and equipment.

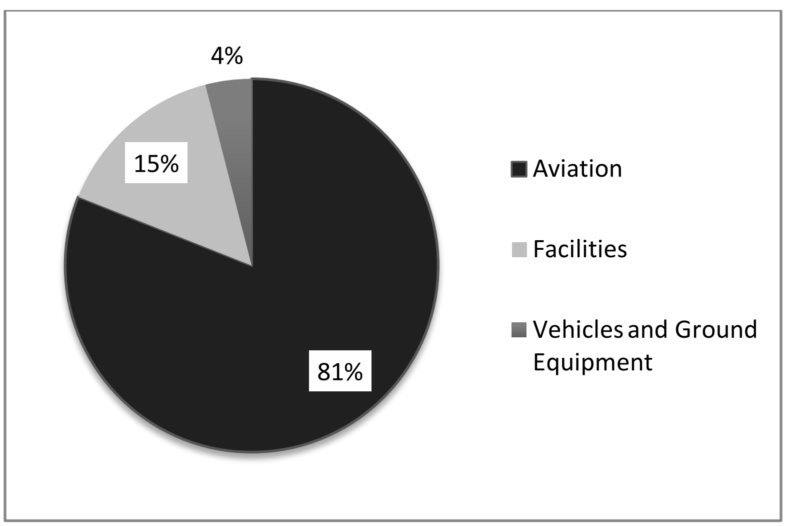



**Figure 4: U.S. Air Force Energy Utilization for FY 2007**
(Source: Energy Strategy, 2008)

In the near term, alternative energy implementation and advancement in these areas may be easier for the Air Force to address. This is because there are numerous types of mature technologies presently available for these fields. The Air Force has already taken many steps in this direction through the use of alternative energy implementation at Air Force bases around the world. We will discuss many of these efforts in further detail in Chapter 2.

***Pollution and Greenhouse Gas Emissions***

The production of energy by burning fossil fuels such as coal, oil, and gas contributes to numerous health and environmental issues. Electric utilities in the U.S. are one of the main producers of harmful pollutants such as sulfur dioxide ($SO_2$), nitrogen oxides ($NO_X$), and $CO_2$. $SO_2$ causes corrosion, acidifies soil and water, and can trigger asthma and lead to health damages. $NO_X$ can also lead to health damages and is a major component of ozone smog (Electric, 2008). Harmful heavy metals such as mercury and lead can also be generated from electrical utilities.

The majority of health damage caused by air pollution can be attributed to the amount of pollution inhaled relative to the individual's body weight and the surface area of the organ being affected. For this reason, children tend to be more severely affected by air pollution than adults. Children, on average, spend a greater amount of time outdoors and have higher rates of breathing than adults do, relative to their body weight and lung surface area (Children, 2008). The damage caused by chronic air pollution exposure can lead to respiratory illnesses such as asthma and lung cancer as well as decreased lung function.

Recognition of the many damaging results of air pollution has led to legislative initiatives such as the Clean Air Act. The Clean Air Act requires the Environmental Protection Agency (EPA) to set air quality standards for pollutants which are believed to cause damage to public health and the environment. These standards are referred to as National Ambient Air Quality Standards (NAAQS) and consist of six primary pollutants. These pollutants include Carbon Monoxide (CO), lead (Pb), $NO_2$, Particulate Matter ($PM_{10}$ and $PM_{2.5}$), Ozone ($O_3$), and $SO_2$. A description of the tolerance standards for these pollutants can be found in Appendix A.

Although the U.S. has made some progress in addressing air quality issues, there is still a great amount of room for improvement. A recent study by the EPA in 2007 found that over 150 million Americans live in counties which do not meet the NAAQS. Figure 5 illustrates how many Americans were living in counties that exceeded each of the different pollutant levels.

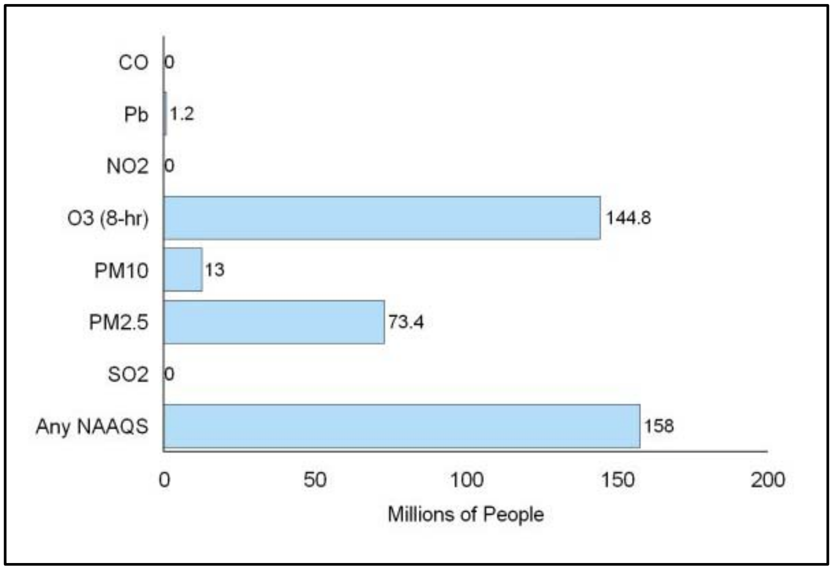



**Figure 5: Number of People Living in Counties with Air Quality Concentrations Above the Level of the NAAQS in 2007.**

(Source: EPA – Air Trends, 2008)

Through the use of alternative forms of energy generation, such as wind and solar, energy producers would be able to help reduce harmful air pollutants and mitigate the harmful effects facing Americans today. Increased energy efficiency, through the use of technologies such as unglazed transpired collectors (UTCs), can have a similar effect. For this reason, we find that researching UTCs (aka SolarWalls®) use can be a worthwhile endeavor which could possibly benefit the health and well-being of the American public. In addition, the use of UTCs can help the Air Force meet the aggressive energy mandates which will be discussed further in the following chapter.

$CO_2$ is another harmful byproduct caused by energy utilities which burn fossil fuels to generate electricity. $CO_2$ is a Greenhouse Gas (GHG) which is widely considered the largest controllable contributor to global warming. As depicted in Figure 6, for the past 50 years there has been a steady increase in the amount of $CO_2$ emissions generated in the U.S.

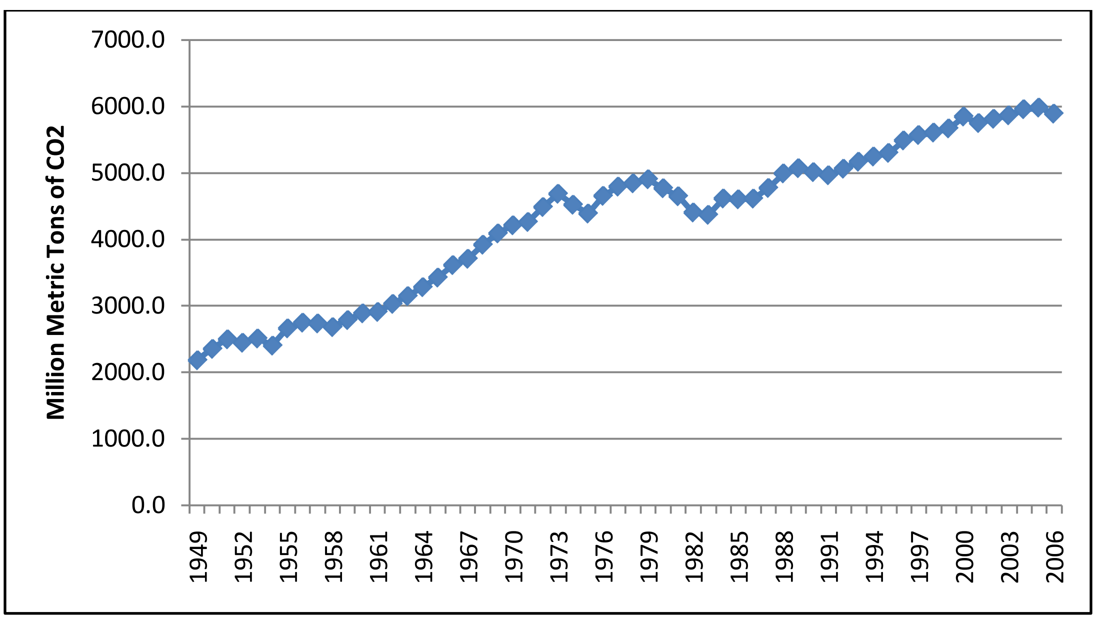



**Figure 6: Total U.S. Carbon Dioxide Emissions 1949 – 2006**
(Source: EIA, 2008)

The Air Force is the largest energy consumer in the federal government and is responsible for emitting millions of tons of $CO_2$. Air Force leaders recognize this impact and have made it an agency priority to be at the forefront of addressing the situation. William Anderson further emphasizes this point by stating, "Not only have we committed to purchase only alternative energy sources, the Air Force has committed to be a leader in establishing a global consortium to tackle the reduction, capture, and reuse of greenhouse gas emissions" (Weckerlein, 2008). As one of the largest energy consumers in the world, the Air Force has the potential to explore and implement a variety of alternative energy and energy efficiency measures.

**Problem Statement**

Presidential and Congressional mandates have challenged energy managers to try to improve the methods in which energy is generated and used at federal installations. This can be a difficult task because there are no "cookie cutter" solutions to implementing the proper alternative energy technologies. Every individual base, and individual building, has its own unique needs and characteristics. Energy managers must be familiar with numerous technologies, many of which have only recently emerged in the industry. For this reason, it is difficult for energy managers to be aware of all of the different types of renewable and alternative technology that are currently available in this rapidly advancing market. UTCs are only one of the numerous options that are available for energy managers to consider. The specific problem addressed by this research is whether UTCs are a useful option for energy managers to consider, and if so, which Air Force installation energy managers would likely benefit most from their utilization.

## Research Objective

The purpose of this thesis is to evaluate UTC technology and determine if it is an effective technology which Air Force energy managers should include in their portfolio of alternative energy options. This evaluation will attempt to quantify the potential cost savings at various Air Force installations to help Air Force energy leaders determine which installation energy managers should consider UTC use. This evaluation will also provide a consolidated source of lessons learned from the various military installations which have already utilized UTC systems. This information can help ensure that future users of UTC systems utilize them in the most effective manner possible. The research questions we will attempt to answer include: Should the Air Force continue to pursue UTC use? If so, which bases? What type of buildings? What type of energy cost savings and GHG emission reduction savings could be expected from UTC systems?

## Approach/ Methodology

To accomplish the research objectives, we will follow a three-part approach. First, we will conduct a thorough literature review in order to better understand the various facets of this research topic. Second, we will examine previous UTC uses across the DoD by conducting case studies on various installations. Finally, we will use a software modeling program to perform economic and environmental assessments on various Air Force installation locations in an attempt to capture the viability of UTC use at future locations.

## Scope

This research will evaluate UTC technology at various Air Force installation locations. The analysis will provide a comparison as to how effective UTC systems could be expected to perform in different geographic locations. The data used to model the effectiveness at these various locations will be based on specific climatic data associated with the particular locations being assessed. In addition, a case study analysis will be performed on U.S. military installations which have already utilized UTC systems.

**Significance**

This research effort will uncover and consolidate the lessons learned from previous UTC users in the DoD and provide potential users with information on its real world application. We will show future users of UTCs how to implement the technology in a more efficient and effective manner; saving the Air Force time, money, and energy. In addition, this thesis will present energy managers and Air Force leaders with a better understanding of UTC technology and its potential use in the future.

**Chapter Preview**

Chapter 2 contains a literature review of transpired solar collectors as well as other renewable energy sources which have been utilized within the Air Force. This chapter will also detail congressional legislation and funding programs which are applicable to transpired solar collectors. Finally, this chapter will explore previous research related to transpired solar collectors. Chapter 3 provides a basic overview of the methodology used to evaluate transpired solar collector use in the DoD. This includes a description of the case studies performed to evaluate previous users and the economic methods used to evaluate potential future users. Chapter 4 presents the results from these evaluations. Chapter 5 concludes the research and provides policy recommendations for future transpired solar collector use.  In addition, Chapter 5 provides limitations of the research and potential areas for future research.

# II. Literature Review

This chapter discusses the reasons why Air Force interest in alternative forms of energy has been rapidly increasing over the past decade. We include a summary of presidential and congressional legislation, Air Force policies, and funding opportunities which have led to this movement, as well as various renewable energy projects which have resulted from this legislation. We will also provide a description of the basic principles of Unglazed Transpired Collector (UTC) technology and emphasize some of the potential benefits and limitations of its use. We will also discuss some of the previous research which has been done on UTCs.

## Renewable Energy

Renewable energy resources are those sources of energy which are constantly replenished and will never run out. Some of the most commonly used forms of renewable energy include solar, hydroelectric, geothermal, biomass, and wind. Coal, oil, and natural gas are examples of nonrenewable energy sources because they draw on finite resources which will eventually dwindle and become too expensive or environmentally damaging to retrieve and utilize (Learning, 2008). As of 2007, renewable power sources generated seven percent of the U.S. energy supply. Figure 7 shows a breakdown of the U.S. energy supply by type.

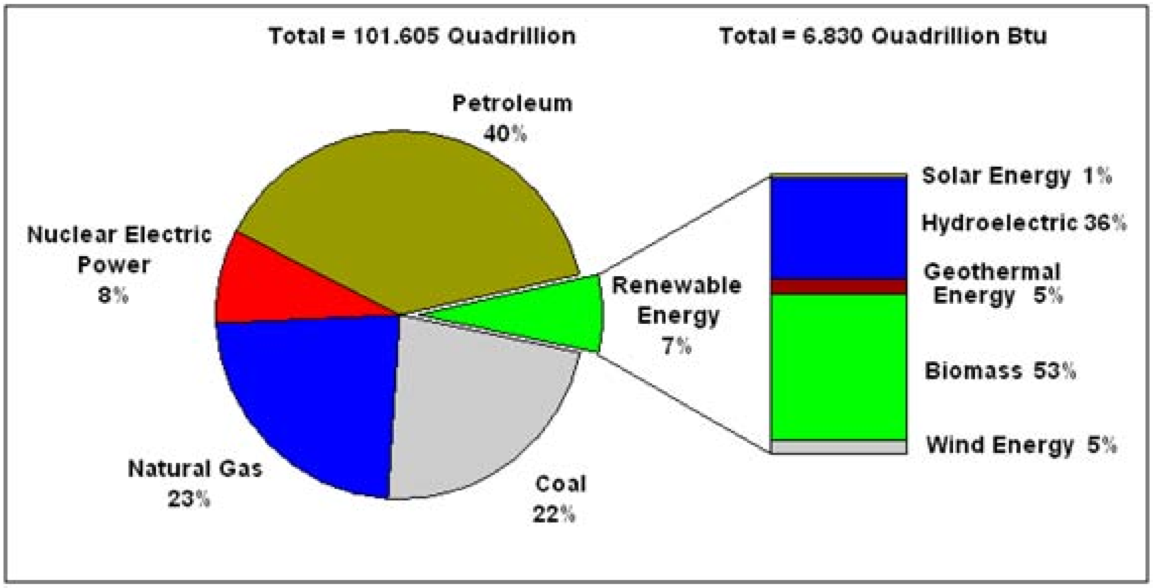



**Figure 7: Renewable Energy Consumption in the U.S. Energy Supply, 2007**
(Source: EIA, 2008)

## Related Legislation

Numerous presidential and congressional mandates have been enacted in an effort to steer the U.S. towards a national energy policy that is more efficient, more environmentally responsible, and less dependent upon fossil fuels. In this section, we will explore applicable legislation that could be addressed through the use of UTCs.

### *Executive Orders*

On 3 June 1999, President William J. Clinton signed Executive Order 13123 - *Greening the Government through Efficient Energy Management*. This Executive Order (EO) went on to become a driving force towards a collective goal by all agencies within the federal government to reduce energy use and focus on clean and renewable forms of energy. The main goals of the EO pertinent to this research were that each agency shall:

1. Reduce greenhouse gas emissions attributable to facility energy use by 30 percent by 2010 compared to such emission levels in 1990.

2. Reduce energy consumption per gross square foot of its facilities by 30 percent by 2005 and 35 percent by 2010 relative to 1985 levels.

3. Strive to expand the use of renewable energy within its facilities and in its activities by implementing renewable energy projects and by purchasing electricity from renewable energy sources.

4. Reduce the use of petroleum within its facilities. Agencies may accomplish this reduction by switching to a less greenhouse gas-intensive, nonpetroleum energy source, such as natural gas or renewable energy sources; by eliminating unnecessary fuel use; or by other appropriate methods. Where alternative fuels are not practical or life-cycle cost effective, agencies shall strive to improve the efficiency of their facilities.

5. Strive to reduce total energy use and associated greenhouse gas and other air emissions, as measured at the source. To that end, agencies shall undertake life-cycle cost-effective projects in which source energy decreases, even if site energy use increases. In such cases, agencies will receive credit toward energy reduction goals through guidelines developed by the Department of Energy (DOE) (EO 13123, 1999).

UTC's would be a viable option in addressing each of these goals. They could help reduce the energy consumption and greenhouse gas emissions that result from meeting heating demands for facilities. UTCs can assist in eliminating unnecessary fuel use and can provide a means of increasing efficiency for facilities which cannot utilize alternative fuels.

On 26 January 2007, President George W. Bush signed EO 13423 – *Strengthening Federal Environmental, Energy, and Transportation Management*. In many ways, this EO was intended to be a continuation of EO 13123. The goals are similar in their intentions; however, there were slight adjustments made. Some of the goals set forth in the EO that are applicable to this research are that the head of each government agency shall:

1. Improve energy efficiency and reduce greenhouse gas emissions of the agency, through reduction of energy intensity by three percent annually through the end of fiscal year 2015 or 30 percent by the end of fiscal year 2015. This is relative to the baseline of the agency's energy use in fiscal year 2003.

2. Ensure that at least half of the statutorily required renewable energy consumed by the agency in a fiscal year comes from new renewable sources, and to the extent feasible, the agency implements renewable energy generation projects on agency property for agency use.

3. Require in agency acquisitions of goods and services use of sustainable environmental practices, including acquisition of biobased, environmentally preferable, energy-efficient, water-efficient, and recycled-content products, and use of paper of at least 30 percent post-consumer fiber content.

4. Ensure that the new construction and major renovation of agency buildings comply with the *Guiding Principles for Federal Leadership in High Performance and Sustainable Buildings set forth in the Federal Leadership in High Performance and Sustainable Buildings Memorandum of Understanding (2006),* and 15 percent of the existing Federal capital asset building inventory of the agency as of the end of fiscal year 2015 incorporates the sustainable practice in the Guiding Principles. (EO 13423, 2007).

Implementation of UTC technology at federal government installations would be a viable contributor towards meeting the goals set forth in EO 13423 as well. UTCs use sunlight, a sustainable source of energy, to reduce energy demands. UTCs could potentially: increase energy efficiency, reduce energy demands that are met through GHG producing technologies, and comply with guiding principles. In addition, UTCs could also be considered an environmentally friendly practice since most of the components of a UTC system could be constructed using recycled materials, i.e., the steel or aluminum used for the collector walls or using recycled ductwork material.

***Energy Policy Act of 2005***

On 8 August 2005, President George W. Bush signed the Energy Policy Act of 2005. The purpose of the bill is "to ensure jobs for our future with secure, affordable, and reliable energy" (Congress, 2005). The bill was created in an effort to combat American energy concerns and help provide a national energy strategy. In his speech minutes before signing the bill, President Bush referred to it as "an economic bill, but… it's also a national security bill" (Bush, 2005). This statement provides further evidence that the highest levels of the federal government recognize the relationship between oil dependencies and national security. Some of the main components of the bill include tax incentives and loan guarantees for clean energy producers, requirements for increased usage of biofuels, authorization for further production of nuclear power plants, and tax rebates for hybrid vehicles.

The bill encouraged the use of renewable energy by providing tax credits for photovoltaic equipment purchases, energy produced by wind technology, investments in clean coal technology, geothermal energy investments, and hybrid vehicle purchases. The bill also encourages increases in energy efficiency by offering tax credits to builders who produce or renovate buildings and homes that meet a 30 percent energy reduction standard (Congress, 2005). Although many of these credits expired at the end of 2007, the purpose behind the bill makes clear the direction in which the President and Congress are pushing the nation.

***Energy Independence and Security Act of 2007***

On 17 December 2007, President Bush signed the Energy Independence and Security Act of 2007. The primary purposes behind the Act are to:

1. Move the U.S. toward greater energy independence and security
2. Increase the production of clean renewable fuels
3. Protect consumers

4. Increase efficiency of products, buildings, and vehicles

5. Promote research on and deploy greenhouse gas capture and storage options

6. Improve the energy performance of the Federal Government

The Energy Independence and Security Act of 2007 set new energy reduction goals for federal buildings. Section 431 of the Act amends section 543(a)(1) of the National Energy Conservation Policy Act (42 U.S.C. 8253(a)(1)) by creating more aggressive conservation goals. The changes made to these conservation goals are listed in Table 1.

**Table 1: Energy Reduction Goals for Federal Buildings**

| Fiscal Year | Previous Percent Reduction Goals | Amended Percent Reduction Goals | Delta |
|---|---|---|---|
| 2006 | 2 | 2 | - |
| 2007 | 4 | 4 | - |
| 2008 | 6 | 9 | + 3 |
| 2009 | 8 | 12 | + 4 |
| 2010 | 10 | 15 | + 5 |
| 2011 | 12 | 18 | + 6 |
| 2012 | 14 | 21 | + 7 |
| 2013 | 16 | 24 | + 8 |
| 2014 | 18 | 27 | + 9 |
| 2015 | 20 | 30 | + 10 |

(Sources: Congress, 2005, 2007)

To ensure progress towards these goals, energy managers are required to perform comprehensive water and energy evaluations annually on 25 percent of the buildings under their span of control. These evaluations must be conducted in a way that ensures that every facility is evaluated at least once during each four-year period. No later than two years after an evaluation is conducted, energy managers may implement "any energy- or water-saving measure that the Federal agency identified in the evaluation conducted… that is life cycle cost-effective" (Congress, 2007). Upon implementation, the Act then requires that energy managers ensure that equipment is operating at design specifications, that a plan has been developed to ensure proper operation, maintenance, and repair, and finally, that performance and savings are being measured throughout its use (Congress, 2007). If it is discovered that a UTC system would be an advantageous project for an energy manager to implement, this act would apply and the energy manager would be required to ensure Energy Independence and Security Act of 2007 compliance is met.

## Air Force Policies

### *LEED Certification*

The Leadership in Energy and Environmental Design (LEED) Green Building Rating System™ is a consensus-based system developed by the U.S. Green Building Council (USGBC) to provide a benchmark for the design, construction, and operation of high performance green buildings (USGBC, 2008). There are four different levels of LEED certification that can be obtained: certified, silver, gold, or platinum. In order to reach these different certification levels, a certain amount of "green" points must be earned through the use of sustainable and efficient building design. There are six different credit categories in which LEED certification points can be earned: sustainable sites (14 points), water efficiency (5 points), energy and atmosphere (17 points), materials and resources (13 points), indoor environmental quality (15 points), and innovation and design process (5 points). The point scale used to determine these various levels is reflected in Table 2 below:

**Table 2: LEED Point Scale**

| | |
|---|---|
| Platinum | 52 – 69 Points |
| Gold | 39 - 51 Points |
| Silver | 33 – 38 Points |
| Certified | 26 – 32 Points |

(Source: USGBC, 2008)

On 19 December 2001, the Air Force Civil Engineer established a sustainable development policy which directed the implementation of sustainable use in Air Force construction programs. The policy memorandum stated that LEED would be the preferred self-assessment metric and that by 2004 at least 20 percent of each major command's projects would be LEED pilot projects (DOE – Federal, 2004). In harmony with the requirements later set forth by the Energy Policy Act of 2005 and Executive Order 13423, the Civil Engineer of the Air Force expanded upon the policy by releasing an updated memorandum in July 2007. This new policy memorandum set forth a clear goal of obtaining LEED certification for all future vertical construction projects:

> Beginning in FY09, 100 percent of each MAJCOM's MILCON vertical construction projects, with climate control, shall be designed so that it is capable of achieving LEED silver certification. This is not an option; sustainable features [cannot] be eliminated to save scope or cut cost. (DCS, 2007)

The policy also requires that beginning in FY09, "each MAJCOM must select five percent (by project cost) of the total MILCON, per FY, for formal LEED registration and certification." The requirements would then increase and remain at ten percent starting in FY10 (DCS, 2007). This increased emphasis on LEED certification is particularly interesting in regards to our research because UTC systems are capable of contributing up to six “green” points towards certification (SolarWall® - Designing, 2008).

***Ventilation Requirements***

Proper ventilation in working environments is required to ensure a healthy and productive workforce. This presents a challenge to most Air Force facilities, as the Air Force mission requires the use of a great deal of equipment and materials that emit harmful particles and vapors into the air. This includes, but is not limited to, diesel and jet fuel fumes, chemicals and cleaning solvents, paints, and other toxic industrial materials. The Air Force refers to these types of threats as Occupational and Environmental Health (OEH) threats. The Air Force definition of a health threat is a “potential or actual condition that can cause short or long-term injury, illness, or death to personnel” (DOD, 2008:3). The primary factors that can affect the intensity of OEH exposure are: the threat source, route of exposure, work patterns and practices, concentration, and frequency and duration of exposure (DOD, 2008:3). Ventilation is a method which reduces the concentration of OEH threats by drawing the contaminated air out of the workspace and bringing in clean, fresh air to replace it. The national standard for ventilation rates are set by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The standards for proper ventilation are found in ASHRAE standard 62.1-2007, *Ventilation for Acceptable Indoor Air Quality.*

The necessity of adequate ventilation in working areas where airborne OEH threats are present can create a challenge to Civil Engineering (CE) who must balance the amount of fresh air brought into buildings with the health and well being of the users working there. This is because temperature differences between the inside and outside of buildings require that fresh air be either heated or cooled to maintain the desired temperature in the building. If air could simply be re-circulated within a building, the amount of energy required to maintain a desired temperature would be far less than that associated with a building that requires a consistent input of fresh air. UTCs work especially well at addressing the combination of ventilation and heating requirements needed in most buildings. This is because UTCs can reduce the amount of electricity needed to heat the fresh air required to meet ventilation standards.

This research may be of particular interest to Bioenvironmental Engineering (BE) who is responsible for ensuring appropriate controls are in place to ensure hazardous exposures are being maintained at acceptable levels. In instances where acceptable health levels are being breached, BE must determine and recommend which controls are necessary to correct the situation (DOD, 2008:6). Air Force Manual 48-155 sets the priority of OEH threat control selection as shown in Figure 8:


**Figure 8: Priority of OEH Threat Control Selection**
(Source: DOD, 2008:5)

Engineering controls consist of methods used to isolate, enclose, reduce, attenuate or remove health threats from an area of exposure and are the most desirable control method. Ventilation systems would be an example of an engineering control. Administrative controls consist of any procedure or particular set of actions undertaken in order to significantly limit OEH threat exposure. An example of an administrative control would be reducing the exposure time limitations for personnel working in areas with high levels of OEH threats.  Personal Protective Equipment (PPE) includes physical barriers between personnel and the OEH threat.  Examples of PPE include respiratory protection masks, ear plugs, or rubber gloves (DOD, 2008:5-6).

The added ventilation provided by a UTC system could make it a viable engineering solution that BE could implement when addressing air quality concerns. Implementation of a UTC system would address the BE requirements to control exposures while simultaneously addressing several of the CE energy challenges we addressed earlier in the literature.

The aforementioned mandates and requirements make it clear that having a basic understanding of the various types of alternative energy options that necessitate meeting these goals is critical – not only to energy managers, but to all Air Force leaders and decision-makers.  The primary focus of our research effort will be to evaluate the use of UTCs to meet these goals in a cost effective manner.  We have also included additional information on various alternatives that have already been utilized by the Air Force, which we provide in Appendix B:  U.S. Air Force Alternative Energy Initiatives.  In the following section, we will discuss some of the methods which can be used to alleviate many of the financial hurdles associated with implementing alternative energy programs.

**Alternative Energy Funding**

Rising energy costs make the idea of a cost effective alternative energy program extremely desirable.  One of the benefits of pursuing alternative energy programs is that it provides a means of shielding against potential rises in energy costs.  This benefit can be realized through the way in which the energy solution in procured.  One of the major obstacles faced by UTCs, and most other forms of alternative energy, is that the majority of life-cycle costs (LCC) are incurred during the initial phase of the program, prior to construction. The financial rewards from implementing the new renewable energy system is then paid back over time, often over the course of many years. This creates a challenge to decision-makers, particularly in the Air Force, due to the fact that many commanders are only leading their organizations for one to four years. If the initial costs are significant, and the financial benefits during the commander's short tenure only make up a fraction of these costs, it may make them less likely to actively pursue such efforts. To address this issue, there have been a number of different financial incentives and programs put in place. Two such programs are the Energy Conservation Investment Program and Performance Based Contracts.

***Energy Conservation Investment Program***

In response to rising energy costs facing the DoD, the federal government established the Energy Conservation Investment Program (ECIP). This program is a subset of the defense agencies' Military Construction (MILCON) program and was established in 1993 to replace Defense Energy Program Policy Memorandum (DEPPM) 92-2 (ECIP, 1993). The purpose of the ECIP is to provide funding for programs which will help increase efficiencies in energy and water use by the U.S. military. Since its inception, ECIP investments of $553 million have returned approximately $1.5 billion in energy and water reductions. The Savings-to-Investment Ratio (SIR) of the program is nearly 3:1, which is one of the highest across the federal government (Program Assessment, 2008).

To apply for ECIP funding, each military service and defense agency must submit documentation on the potential projects to the Deputy Assistant Secretary of Defense (Logistics) through the normal Military Construction review by the fifteenth of February for the following fiscal year. If the funding is approved and the project is implemented, an annual report must be provided to indicate the progress of the ECIP project. This information will ultimately be incorporated into the DOE's report to Congress.

The awarding of ECIP funding is based on the strength of the program's SIR and the payback period of the investment. Prioritization between programs is based on which have the highest SIR and shortest payback period. The payback threshold must be less than 10 years and the minimum acceptable SIR is 1.25. This means that for every dollar invested, the minimum acceptable return is $1.25. The extra 25 cents on the dollar is to allow for a 25 percent variation allowance to ensure a positive return on the investment over the life of the project (ECIP, 1993). A summary of ECIP funding from fiscal year 2001 to fiscal year 2009 is shown in Table 3. ECIP funding will continue to rise through 2013, when the annual funding is estimated to reach $130 million.

**Table 3: Summary of ECIP Funding, 2001 - 2009**

| YEAR | Cost ($M) | Total Projects | SIR | Payback |
|---|---|---|---|---|
| 2001 | $14.90 | NA | 4.86 | 3.69 |
| 2002 | $26.67 | 22 | 3.90 | 5.10 |
| 2003 | $34.53 | 32 | 3.40 | 5.51 |
| 2004 | $49.82 | 36 | 2.53 | 6.74 |
| 2005 | $49.70 | 42 | 2.22 | 3.64 |
| 2006 | $49.81 | 43 | 2.49 | 5.94 |
| 2007 | $54.62 | 46 | 1.98 | 7.57 |
| 2008 | $70.00 | NA | NA | NA |
| 2009 | $80.00 | NA | NA | NA |

Information marked “NA” were not provided by source.

(Source: ECIP, 2008)

***Performance Based Contracts***

Performance Based Contracting (PBC) would be a viable option for the Air Force and it could allow for accelerated growth in alternative energy participation. PBC is a form of contracting in which a third party contractor takes responsibility for the management of a specific part of the business. For example, a contractor could take responsibility for the electricity requirements to satisfy operations at a particular Air Force installation. The contractor then adopts the risk for managing that part of the business but also gets to realize all of the initial financial rewards for making it more efficient. The efficiency gains are then ultimately shared between the contractor and the Air Force installation (Australian, 2007).

Alternative energy programs such as wind and solar power are specific examples in which PBC would provide a great opportunity for numerous Air Force and DoD installations. There are PBCs who will pay for and build the wind turbine or solar panels for the user, on the user’s own land. In exchange, the user continues to pay historical energy prices for a specified length of time. The PBC, in turn, gets to realize the energy cost savings that they have created with their alternative energy system. At the end of the contract, the company lets the user keep the system, and the user no longer has to pay the historical energy prices. In the end, the user has a long-term producer of energy in the form of an alternative energy system, and they never have to pay the substantial, one-time cost of initially putting the system in place. Therefore, it is feasible to put such systems in place in large quantities, without having to incur a large up-front cost.

This form of procurement is a viable, and excellent, option for the U.S. government. It will save tax-payer dollars in the long run, and perhaps more importantly, not increase energy expenditures during a time period when the U.S. is operating in a deficit-spending state. For example, the initial cost of building and installing a wind generator makes up roughly 90 percent of the life-cycle cost of wind power (Combs, 2005). This cost is viewed by many as a “barrier to entry” in terms of using wind power, and is commonly presented as a legitimate argument against its utilization. However, by using a PBC you can circumvent this extraordinary cost while also shielding from the rising costs of energy. Instead of being held at the mercy of fluctuating energy prices, wind power users are concerned instead with how much wind is present at the site of the generator(s). Wind is a renewable resource, and unlike oil, there is no risk that there will be a prolonged reduction in supply that leads to increases in demand, and ultimately, price. Also, aside from the emissions generated during the manufacturing process, operating wind generators emit zero emissions that are harmful to the environment. In addition to being a beneficial method of procuring wind power, other alternative energy systems would certainly benefit as well. This is because with most alternative energy systems, the initial costs are typically a large portion of the system's overall LCC. UTC systems are no exception and future users could also benefit from this form of procurement.

**Air Force Renewable Energy Programs**

The Air Force has already made great strides in the alternative energy campaign. This is in large part due to adherence to the executive orders and energy acts which were previously discussed. The Air Force has adopted a three-part energy strategy focusing on reducing energy demand through efficiency and conservation, increasing energy supply through the use of alternative energy sources, and creating a cultural shift in the Air Force in which energy is a consideration in all that Airmen do.

Effective implementation of this strategy is apparent. Numerous installations have participated in the Green Power Partnership program with the EPA and have taken steps to utilize alternative energy. Currently, four percent of Air Force power comes from "green energy" and the Air Force has received the EPA Green Power Leadership Award in 2004, and the Partner of the Year award in 2003 and 2005 (EPA, 2007). The Air Force is the leading federal government organization in green energy use, and ranks third across all national participants in the EPA's Green Power Partnership Program (EPA, 2008). These commendable accomplishments, however, mark only the beginning of what Air Force leadership hopes to accomplish. Mr. William Anderson made this clear in his statement that,

> Even though we are the largest green power customer in America and the third largest in the world, we are still just scratching the surface right now. We know there is unlimited potential for energy conservation ahead of us, and we are continuing to be an energy-conscious force for years to come (Woodbury, 2006).

Table 4 and Table 5 provide further detail on where the Air Force ranks in "green" energy use.

**Table 4: Top 10 Federal Government Partner List**

| Rank | Partner | Annual Green Power Usage (kWh) | GP % of Total Electricity Use | Green Power Resources |
|---|---|---|---|---|
| **1** | **U.S. Air Force** | **899,143,000** | **9%** | **Biogas, Biomass, Geothermal, Solar, Wind** |
| 2 | U.S. Environmental Protection Agency | 299,331,375 | 100% | Biogas, Biomass, Geothermal, Wind |
| 3 | U.S. Department of Energy | 157,964,000 | 3% | Biogas, Biomass, Geothermal, Small-Hydro, Wind |
| 4 | U.S. Department of Veterans Affairs | 100,000,000 | 3% | Biomass |
| 5 | U.S. General Services Administration | 78,930,000 | 34% | Biogas, Wind |
| 6 | U.S. Army - Fort Lewis | 48,000,000 | 20% | Biogas |
| 7 | U.S. Army - Fort Carson | 40,000,000 | 29% | Biomass, Wind |
| 8 | Statue of Liberty / Ellis Island | 9,414,000 | 100% | Wind |
| 9 | U.S. Internal Revenue Service | 7,500,000 | 3% | Biomass |
| 10 | U.S. Department of Agriculture | 6,520,000 | 15% | Biogas |

(Source: EPA – Partnership: Federal Top 10, 2008)

**Table 5: National Top 10 Partner List**

| Rank | Partner | Annual Green Power Usage (kWh) | GP % of Total Electricity Use | Green Power Resources |
|---|---|---|---|---|
| 1 | Intel Corporation | 1,302,040,000 | 47% | Biomass, Geothermal, Solar, Wind |
| 2 | PepsiCo | 1,144,773,154 | 100% | Various |
| **3** | **U.S. Air Force** | **899,143,000** | **9%** | **Biogas, Biomass, Geothermal, Solar, Wind** |
| 4 | Wells Fargo and Company | 550,000,000 | 42% | Wind |
| 5 | Whole Foods Market | 509,104,786 | 100% | Biogas, Solar, Wind |
| 6 | The Pepsi Bottling Group, Inc. | 470,216,838 | 100% | Various |
| 7 | Johnson & Johnson | 434,854,733 | 38% | Biomass, Small hydro, Solar, Wind |
| 8 | Cisco Systems, Inc. | 378,000,000 | 44% | Biogas, Biomass, Solar, Wind |
| 9 | City of Houston, TX | 350,400,000 | 27% | Wind |
| 10 | City of Dallas, TX | 333,659,840 | 40% | Wind |

(Source: EPA – Partnership: National Top 25, 2008)

As of FY 2007, 37 different Air Force bases have met a portion of their energy demands through renewable energy supply (Energy Strategy, 2008). Dyess Air Force Base (AFB) was the first DoD installation to be completely powered by renewable energy. Following Dyess AFB's lead, at least nine other Air Force bases have taken the initiative to follow suit. This includes the following Air Force bases: Cannon, Edwards, Ellsworth, Fairchild, Goodfellow, Laughlin, Minot, Sheppard, and Tyndall. To date, Minot and Fairchild have both accomplished the feat of being powered by 100 percent renewable energy.

In regards to future green energy projects, the Air Force is developing a new energy initiative test program. Barksdale AFB and McGuire AFB will each serve as test bases where officials will be looking at buildings, offices, hangars, and all other facilities to develop best practices in alternative energy and energy efficiency to implement across the Air Force (Air Force News, 2007). Another function of the program will be to monitor fuel efficiencies and introduce the use of alternative fuels in ground vehicle fleets and in aviation operations. In addition, evaluations will be made on ways to improve aviation fuel efficiencies by looking at flight planning, reducing excess weight, and other initiatives (Air Force News, 2007). With the lessons learned from these two bases, the Air Force hopes to improve not only their own operations, but those of its sister services across the DoD as well.

**Solar Air Heating**

This research focuses on a particular form of Solar Air Heating (SAH) called SolarWall® which is a patented technology developed by Conserval Engineering, Inc.

SolarWalls® are a type of UTC which harnesses solar energy from the sun to heat the air used in ventilation systems for buildings.

***History***

Conserval Engineering is a Canadian based company formed in 1977. The original SolarWall® was created in 1985 and Ford Motor Company installed the first commercial-use system the following year. SolarWalls® were patented in 1988 under U.S. patent 4,774,932 (Hollick, 1988). In addition, SolarWalls® are protected by U.S. patents 4,899,728; 4,934,338; 5,935,343; and 7,032,588 as well as Canadian patents 1,196,825; 1,283,333; 1,326,619; 2,230,471; and 2,503,395.

In 1992, SolarWall® technology received recognition from the United States Department of Energy by being rated in the top two percent of energy inventions. Since that time, SolarWall® has received awards from Popular Science, R&D Magazine, Natural Resources Canada, the Manning Awards, Toronto Construction Association, and the Swiss Solar Prize. To date, over 1,000 SolarWall® systems have been installed in 25 different countries (Milestones, 2008). Figure 9 provides a visual reference as to what a typical UTC application looks like before, during, and after installation.

**Figure 9: Picture of UTC Wall - Before, During, and After Installation**
(Source: Rowley, 2006)

***Description of UTCs* (or SolarWalls®)**

UTCs consist of aluminum or steel cladding that is placed six to ten inches away from the existing conventional walls to create an air space between the existing wall and the cladding. Solar energy from the sun then heats the metal cladding of the solar wall. The cladding has small perforations throughout the surface of the wall, and a fan is used to create negative pressure to draw fresh air in through these perforations. The fresh air drawn through these holes are heated by the cladding which has been warmed by the sun's energy. Once the warm air enters the air space, convection causes the air to rise to the top of the wall. From there, the fan continues to draw the air into the Heating, Ventilation, and Air Conditioning (HVAC) system. The air can then either be heated further by the HVAC system or be distributed at its existing temperature. Figure 10 illustrates a typical application of a SolarWall® UTC system.

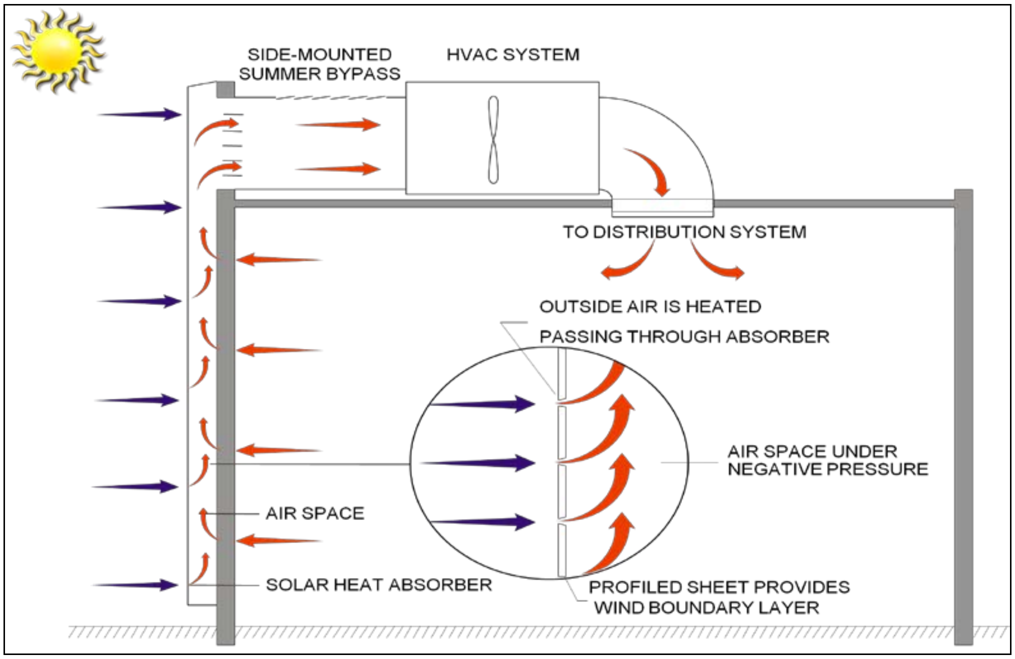



**Figure 10: Depiction of Typical SolarWall® Application**
(Source: SolarWall® - How it Works, 2008)

In addition to helping pre-heat the fresh air being brought into the facility, the UTC wall is also able to help maintain heat energy that is already in the facility. The airspace, or plenum, between the UTC wall and the facility's existing wall is able to capture heat escaping out of that facility wall. The heat is then mixed with the incoming air and returns to the facility. This makes the system particularly effective for buildings with poor insulation properties.

The absorbing wall of the UTC system is corrugated to make it more durable to the elements and help reduce the amount of wind that travels across the face of the wall. The corrugation also creates more surface area, allowing for more exposure to sunlight and room for a greater number of perforations. There can be over 240 perforations per $ft^2$ on the wall and the diameter of the perforations can be customized based on the amount of air flow desired by the user. A closer view of the wall surface can be found in Figure 11. Note the multiple incoming air perforations and the corrugation of the collector wall.

**Figure 11: Surface of a Typical Corrugated UTC Wall**

UTCs are available in a variety of colors which can be customized based on the preferences of the user. The tradeoff in regards to color selection is typically between maximizing solar gain, using near-black colors, while trying to maintain the architectural theme of the building. Each color has its own level of solar absorptivity which is a measure of how much sunlight the color absorbs. Darker colors absorb more light than lighter colors and as a result, they are able to provide greater gains in heat generation. Table 30 located in Appendix C provides a list of available SolarWall® colors along with their respective levels of solar absorptivity.

*Configuration During Cooling Days*

Although the primary purpose of the UTC system is to preheat ventilation air during colder months of the year, it can also add value during the warmer summer months. The system is equipped with a "summer" bypass located above the cladding to allow warm air to be released during cooling days of the year when the heated air is not needed. During the day, the UTC wall can also act as a passive sunscreen to keep direct sunlight from hitting the existing wall of the building. The fan for the UTC system can then draw cooler air through a bypass intake not connected to the warm air space behind the UTC wall. The summer bypass configuration for cooling days is illustrated in Figure 12.

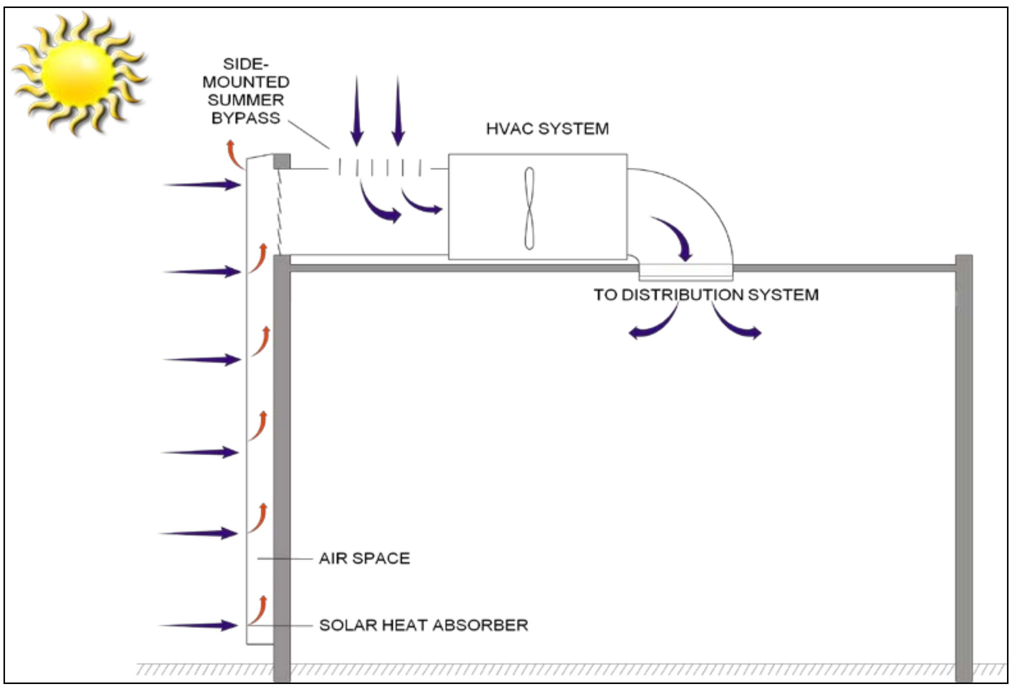



**Figure 12: Bypass Configuration During Cooling Days**
(SolarWall® - How it Works, 2008)

The UTC system can also be used to pre-cool facilities at night during the warmer months of the year. By running the system at night, the cooler night air can be brought into the workspace through the UTC to create a comfortable work area for employees arriving in the morning, while also reducing early morning cooling demands. This application works particularly well in dryer climates where humidity is low and dampness is not an issue.

***Heat Stratification***

Another purpose of UTC systems is to help support proper air temperature balance in facilities. Warm air naturally rises over cooler air because it is lighter, or less dense. For large facilities, such as hangars and warehouses, this stratification of air temperatures can increase heating loads during winter months and make it more difficult to create comfortable working environments. In addition, air handling units typically expend exhausted air from the ceiling of a facility. When this warm air is sent out of the facility, it reduces the pressure in the building and causes cool outside air to be drawn in at the lower areas of the building. This can make a building feel too cold at the floor level, while making it uncomfortably hot at the ceiling level of the building, a particularly bad problem in large facilities with a loft area. A depiction of this stratification occurrence is shown in Figure 13.

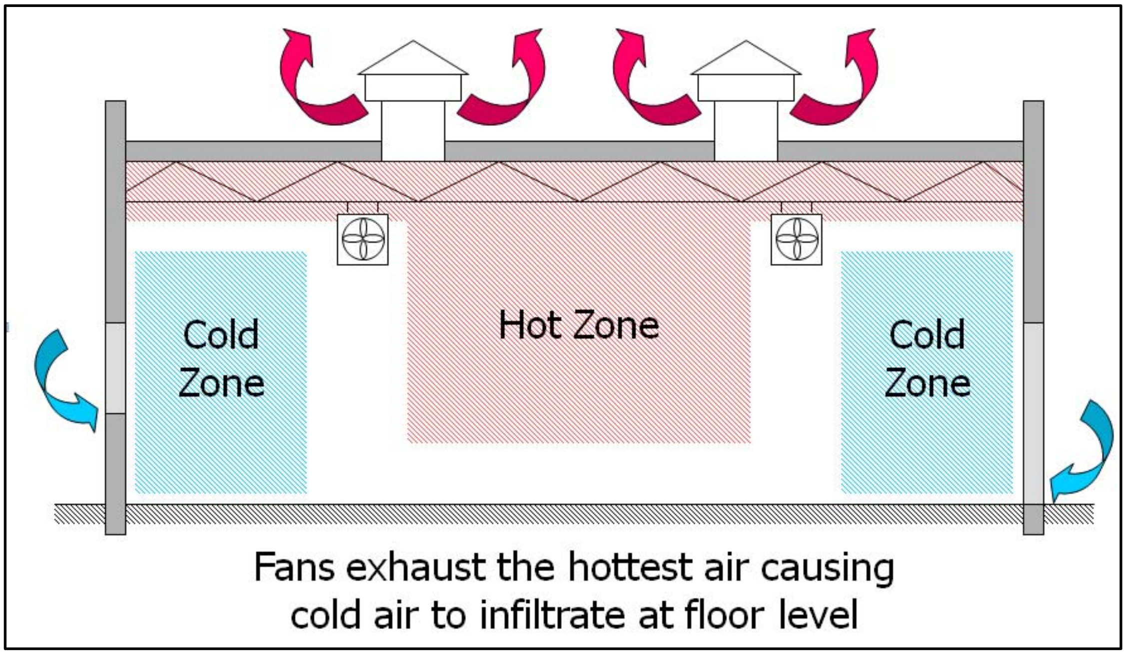



**Figure 13: Air Temperature Stratification in Large Industrial Buildings**
(Source: Rowley, 2007)

In order to balance air temperature, the warmer air at the ceiling level needs to be circulated with the cooler air in the building to provide a more consistent air temperature throughout the building. Industrial applications of UTC systems can help break-up the air temperature stratification by expelling fresh air toward the ceiling of the building. Although the fresh air has been pre-heated by the UTC system, the air temperature of the fresh air is still cooler than the air being heated by the existing heating system. By injecting cooler air at the ceiling level, it mixes with the warmer air, allowing a consistent air temperature to settle throughout the facility. In Figure 14, we demonstrate how adding a UTC system to the industrial building shown in Figure 13 can help reduce the stratification of air temperatures throughout the facility.

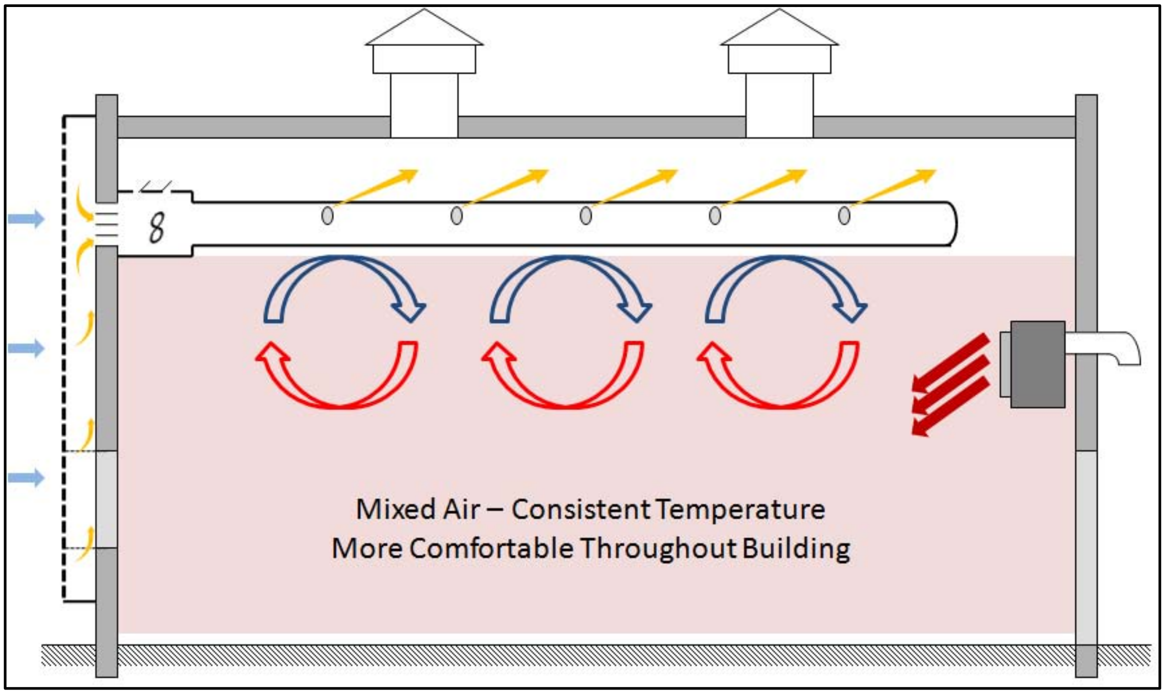



**Figure 14: UTC System Reducing Stratification in Industrial Building**

***Other Applications***

There are other types of applications for UTCs besides preheating ventilation air. One of the most effective uses of UTC systems is for process drying such as drying crops, commercial laundry, fire hoses, or items in paint shops. UTCs can also be used to preheat air for combustion furnaces and assist in heating swimming pools. Although not all of these different uses may be relevant for the Air Force, the use of UTCs for drying purposes at fire stations and paint ships may be worth further investigation.

Most Air Force installations have a dedicated fire station which could use a UTC to not only preheat ventilated air for the fire house, but potentially heat air used to dry fire hoses. Paint shops could also benefit from using UTCs to provide warm ventilated air for their drying and curing process. The Air Force Occupational Safety and Health Standard

91-20 highlights many of the hazards found in paint shops. Mists and vapors from the painting process may be highly flammable and many of the paints used by the Air Force contain highly toxic substances (SECAF – Safety, 2008:5). UTCs can be used for ventilation to help mitigate the fire and health risks created during the painting process. In addition to addressing these ventilation requirements, UTCs can assist in meeting the heat requirements of the painting process. Warm air is needed to help reduce moisture during the painting process and hot air may be required in situations where paint needs to be cured, or heated to high temperatures.

***Use at Military Installations***

UTC technology has already been utilized by a number of different U.S. and Canadian military installations. In 1997, Norfolk Naval Base in Virginia was the first to utilize UTCs by outfitting two maintenance buildings with the technology (SolarWall® - *Military*, 2008). Since that time, UTCs have been used at the following U.S. bases: Buckley AFB, Colorado; Edwards AFB, California; Elmendorf AFB, Alaska; Peterson AFB, Colorado; Fort Drum, New York; Fort Carson, Colorado; Fort Lewis, Washington; and Fort Huachuca, Arizona. The funding for these UTC projects has been provided by energy funding programs, to include ECIP. UTC systems have also been used in Alberta by the Canadian military at CFB Suffield and CFB Wainwright (Military, 2008).

***Potential Benefits of UTCs***

The main benefit of a UTC system is that it reduces the amount of heating fuel required to operate air heating systems by preheating fresh air for the HVAC system. If used properly and in the appropriate environment, UTCs can provide fresh ventilated air in an economically and environmentally friendly manner for decades. In the following two sections, we highlight the potential for realizing life-cycle cost savings and earning points towards LEED certification through UTC use.

### *Life-Cycle Cost (LCC) Savings*

UTC costs are almost 100 percent initial costs and the payback period to recoup these costs is much shorter than other popular solar technologies, such as photovoltaic (PV) cells. Due to the long life of UTCs, typically 30 years or longer, the life-cycle cost (LCC) savings of these systems can be substantial. Since installing SolarWalls® at seven different plants in the mid 1980s, Ford Motor Company has lowered energy usage by 350,000 Million British Thermal Units (MBTU) per year, which has yielded over $10 million in costs savings (Ford, 2008). This demonstrates the long-term potential cost savings that can be realized through the use of a UTC system.

### *LEED Certification Points*

UTC systems can provide up to six "green" points towards meeting the LEED certification requirements set forth in the Sustainable Design and Development (SDD) policy memorandum. Five of these six points would fall under the "Energy and Atmosphere" LEED category while the other point that can reasonably be obtained falls within "Indoor Environmental Quality." UTC technology can also contribute towards achieving "Materials and Resources – Recycled Content;" however, it should be noted that the contribution made by a UTC is relatively small in relation to the complete building construction (SolarWall® - Designing, 2008).

From Table 2, found on page 24, we can see the significance that each individual "green" point has on obtaining different certification levels. The difference between obtaining a "certified" rating and the mandated "Silver" rating is only a matter of seven points. We can therefore see how UTC implementation could possibly benefit engineers who are having a difficult time accumulating enough points to earn "Silver" LEED certification for a proposed project.

**Previous Research**

Published research on UTCs can be traced back to the early 1990s. The majority of applicable published research has focused on heat transfer theory, modeling, and potential applications of UTCs. Measuring the efficiency and effectiveness of UTCs is a complex and arduous task. However, by gaining a better understanding of UTC systems through these studies, researchers can create more accurate UTC models which can lead to more effective use of the systems in the future. Potential customers of UTC systems would be better able to gain a more realistic understanding of how a UTC system would perform for them due to these improvements in modeling. UTC system designers would also be able to provide a more effective product to these customers because they would have a better understanding of the characteristics that drive UTC performance.

Previous research has primarily explored the effects on UTCs based on the following characteristics: the pitch, diameter, and shape of the perforations on the UTC; the surface area of the UTC; the type of material (conductivity) used for the absorber; the wind speed and direction on the UTC absorber surface; the various levels of porosity of the UTC surface area; the amount of pressure being generated by the UTC fan; the amount of exposure to solar radiation; and the addition of a PV panel to be used in conjunction with the UTC.

### *Heat Transfer Theory*

Kutscher *et al.* (1993) examined the major heat loss mechanisms associated with the concept of UTC systems. They state the importance of having a sufficiently high pressure drop across the absorber to provide reasonably uniform flow with a UTC. The reason for this importance is to avoid the issue of having any localized outflow across the absorber surface. They created a predictive model which predicts collector efficiency based on suction velocity, wind speed, ambient temperature, and radiation. Their results showed that as suction velocity decreases, the effect of wind speed on collector efficiency increases, particularly for absorbers with lower emissivity. They also found that the benefits of using a lower emissivity absorber generally increase as suction velocity decreases. In conclusion, Kutscher *et al.* (1993) found that heat losses due to natural convection are minimal, and that the losses due to wind should be small for large collectors which are operated at normal suction velocities. This theory, however, was based on fairly ideal circumstances in regards to parallel laminar external flow and homogeneous suction across the absorber surface. The limitation is addressed and the authors state that further work is underway to extend the research to less ideal circumstances. Additional studies have been performed to determine the minimum fan speed required to maintain an adequate boundary layer which can sustain cross-winds and prevent outflows along the absorber surface.

In his subsequent research, Kutscher (1994) further investigated convective heat transfer effectiveness in an environment of low-speed air flow through thin, isothermal perforated plates with and without crosswind on the upstream face. Through this research, Kutscher (1994) hoped to determine the optimum hole size and spacing for

UTC design. His results showed that the major factors which affect heat transfer are suction flow rate, crosswind speed, hole pitch, and hole diameter. He concluded that effectiveness increases with increases in wind speed but that effectiveness decreases with increases in suction flow rate, hole pitch, or hole diameter. When a cross-wind is present, he found that the major orientation of the holes along the absorber plate were important. He found that higher effectiveness values were present in the case in which the holes had less spacing between them in the cross-stream direction of the hole rows (Kutscher, 1994).

In 1996, Gunnewiek *et al.* studied the flow distribution in large-area UTCs by using a two-dimensional Computational Fluid Dynamics (CFD) model. A UTC with a large surface area may be more susceptible to problems with uniform flow or areas of outflow. Six parameters were studied to gain a better understanding of their effects on a large UTC to help address this issue. These parameters included collector height, plenum aspect ratio (height to depth ratios), heat exchange effectiveness, average suction velocity, plate hydraulic impedance range, and net absorbed solar irradiance. The results from the study concluded that an average suction velocity of 0.0125 m/s should be maintained to avoid reverse flow. They also found that in instances where air flow is non-uniform, substantial heat transfer occurs on the back of the absorber plate as air rises up the plenum. It should be noted that this two-dimensional CFD model was conducted under no-wind conditions (Gennewiek *et al.*, 1996).

Arulanandam *et al.* (2000) also analyzed heat transfer effectiveness using CFD simulations. The stated limitations of the study were that the assumption of no-wind conditions was used and the CFD simulations excluded the effect of heat transfer occurring at the back of the absorber plate. In real-world applications, these two factors would certainly have an impact on the heat transfer effectiveness of a UTC. The authors stated that despite these limiting assumptions, the model used in the study can be combined with experimental data to permit a wider-ranging correlation equation to be obtained. A correlation for the Nusselt number was determined based on four dimensionless parameters: the Reynolds number, plate porosity, non-dimensional plate thickness, and plate admittance. A Nusselt number is the ratio of convective to conductive heat transfer across a boundary surface, in this case the face of a UTC wall. The research also demonstrated the potential for using lower conductivity materials for the absorbing material of a UTC. It was found that although effectiveness dropped when lower conductivity absorbers were used, the drop was not significant enough to discard the idea of using lower conductivity materials to achieve acceptable efficiencies. An example of a lower conductivity material that was mentioned is using plastics rather than more conductive materials such as steel or aluminum, which are the standard materials used with UTC systems (Arulanandam *et al.*, 2000). However, unless the cost benefit of using lower conductivity materials outweighs the losses in effectiveness that would be created, there may be limited potential for such application. In addition, structural durability should be addressed in deciding between various materials to be used for the UTC absorber plate.

Van Decker *et al.* (2001) extended upon the previous research of Kutscher *et al.* (1993)by incorporating a wider range of plate thicknesses, hole spacings (pitch), suction velocities, and also included a square layout of the holes. Van Decker *et al*. (2001) found that in areas in which the two experiments overlapped, the agreement between the two was excellent. One difference between Van Decker *et al*. (2001) and previous studies was that their model was developed to capture the individual heat transfer contributions made at the three main sections of the absorber plate: the front, hole, and back. The overall range of effectiveness that was found in the study ranged from 0.32 to 0.91 based on the various parameter settings in the study. The parameters include suction velocity, wind speed, hole pitch, plate thickness, hole diameter, and plate thermal conductivity. It was concluded that effectiveness decreased with increases in suction, hole pitch, and hole diameter. Effectiveness was found to increase with increasing wind speed and plate thickness. Suction velocity and plate thickness had the most significant effect and thermal conductivity had the least significant effect. The model developed by Van Decker *et al*. (2001) found that "under typical operating conditions, about 62 percent of the ultimate temperature rise of the air is predicted to occur on the front of the surface, 28 percent in the hole, and 10 percent on the back of the plate."

In 2002, Gunnewiek *et al*. extended their prior research from 1996 by including the presence of high wind conditions. They found that wind has a pronounced effect on the velocity distribution, but that this effect was not so large that it should keep users from operating UTCs during windy conditions. They found that the previously recommended minimum suction velocity of 0.0125 m/s should be raised to avoid reverse flow under various conditions. They recommended that this velocity be raised to 0.017 m/s for long buildings in which the collector is facing into the wind, 0.026 m/s for cubical buildings in which the collector is facing into the wind, and to 0.039 m/s for a cubical building with the wind incident on the collector at a 45 degree angle (Gunnewiek *et al.*, 2002).

Gawlik *et al.* (2002) investigated the convective heat loss on a corrugated UTC absorber surface that is caused as a function of wind speed, suction velocity, and plate geometry. The study was conducted using a numerical model which was then validated by wind tunnel tests and hot wire anemometer/resistance thermometer measurements. Many of the UTC studies conducted prior to this research focused on absorbing surfaces that used a flat plate rather than a corrugated one. Corrugated plates, particularly in the case of larger scale applications, would be preferred over flat plate surfaces because the corrugation provides greater structural support.

Gawlik *et al.* (2002) found that there are a number of ways in which air flow over a corrugated plate differs from that of a flat plate. Their observations showed that under similar conditions, the starting length for boundary layers along a corrugated plate are greater than those along a flat plate. It was also observed that the boundary layer over the corrugated plate is laminar and may be fully attached or partially separated depending on the cross-wind speed and amount of suction being provided by the UTC fan. In regards to heat loss, it was observed that the separated flow crosswind heat loss from corrugated plates is greater than that from flat plates. It was found, however, that this was more of an issue with smaller UTCs, as the heat loss as a fraction of total incident radiation drops as the size of the collector increases. Wind speeds were shown to play a significant role in maintaining flow attachment. As would be expected, at lower wind speeds the wind heat loss is low. Wind heat loss increases significantly when the wind speed is high enough to cause separation (Gawlik *et al.*, 2002). Criterion for determining flow attachment was developed as well as correlations for determining heat transfer in the case of both attached and separated flow.

In 2005, Gawlik *et al.* performed additional research on the use of practical low-conductivity materials in UTC systems. The results of the study found that using low-conductivity materials such as styrene or polyethylene as a substitute for highly conductive materials like aluminum has only a small negative effect on the thermal performance of a UTC. This is significant because benefits such as cost savings and corrosion resistance could be realized through the use of less conductive materials. In addition, it is possible to use low-conductivity materials with the added benefit of being flexible or portable. This would make it possible to easily remove, transport, and store the UTC absorber wall (Gawlik *et al.*, 2005).

Leon *et al.* (2006) performed a mathematical model to predict the thermal performance of UTC over a range of operating conditions which would be suitable for drying applications (delivering air temperatures in the range of 45 to 55 degrees Celsius). The varying parameters of the model were porosity, airflow rate, solar radiation, and solar absorptivity/thermal emissivity. These parameters were used to determine their effect on collector efficiency, heat exchange effectiveness, air temperature rise, and useful heat delivered. It was found that solar absorptivity, collector pitch, and airflow rate have the most significant effect on collector heat exchange effectiveness and efficiency. In addition, porosity and thermal emissivity were found to have only a moderate effect on heat exchange effectiveness. The results of the study concluded that UTC is an attractive alternative to glazed solar collectors used for drying food products. To achieve the best collector performance, the study found that establishing a good balance between the airflow rate, air temperature rise, collector efficiency and pressure loss are the most important factors (Leon *et al.*, 2006).

### ***Evaluation of UTC Implementation***

Site-specific evaluations of UTC systems utilization has also been found in previous research by Meier (2000), Maurer (2004), Naveed *et al.* (2006), Ashley (2007), and Delisle (2008). In 2000, Meier performed an evaluation of the wind effects on the performance of a SolarWall® collector by performing an experimental study on a SolarWall® at the Canadian Coast Guard Base in Prescott, Ontario. The data gathered on the SolarWall® indicated that efficiency and effectiveness of the system were both influenced by the oncoming wind direction. It was found that efficiencies were generally higher when wind was flowing over the top of the building rather than along the building, parallel to the absorber wall. This is because Meier (2004) found that a recirculation or stagnation zone developed when the wind flowed over the building; however, when the wind flowed parallel to the SolarWall®, the heated air tended to be swept away from the wall. It was also determined that efficiency decreased as turbulence levels increased (Meier, 2000). These findings support much of the previous research which we highlighted in the previous section.

The objective of Maurer's (2004) thesis research was to determine whether UTC use is appropriate in North Carolina, which has a fairly mild climate and a relatively short warming season. It was determined that although the shorter warming season would make UTC implementation less advantageous in such an environment, some industrial and commercial buildings could still benefit from the technology. The effectiveness of such a system in North Carolina depends greatly on the site characteristics and building conditions, however, and the potential application of UTC systems should be considered on a case-by-case basis (Maurer, 2004).

In 2006, Naveed *et al.* did an experiment to measure the performance of a system which uses a PV module in conjunction with a UTC in South Korea. The significance of this configuration is that it is much more space efficient to attach a PV module onto a UTC. South Korea is particularly interested in such a configuration because it has extremely cold conditions during the winter and is a "conventional energy resources deficient country in which over 95 percent of energy requirements are met through imported energy" (Naveed *et al*, 2006). Results of the study found that there were other synergistic benefits in using the two systems together. Results indicated that the temperature of the PV module attached to a UTC was 5 to 10°C cooler than the PV module without UTC. PV systems operate more efficiently at lower operating temperatures and this temperature difference was significant enough to result in a six percent increase in energy generation by the cooler PV panel incorporated with the UTC. They concluded that it is possible to effectively combine PV and UTC to generate electricity and warm air for building heat simultaneously (Naveed *et al.*, 2006). Conserval Engineering has recently begun marketing and offering a combined PV and UTC system and this configuration may be representative of the future direction of UTC implementation.

Ashley (2007) performed two modeling studies in an attempt to better understand how to reduce ventilation energy demand in multifamily high-rise buildings through preconditioning. One of these modeling studies specifically analyzed UTC use across various high-rise buildings located across the state of New York. The locations included Albany, Binghamton, Buffalo, Massena, New York City, Rochester, and Syracuse. Ashley's (2007) model was built upon the previous UTC research models developed by

Summers (1995) and Maurer (2004) using TRNSYS software. Ashley's (2007) model took the TRNSYS model and adjusted it to account for various factors which he felt would improve the ability of the model to accurately predict real-world performance. The method of calculating energy savings was adjusted by Ashley (2007), as he found that the TRNSYS model ignored the cooling load that can be introduced by a UTC if it overheats the building. Ashley's (2007) model attempted to account for both the negative and positive cooling effects of the collector. Due to the uncertainty involved in understanding how the TRNSYS handles different scenarios, Ashley (2007) made several adjustments to the savings predicted by the model in order to "attempt to arrive at the value most appropriate for comparison to the TRNSYS model."

Ashley's (2007) models' concluded that the performance and economic benefits of utilizing UTCs for high-rise residential buildings in New York State is "borderline." One of the major factors leading to such marginal results was the fact that such an application in high-rise buildings does not provide the collector surface area and flow rates desired to provide adequate UTC performance. It is noted that UTC application would be more favorable in warehouse-type buildings where more favorable building conditions are present. Results indicated that at solar radiation levels above 200 $Wh/m^2$, high hourly efficiencies were independent of incident solar radiation. In addition, the control system used was found to play a significant role in determining the annual energy savings of the UTC system. Savings from the recapture of lost heat during the winter and shading effects during the summer cooling months were also discovered (Ashley, 2007).

Delisle (2008) performed a study of a UTC system combined with PV cells mounted directly to the absorber surface. The project involved the development of a

TRNSYS model to predict the performance of a PV/UTC system and then a 2.5 $m^2$ prototype was constructed. Comparisons were then made between the observed performance of the prototype and the predicted performance generated by the adjusted TRNSYS model (Delisle, 2008: iii).

The TRNSYS model developed by Delisle (2008) found that adding PV cells onto the UTC decreased the thermal energy savings by 5.9 percent, but that the electricity produced by the PV cells could recover 13.6 percent of the thermal energy savings. The prototype was tested at various air flow rates over a three-week period. Thermal output and electricity generation were recorded, and the experiment found that 10 percent more electricity was produced by the PV cells during periods in which the UTC fan was in operation. The experiment also found that as suction rates increased, the amount of cooling that occurred on the PV cells increased which has the potential to create higher levels of electricity production as well. The experiment, however, was unable to capture the effect of the PV cells on the thermal performance of the collector because an inadequate amount of absorber surface area was being covered by PV cells (Delisle, 2008). When comparing the resemblance between the TRNSYS simulations and the prototype experiment, Delisle (2008) found that the results were similar. However, Delisle's (2008) predictions did not fall within "experimental uncertainties." Delisle (2008) attributed these variations to the fact that the model was unable to accurately capture wind heat loss and that the prototype experienced non-uniform suction along the absorber surface which did not allow the system to operate at its peak performance.

# III. Methodology

This research evaluated the economic and environmental effectiveness of Unglazed Transpired Collector (UTC) implementation at U.S. Air Force installations. We assessed both the qualitative and quantitative factors associated with UTC use. We addressed the qualitative factors using a case study approach by gathering applicable information from UTC users across the DoD. The qualitative data gathered by this approach will assist in providing a consolidated source of information for potential UTC users in the Air Force and federal government. In addition, this qualitative data can assist in validating previous research addressed in the literature review as well as the quantitative predictions generated in this study.

Quantitative research was performed using RETScreen® Clean Energy Project Analysis Software to generate the estimated performance of hypothetical UTC systems at selected Air Force installations. Through the use of this modeling software, economic and environmental assessments were created at selected locations to assess the potential net present value (NPV), internal rate of return (IRR), savings-to-investment ratio (SIR), payback period, and reduction of greenhouse gas (GHG) emissions. The results of this research can be used to determine which locations provide the greatest potential for UTC implementation across the Air Force. This methodology can serve as a guide for future research and decision-making on implementing UTCs; it can also be applied to other alternative energy projects.

**Case Studies**

In an effort to contribute to the existing body of UTC knowledge in the federal government, objective case studies were performed to learn from the various individual projects that have been implemented across the DoD. The information gained from case studies was then consolidated and summarized to provide future users and researchers with a useful reference. The case studies performed in this research attempted to recognize the various factors which contribute to the ideal use of UTC systems. In addition, case studies helped identify what works well, what does not, and what can be done differently in the future to ensure more effective use of UTC systems. It is also an excellent way to assess risk management issues by highlighting potential pitfalls with UTC use in the DoD.

Our qualitative research method also included a site visit which was made in June 2008 to Fort Drum, New York. Fort Drum is home to the largest and most extensive SolarWall® projects in the world. There are over 50 SolarWall® systems which have been installed on 27 different buildings at the site and the amount of UTC paneling totals over 110,000 square feet (SolarWall® - Fort Drum, 2008). Our visit to Fort Drum not only allowed us to study a vast amount of UTC systems in person, but also provided the opportunity to gain insight from the energy manager at the installation, who is one of the DoD's most knowledgeable experts in SolarWall® technology and application. The knowledge gained from this visit facilitated the formulation of our case study questionnaire which would later be used in our case study analysis.

It is important to ensure that the individual case studies chosen be representative of, and can be accurately generalized to, the potential Air Force applications this research is attempting to address. Fortunately, there is a sample population of DoD UTC users from which samples can be drawn. These include Buckley AFB, Edwards AFB, Elmendorf AFB, Peterson AFB, Fort Carson, Fort Drum, Fort Huachuca, Fort Lewis, and Norfolk Naval Station. Data gathering was performed through the use of an objective list of questions used across all of the sample installations. A list of these questions can be found in Appendix D: Case Study Interview Questions. Although this prescribed list of questions was used in the case study process, the interview process will have inherent flexibility in its ability to gather relevant information that falls outside the scope of the questionnaire.

Data gathering was performed in person, over the telephone, or over electronic mail and was directed toward the most appropriate and informed individual at each installation. The most qualified person at each installation is typically the base energy manager, who is often responsible for implementing and managing the UTC system. The level of knowledge and involvement that the interviewee has on their UTC system will play a role in the quality and quantity of information that can be gathered in each case study. For this reason, great care was taken in recognizing and interviewing the most qualified individual in each case. In an effort to respect the anonymity of those who contributed to our case study, we refrained from including identifying information of the individuals who participated in our study. We consolidated the information gathered from participants to produce a concise report of findings and recommendations.

**Quantitative Assessments**

As is the case with other solar energy technologies, not all geographic locations may be able to effectively utilize transpired solar collectors. Locations with very low solar radiation exposure may find that the cost of a transpired solar collection system cannot be recouped by the financial benefits over the life of the system. In addition, locations which have very few required heating days may not realize the benefits of the system as much as those with a high number of heating-degree days. This is a limitation that certainly faces many regions of the world. One of the purposes of this research is to recognize these various environmental factors to help determine which Air Force installations would likely, and unlikely, benefit from transpired solar collectors.

To address the research objective of recognizing potential installations which could benefit from UTC use, a quantitative study was performed on selected locations. This study assessed the predicted performance of UTC systems under varying circumstances using modeling software. The performance characteristics that this evaluation attempted to capture were the economic and GHG emission reduction benefits that a UTC system would create under each respective scenario. The software program used for this assessment was the Clean Energy Project Analysis Software provided by the Renewable Energy Technology Screening (RETScreen®) International. The following sections will provide further detail on the RETScreen® software and the various economic and environmental assessment methods performed.

***RETScreen® Software***

The objective of RETScreen® International's Clean Energy Project Analysis Software is to provide decision support for the analysis of various clean energy projects. The software is provided by Natural Resources Canada and was created in collaboration with the National Aeronautics and Space Administration (NASA), United Nations Environment Program (UNEP), and the UNEP Global Environment Facility (GEF). The

Clean Energy Project Analysis Software can be used to evaluate the energy production, life-cycle costs, and GHG production of various renewable energy technologies (RETScreen®, 2005:Intro.5).

Aside from solar air heating, the RETScreen® software also has the ability to analyze wind energy, small hydro, photovoltaic, combined heat and power, biomass, solar water heating, passive solar heating, and ground-source heat pump projects. To determine the performance of a particular system, the RETScreen® software combines user-defined system design parameters and combines them with site-specific monthly weather data. The monthly weather data is available for over 4,700 sites and is calculated based on an average of 20 different sources of meteorological data for the period of 1961 to 1990 (RETScreen, 2005).

In regards to validation of the RETScreen® software, it is noted in the RETScreen® textbook that:

> Numerous experts have contributed to the development, testing, and validation of the RETScreen Solar Air Heating Model. Such experts include solar air heating modeling experts, cost engineering experts, GHG modeling specialists, financial analysis professionals, and ground station and satellite weather database scientists. (RETScreen, 2005:SAH.24)

In the solar air heating project analysis chapter of the RETScreen® textbook, two examples are provided to demonstrate the similarity between RETScreen® estimates and the data from real solar air heating system installations and another popular software program known as SWift™. The comparisons demonstrated that the RETScreen® software did an excellent job predicting energy savings, particularly for pre-feasibility studies (RETScreen®, 2005:SAH.28).

***Base Selection***

Before any qualitative modeling could be performed, we first determined which bases to assess in our research. When deciding which installations should be evaluated for UTC use, one of the main factors that we were concerned with is the annual amount of heating-degree days (HDD) at each installation location. A degree day, whether it be heating or cooling, is a measure of the difference between the daily mean temperature and a baseline temperature, typically 65 degrees Fahrenheit (Energy Almanac, 2008). The baseline temperature represents the desired mean temperature for a given facility. An example of how this measure is calculated would be a day that has a mean temperature of 50 degrees Fahrenheit would have 15 HDD, which would represent the difference between the actual mean temperature for the day and the baseline temperature of 65 degrees Fahrenheit. A cooling degree day (CDD) is calculated in the same manner; however, it is used to describe mean temperatures that are greater than the baseline temperature.

The second factor that we analyzed is the amount of daily solar radiation received at each installation. This is an important factor that drives the effective implementation of any technology that harnesses the sun's energy. The RETScreen® database includes daily solar radiation data figures that are a measure of the average amount of solar radiation received during one day on a horizontal surface for each month, represented in kilowatt-hours per square meter per day ($kWh/m^2/d$). Installations with higher amounts of daily solar radiation are better candidates for UTC implementation than those locations with very low daily solar radiation.

The third factor that was assessed is the wind speed at each location. The RETScreen® database includes average monthly wind speeds for each of the installations measured in meters per second (m/s). Wind speed is a concern because previous studies have indicated that high wind speeds can degrade the performance of UTCs by disrupting the boundary layer on the surface of the UTC and lead to undesired points of air outflow (Kutscher et al, 1993; Gunnewiek, 2002; Gawlik et al, 2002).

In determining which installations to analyze for the purposes of our study, we will first analyze each of the three factors for all active duty Air Force installations. We then ranked each installation based on each individual factor in an effort to separate potentially strong candidates from potentially weak ones. We then created thresholds for each factor to eliminate obviously weak candidates and highlight which candidates appear to have the greatest potential. For example, a base with no HDDs typically does not have a requirement to preheat ventilation air and can be eliminated from consideration. We used the knowledge gained from this analysis to systematically narrow down the candidate list until only a select group of installations remained that perform well in each of the three factor categories. These installations were then analyzed along with the four current Air Force installations that have already implemented UTCs: Buckley AFB, Edwards AFB, Elmendorf AFB, and Peterson AFB.

We also determined the climate zones for each location we selected for our analysis. This allowed us to analyze possible relationships between climate zone location and UTC performance. We determined climate zones based on the respective county in which each installation is located. ASHRAE Standard 90.1-2007 presents a map of U.S. climate zones as well as a climate zone index for every U.S. county. Climate zone designations are represented by a number and are typically followed by a letter. The numbers represent the amount of HDDs at each location, where higher numbers indicate higher HDDs. The letter “A” denotes moist climates, a “B” designation represents dry climates, and a “C” designation represents temperate climates. A map of U.S. climate zones can be found in Figure 15.

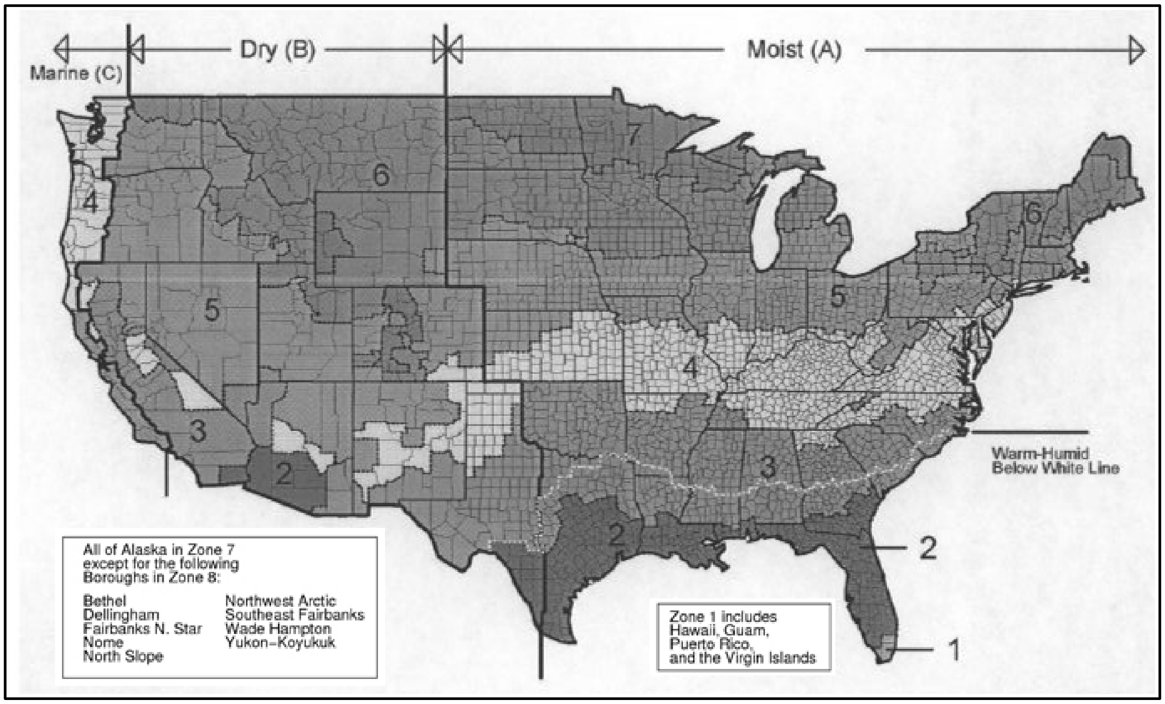



**Figure 15: Climate Zones for United States Locations**

(Source: ASHRAE, 2007:104)

***Energy Modeling***

In the literature review section included earlier, we showed that modeling solar air heating is a difficult task that has evolved a great deal since the inception of UTCs in the 1980s. Unfortunately, due to the broad scope involved in assessing various installations across the Air Force, we are unable to assess individual buildings at every location which may be possible candidates for UTCs. However, it is possible to define typical building characteristics in order to create comparable scenarios. In other words, we can create different hypothetical buildings which are representative of those found across Air Force installations, and then use the characteristics of these buildings as our input parameters for our RETScreen® modeling.

The three hypothetical buildings that we analyzed were a hangar, industrial warehouse, and a maintenance facility. Each of these different buildings could then be analyzed for each location to provide a basis for comparison among the various installations. We first performed a broad assessment across all of the locations included in our study, and then performed sensitivity analysis to gain a better understanding of how various factors can influence the performance of a UTC system.

There were numerous input parameters that we had to carefully consider before performing RETScreen® energy modeling for our proposed UTC systems. The RETScreen® program allows for the use of either metric or imperial units and can compute financial assessments using various forms of currency. For our evaluation, we used the widely considered U.S. standard of imperial units and 2008 constant–year (CY) U.S. dollars ($). The required inputs for our model can be broken out into four categories: load characteristics, solar air heater description, heating system characteristics, and financial analysis parameters. All of these inputs can be adjusted accordingly to represent changes made in our assumptions or when sensitivity analyses are performed.

In the first section of the energy model, load characteristics, we input our assumptions of the candidate facilities' characteristics. These inputs include the facility type, desired indoor temperature, minimum temperature, maximum temperature,

temperature stratification, floor area, thermal resistance (R-value) for both the roof and walls, desired airflow rate, operating days per week and hours per day, and the percent of each month that the system will be utilized. This section also includes orientation inputs about the UTC wall, to include the slope of the UTC wall and the azimuth of the UTC wall. A ninety degree slope would be indicative of a completely vertical wall while a zero degree slope would represent a completely horizontal surface. The azimuth is a measure of the degrees the wall faces away from true south. For example, a measure of zero degrees for the azimuth would indicate the wall faces true south, while a twenty degree measure would indicate the wall faces slightly east or west, twenty degrees from true north. The model does not distinguish between whether it is twenty degrees east or west, as the estimated exposure to sunlight is assumed to be similar in either case.

The second section of the UTC energy model includes our chosen characteristics of the solar collector. These inputs include the design objective of the collector, the price paid for the UTC system, the model and color of the collector, the area of the collector wall, shading of the collector, incremental fan power, and the electricity rate. For our electricity rate inputs, we used FY2008 rates for each individual installation based on Defense Utility Energy Reporting System (DUERS) data represented in dollars per kilowatt hour ($/kWh). We estimated the UTC system price based on cost information obtained from various sources which include Conserval Engineering, DoD UTC users, and RETScreen® design cost recommendations.

The third section of the UTC energy model includes our assumptions of the heating system used for the facility being analyzed. The system characteristics include the type of heating fuel used, the seasonal efficiency of the heating system, and the fuel rate. As with the electricity rate data, the fuel rate data used for each location comes from the DUERS database.

For the final section of the UTC energy model, we included all of our financial parameters. In this section, we included the assumed rate of inflation, project life, debt information, and other miscellaneous costs or incentives that were not addressed previously in the model. Once we completed this section of the model, along with the previous three, we could then begin to analyze the estimated results produced for our proposed UTC system.

***Financial Analysis***

Once we narrowed down the list of bases, gathered energy cost data for each location, and finalized the RETScreen® energy model specifications for our analysis, we were then able to generate our predicted UTC performance report for each location. Using the cost and savings data produced by the RETScreen® energy model, we determined the Net Present Value (NPV), Internal Rate of Return (IRR), SIR, and payback period.

We calculated these economic measures following the methods prescribed by the National Institute of Standards and Technology (NIST) Handbook 135, *Life-Cycle Costing Manual for the Federal Energy Management Program*. NISTR 85-3273-X, *Energy Price Indices and Discount Factors for LCC Analysis* is an annual supplement to NIST Handbook 135 that provides the updated discount rates to be used for LCC analysis. Federal projects involving energy and water conservation, as well as renewable energy, are required to use DOE established discount rates. The majority of other federal projects are required to use Office of Management and Budget (OMB) discount rates which are set forth in OMB Circular A-94 (Fuller, 1996:3-3). For the purposes of our research, we used the 2008 DOE real inflation rate of 3.0 percent, which is the applicable discount rate for an energy conservation or renewable energy federal project. This inflation rate is similar to the 2008 OMB real interest rate of 2.8 percent, which is the applied discount rate for a 30-year project subject to OMB Circular A-94 (Rushing, 2008:1). This coincides with the estimated useful life of a UTC system which is 30 years or greater (SolarWall® - Solar, 2008).

Although we expect the life of a typical UTC system to extend beyond 25 years, we assumed a 25-year project life for our analysis. We made this assumption to remain consistent with Title 10, *Code of Federal Regulations* (CFR) part 436, *Methodology and Procedures for Life Cycle Cost Analyses* which states: "For evaluating and ranking alternative retrofits for an existing Federal building, the study period is the expected life of the retrofit, or 25 years from the beginning of beneficial use, whichever is shorter" (DOE – Title 10, 2008:436.14).

***Net Present Value (NPV)***

NPV is a measure of the present value of a series of future cash flows combined with an initial investment. NPV takes into account the time value of money and allows decision-makers to determine the added, or subtracted, value an investment is expected to make to an organization. For mutually exclusive alternatives, the investment with the higher NPV should be selected. For independent projects, any investment with a NPV greater than zero should be accepted. Projects with a NPV less than zero provide no added value to an organization and should be rejected. A NPV of exactly zero means that the value added by the project is exactly enough to cover the opportunity cost of taking on the project.  In such a case, decision-makers would be indifferent and would need to take into account the various other factors involved in pursuing the project before coming to a decision.  In regards to energy investments, the positive cash flows used in all of the economic calculations in this research are represented by the cost savings incurred.  The following equation is used to calculate the NPV of an investment:

$$NPV = \sum_{t=0}^{N} \frac{CF_t}{(1+i)^t}$$

where (1)

*CF = cash flow*

*i = discount rate*

*t = single time period in a series of N periods in the life cycle*

*N = total number of time periods in the life cycle*

***Internal Rate of Return (IRR)***

The internal rate of return (IRR) is the rate of return that is required to result in a zero NPV when it is used as the discount rate (Ross, 2003:288).  This rate is useful in financial analysis because it provides a clear indicator of whether or not an investment will yield adequate results.  If the IRR exceeds the required rate of return, then decision-makers know that by taking on the investment they can expect to yield a favorable return.  This "required rate or return" can also be referred to as the cost of capital, or hurdle rate.

As an economic investment tool, it is important to note that IRR should not be used to rank or rate mutually exclusive projects against one another.  This is because an alternative may have a higher IRR than its challenger while the challenger may actually provide a greater NPV, making it the more favorable choice. The IRR is an important tool to decide whether an individual project is worth investing in and indicates the return as a percentage rate rather than an order of magnitude, as NPV calculations do. This allows decision-makers to determine the efficiency of investment dollars.

***Savings-to-Investment Ratio (SIR)***

The savings-to-investment ratio (SIR) is a cost-benefit ratio that represents the present value of the cost savings of an investment in relation to the present value of the investment costs. This economic measure is particularly important in this research because the ECIP program requires that projects have a SIR greater than or equal to 1.25. The SIR equation is:

$$\mathrm{SIR} = \frac{\mathrm{PV}(\mathrm{S_c})}{\mathrm{PV}(\mathrm{I_c})} \tag{2}$$

where

SIR = Savings to Investment Ratio

$PV(S_c)$ = Present Value of Cost Savings

$PV(I_c)$ = Present Value of Investment Cost

***Payback Period***

The payback period is another economic measure which is important in determining whether an investment is a competitive candidate for ECIP funding. The payback period simply refers to the amount of time that it takes for an investment to generate enough cost savings to surpass, or "payback" the investment costs. The cost savings cash flows can either ignore or include the effects of time value of money. When time value of money is ignored, the measure is referred to as the simple payback period

(SPBP). When future cash flows are discounted to reflect the time value of money, we refer to such a measure as the discounted payback period (DPBP). To qualify for ECIP funding, the threshold is a SPBP of less than 10 years.

It should be noted that payback period analysis has its limitations. When comparing between mutually exclusive alternatives, it is not appropriate to simply choose a project based on the length of its payback period. A project can have a payback period significantly shorter than its challenger; however, the challenger can have twice as high of a NPV. It would be inappropriate to simply choose the project with the shorter payback period because it ignores all of the future cash flows of the investment that can be realized after the payback period is surpassed.

When assessing various energy investment projects, it would be more beneficial to focus on the NPV and SIR of a project rather than simply the length of the payback period. In the case of UTC systems which have a useful life of roughly 30 years or greater, would it make sense to disregard the opportunity to invest in the technology if the payback period were 15 years? What if the NPV for the life of the UTC project were substantially higher than an alternative project with a payback period of 8 years? Decision-makers who must make the tough choice of which energy projects to invest in should reconsider their approach and focus on life-cycle cost savings rather than simply the time period in which it takes to recoup investment dollars. The payback period should always be treated as a secondary measure of the financial feasibility of a project and never be used as a stand-alone decision analysis tool. Despite these limitations of using payback period as a measure, we included SPBP in our analysis to address ECIP funding requirements and also included DPBP to demonstrate the effect of time value of money. It should also be noted that NIST Handbook 135 states that DPBP analysis is the preferred method of computing payback periods (Fuller, 1996:6-9).

***Emission Analysis***

In addition to assessing the cost saving potential from using UTC systems at different Air Force installations, we also assessed the GHG emission reduction potential. One of the analysis tools included in the RETScreen® software is an emission report which estimates the annual amount of GHG gas produced by the base case and proposed case entered by the user. The report includes the net annual reduction in GHG emissions that would be realized if the proposed case were to replace the base case. For our analysis, the base case and proposed case share the same assumed characteristics, except the proposed case would include the use of a UTC system. Projections showing the GHG emission reductions through UTC utilization can add to the purely financial arguments made in undertaking UTC projects.

The RETScreen® software reports GHG emissions based on the amount of $CO_2$, methane ($CH_4$), and nitrous oxide ($N_2O$) gases produced by the proposed UTC facility and the facility before UTC implementation, also referred to as the base case. The $CH_4$ and $N_2O$ gases are converted into equivalent units of $CO_2$ to create the overall level of GHG emission, which is represented in tons of $CO_2$.

The central method behind how RETScreen® software calculates reductions in GHG emissions is by analyzing the difference in how much of the heating demands of the facility are being provided by the fuel source, and how much is being provided by the UTC. In the base case, where no UTC wall is being used, the fuel source provides 100 percent of the heat required. Once the proposed case using a UTC is entered into the software, the emission analysis provides new percentages which indicate the amount of heat being provided by the fuel source and the UTC. The percent of heat energy provided by the UTC will be represented by the variable "%Solar." In our emission results section, we included %Solar for each of our sample bases. This variable provides a good measure of how well the UTC system is able to meet the heating demands of each location.

***Sensitivity Analysis***

Once we performed our economic and environmental analysis, the final step was to analyze how changes in our assumptions would change our measured results. To do this, we performed a sensitivity analysis using PrecisionTree™ software in conjunction with Microsoft Excel®. We first developed tornado diagrams for each measure to determine how sensitive each measure was to changes in our assumed variables. The variables we analyzed were initial UTC system cost, heating fuel cost, heating system efficiency, UTC surface area, designed airflow rate, the absorptivity of the UTC color choice, air temperature stratification, floor area of the facility, and the R-values for the walls and roof. After analyzing our tornado diagrams, a one-way sensitivity analysis was performed for each of the factors with high levels of sensitivity. The one-way sensitivity analysis was used to capture how changes in these factors would affect each of our performance measures. A two-way sensitivity analysis was also performed to highlight potential interactive effects between variables and show how simultaneous changes in these factors could influence our performance measures.

# IV. Results and Analysis

This chapter includes the results of our research efforts. The first portion of the chapter presents the qualitative information obtained from the literature, case studies, and subject matter experts. We will present this information to serve as "lessons learned" for future Unglazed Transpired Collector (UTC) users, highlighting the potential benefits and challenges that can result from UTC implementation.

In the second portion of this chapter, we will summarize the quantitative assessment performed on various Air Force installations using the RETScreen® UTC modeling software. The purpose of this assessment is to uncover potential Air Force installation UTC candidates and gain a better understanding of the factors that drive the feasibility and performance of UTC use. By gaining a better understanding of these factors, we can improve the decision-making process in regards to optimizing the use of a UTC system.

## Case Studies – Findings and Recommendations

We gathered information from all nine DoD installations which have UTC systems: Buckley AFB, Edwards AFB, Elmendorf AFB, Peterson AFB, Fort Carson, Fort Drum, Fort Huachuca, Fort Lewis, and Norfolk Naval Station. We were able to contact qualified individuals from eight of the nine bases, typically energy managers and civil engineers, who have an adequate understanding of the UTC system(s) at their base and could provide useful and informative feedback on our questionnaire. We were unable to gather adequate information from Edwards AFB, although we did review literature which discussed the implementation and basics of the Edwards AFB UTC system. A brief summary of the UTC systems at each installation can be found in Table 6.

**Table 6: Summary of U.S. Military UTC Use**

| Installation | Number of Buildings (Number of Walls) | Year of Initial Installation | Type of Buildings |
|---|---|---|---|
| Buckley AFB | 1 (1) | 2007 | Material Handling Facility |
| Buckley Annex (Army) | 1 (2) | 2004 | Aviation Hangar |
| Edwards AFB | 1 (1) | 2001 | Aircraft Support Facility |
| Elmendorf AFB | 1 (2) | 2008 | Warehouse Shop |
| Peterson AFB | 1 (1) | 2007 | Defueling Hangar |
| Fort Carson | 2 (3) | 2006 | Aviation and Vehicle Maintenance Facilities |
| Fort Drum | 27 (50) | 2005 | Various |
| Fort Huachuca | 2 (2) | 2001 | Aviation Hangars |
| Fort Lewis | 1 (1) | 2006 | Maintenance Facility |
| Norfolk Naval Station | 2 (2) | 1997 | Maintenance Facility / Training Gymnasium |
| **TOTAL** | 39 (65) | | |

As with any alternative energy, there are a number of different factors that are commonly considered when implementing an energy project at an installation. In this section, we will discuss some of the discoveries we made regarding the following factors:

- Architectural theme
- Installation
- Noise and comfort

- Maintenance and reliability
- Control systems
- Design and configuration
- Education and awareness
- Performance Monitoring
- Additional comments

***Architectural Theme***

Those responsible for the design of buildings across the DoD tend to be protective of the architectural theme. The potential that the "curb appeal" of buildings could be diminished by a UTC being placed on them can lead to apprehension by those involved in the decision-making process as well. This is because great time and effort is invested by designers and architects to engineer buildings to be functional and aesthetically appealing. In an attempt to accommodate such concerns, UTCs are offered in a variety of colors.

Even with the large selection of colors, there can still be resistance during design and approval phases, as was the case at two of the installations. In one case, the architectural theme was initially an issue until it was realized by decision-makers that the UTC was being considered for placement on a metal hangar which was already lacking in terms of aesthetics. In the other case, there was apprehension from architects that had to be overcome by choosing a rocky grey color over black for most of the UTCs, ensuring a more aesthetically pleasing architectural theme. Although this color choice was better suited for the appearance of these buildings, it was not optimally suited for the performance of the UTC systems. As shown in Table 30 located in Appendix C: Solar Absorptivity of Various SolarWall® Colors, the reduction in solar absorptivity from choosing rocky gray over black goes from 0.94 to 0.85. Other bases did not have conflicts with architectural themes and all were able to utilize dark colors which optimize system efficiency.

Recommendation:

The UTC color selected should always be the one with the highest solar absorptivity that is architecturally acceptable. In situations where the side of the building that the UTC wall is being placed on is out of general view, black should be the color chosen to optimize system efficiency. If a UTC system is being designed into a new construction project, architects should incorporate the use of darker UTC colors in their architectural design.

***Installation***

Our feedback indicated that the UTC installation process has been a positive one for military users. The process requires a small number of workers to handle and install the sheet metal of the UTC system and a minimal amount of electricians to ensure that the control systems and fan(s) are properly installed. Fort Drum, the largest single user of SolarWall® systems in the world (SolarWall® - Fort Drum, 2008), was able to install all of their UTCs through the use of two sheet metal workers and two electricians. A picture of this installation process at Fort Drum is shown in Figure 16.

**Figure 16: Installation of UTC at Fort Drum, NY**
(Source: SolarWall® - *Fort Drum*, 2008)

The amount of time that it takes to complete the installation process of a UTC system varies from one project to the next, depending on the magnitude of the project. The shortest amount of time it took to complete a UTC system was one week, but construction has taken as long as three months or more depending on whether the system is being installed in conjunction with other engineering projects. In one case, a UTC system was installed in conjunction with another ventilation project and it was reported that this helped alleviate some of the issues that they may have experienced if it had been a stand-alone project.

As with any construction project, the potential exists that installing the UTC wall can temporarily disrupt activities taking place in the building on which the UTC is being installed. Conversely, the UTC installation process may be delayed to accommodate the mission being performed in the building. There were no significant disruptions reported by our samples; however, it is worth noting that the potential exists.

A UTC can typically be installed to accommodate existing structures, such as windows and doorways, and we found that users had little to no issue in situations where this was applicable. One individual claimed that the UTC system cost slightly more than expected due to ducting modifications to the outside wall that were required to accommodate the system.

Recommendation:

Ensure that mission requirements are taken into account when scheduling the UTC installation. The UTC installation period may be a beneficial time to perform related construction and maintenance since there may be economies of scale involved in certain aspects of the project, such as electrician costs. In addition, there is potential for less down-time experienced at a facility when two separate projects are constructed at the same time, rather than constructing each project on separate occasions. Ensure that energy monitoring systems are designed and implemented to capture the independent performance data of separate efficiency systems, when applicable.

***Noise and Comfort***

A potential drawback of UTC use we discovered at one installation was that the noise created by some of the UTC fans could be disruptive to those who worked in the facilities that have a UTC. This has caused problems because the users of these facilities would then tamper with the systems to turn them off. Silencers are available to assist in reducing the noise generated by the fans. These silencers are not able to completely eliminate noise but they do make a difference in the comfort level of those working in facilities where fan noise can be an issue.

The amount of fan noise is dependent upon the configuration of the UTC system and the characteristics and location of the fan used. Noise was only reported to be an issue at one installation. One of the solutions used to mitigate fan noise was the use of variable speed drives on the UTC fans which could be slowed down to reduce noise. It is important to understand that manually adjusting a UTC's fan speed could adversely affect the performance of the system. Recall from our review of previous UTC research that reducing the suction velocity of a UTC system can potentially lead to undesirable outcomes such as outflow along the face of the UTC wall.

<u>Recommendation:</u>

In facilities where fan noise may be an issue, we recommend that silencers be installed. It may be worth paying a premium for higher quality fans that are more efficient and generate less noise as well. Once the required fan size is determined, fan noise should be a consideration when deciding between various types of fans to utilize for a UTC system, i.e., a belt driven fan versus a direct drive fan. Maintenance, reliability, energy efficiency, and cost are the other factors to consider when choosing a UTC fan.

***Maintenance and Reliability***

We found that maintenance and reliability of UTC systems has been very favorable among military users. Although most military UTC systems have been installed fairly recently, typically in the past five years, it is still worth noting that no significant issues were reported in regards to maintenance and reliability of UTC systems. Norfolk Naval Station, the first DoD user to install UTC walls, did report that they had to replace a UTC fan recently and that one of the nylon ducts needed to be replaced; however, there have been no issues at all with the actual UTC walls.

One user reported that the UTC systems at their installation have survived three major wind storms with no damage. Other users have reported that their walls have held up very well and they do not anticipate any issues in the future. The UTC walls are made of metal, steel or aluminum, and are typically corrugated to increase durability. The walls also have no moving parts, which decreases the likelihood of reliability issues over the long life of a UTC system.

While the low frequency of maintenance associated with UTC systems could generally be considered one of its strengths, it can quickly become a weakness should maintenance actually be required on one of the fans. This is because the fans are typically located inside the building near the roof. If maintenance on these fans is required, it may be very difficult to access them because they are elevated so high up. Also, when maintenance is required, the mission being performed by that building may likely be disrupted. One of our subjects suggested using direct drive fans instead of belt driven fans to avoid having to replace a belt that breaks or falls off.

Recommendation:

Maintenance and reliability factors should be balanced with noise and airflow requirements when selecting the type of fan to use for the UTC system. Decision-makers should take into account the maintenance and reliability benefits of UTC systems when determining whether or not to implement a system.

***Control Systems***

To ensure successful implementation of a UTC system, it is important that adequate control systems are utilized to manage its operation. Our study found the experience that users have had with UTC control systems has been fairly mixed. These mixed results are the result of differences in UTC configurations and control systems across the various installations.

Conserval Engineering does not manufacture control panels specifically for their SolarWall® systems. However, there a number of different manufacturers that offer Commercial Off-the-Shelf (COTS) control systems that can be used to operate a UTC system effectively. In many of the UTC cases we researched, users' were able to adapt existing energy control systems to their UTC systems. One user reported that they were very happy with the ease in how they were able to use the existing system in place at other facilities to operate the UTC. At least two other users, however, did have to invest in new control systems to effectively operate their UTC systems.

The type of control system required varies depending on the configuration of the UTC and the capabilities desired. As a result, an issue that may arise if UTC systems are used at multiple facilities at a single installation is that different UTC system may require different types of control system if they are configured differently. This would require energy managers to be proficient at using multiple types of systems. This could adversely affect the learning curve associated with operating the systems and potentially create a greater need for continuity when it comes time it teach new users how to operate all of the UTC system across the base. Although most control systems are fairly easy to operate and this issue is certainly not significant, we felt it was worth noting.

Nearly all of our subjects highlighted the importance of ensuring the UTC control system is able to automatically shutdown anytime the building fire alarm goes off. If the UTC system continued to operate during a fire, the oxygen from the fresh air would enhance the combustion rate of the fire. The UTC control system could then be set to reactivate once the fire alarm system is reset.

Recommendation:

Since the company that developed UTCs is not a control systems company, it has been recommended that future users of UTCs bring in their own controls representative during the design process. This will help ensure that users take responsibility to ensure that they are able to get the capabilities they desire out of the system controls.

We believe that it may also be worth researching whether control systems can be implemented to adjust the flow rate into the collector automatically based on the wind velocity at the face of the UTC wall. Higher wind speeds require a higher flow rate to maintain a proper boundary layer and reduce the potential for outflow along the face of the absorber. During times of lower wind speeds the flow rate can be reduced to maximize temperature gain through the wall.

It is imperative that the UTC control system is able to automatically shutdown in the event of a fire. This typically requires that the UTC control system function in conjunction with the fire alarm. UTC users must coordinate with appropriate fire safety representatives to ensure that the UTC system is operating properly in this regard.

***Design and Configuration***

There are typically two ways in which UTCs are configured: a UTC system can preheat air before it arrives at a heating unit or a UTC system can heat air that flows directly into a workspace. One of the ways in which air can be directed into a workspace is through the use of through-the-wall dampers that use a small fan to pull air from the

UTC wall plenum into the workspace.  Figure 17 provides examples of these dampers being utilized at waste handling and recycling facilities at Fort Drum.

**Figure 17:  Examples of UTC Gravity Dampers**

These dampers are referred to as “gravity” dampers because gravity keeps the vent closed during time periods when the fan is off.  Once the fan is turned on, the incoming air being forced through the damper lifts the vent upwards, allowing air to pass into the workspace at a downward angle.  Since the air being brought through the vent has only been heated by the UTC wall, it is typically colder than the air that is already in the workspace.  As a result, the cold air being blown downward can be uncomfortable for those working in the immediate area of the damper.  In addition, the resistance to airflow created by gravity dampers makes the system less efficient than more free-flowing dampers.

Regardless of how a UTC system is configured, the goal of the system is to provide fresh air for a given facility. When determining possible UTC wall locations, it is important to consider the level of air quality that is present at the potential location of the walls. One interesting issue that we discovered during our analysis was the effect that parking lots can have on UTC systems if they are in close proximity to one another, as depicted in Figure 18. The exhaust fumes from parked cars can become absorbed by the UTC wall and expended into the work space inside the facility. This issue can be amplified in colder climates where individuals often choose to let their vehicles run idle in the parking lot to warm up before departing from work.

**Figure 18: Example of Potential Air Quality Issue**

There are a number of engineering and administrative controls that can be used to overcome OEH threats. In regards to the previous example, one way the energy manager was able to mitigate this issue was to have the UTC wall automatically shut down toward the end of the day before workers typically start their cars to depart from work. The drawback of this control is that the benefits of the UTC system cannot be realized during time in which the system is off. Also, there are still other times during the day when the system is operating and vehicles are emitting fumes in the immediate area of the wall. An administrative control that could mitigate this OEH threat would be to implement a policy in which individuals are prohibited from backing their cars into parking spaces along the UTC wall. If the parking area is large enough, barriers could also be put in place to move the parking spaces further away from the UTC wall.

Recommendation:

Motorized dampers that blow air upwards should be used instead of gravity dampers. This will allow cooler, incoming air to mix with the warmer air that has risen to the roof of the workspace from convection. This will help make a more comfortable working environment by breaking up some of the heat stratification that is prevalent in larger buildings.

Potential OEH threats must be considered when designing and configuring UTC systems. Threat control selection should be carried out in accordance with Air Force Manual 48-155. Further detail on OEH threat mitigation can be found in the "Ventilation Requirements" section located in Chapter two.

***Education and Awareness***

Transpired solar collectors are not as well known as many other forms of alternative energy such as wind, geothermal, PV, hydro, and biofuels. Therefore, efforts to inform decision-makers, energy managers, and building inhabitants about the technology are often necessary. Decision-makers cannot make an educated decision on whether or not to use transpired solar collectors unless they understand the basics of what they are, how they work, and what the advantages and disadvantages of the systems are. Energy managers must be aware of the systems as well. If installation energy managers are not aware of transpired solar collectors, then it would be impossible for them to consider utilizing the systems at their base. Currently, the energy managers who have successfully installed transpired solar collectors have been able to do so because they were educated and aware of the technology. The inhabitants of the buildings which use transpired solar collectors should also understand the basics behind the technology, particularly if they are able to access the HVAC control system.

Having a basic understanding of how the transpired solar collector systems work, and the benefits that are associated with it, can also help alleviate some of the other challenges mentioned in this section. Some individuals may be more willing to accept minor inconveniences such as noise, aesthetics, or disruptions during installation or maintenance if they are aware of the health, environmental, or cost benefits realized from using the system. For this reason, it is also important that when a transpired solar collector improves the air temperature and air quality in a building, that the inhabitants are made aware that the transpired solar collector is responsible for those improvements. These efforts may require commitments in resources such as time, money, and effort.

Recommendation:

Energy managers should maintain periodic contact with those who work in buildings that use UTC systems. Feedback provided by workers can help energy managers determine what changes may need to be made to improve UTC system operation.

***Monitoring UTC Performance***

Prior to approving the implementation of a UTC project at any DoD installation, cost and energy savings should first be estimated. All of the bases involved in our case study had these savings estimates conducted prior to UTC implementation. It is important that these estimates are accurate, since they are typically used by decision-makers to choose optimal energy projects among various candidates. If these decisions are made using radically inaccurate estimates, then the likelihood that optimal choices are being selected is reduced.

In order for these case study bases to determine whether their estimates were accurate, it is necessary to monitor the performance of their UTC systems after they become operational. If this monitoring is not performed, then the realized energy savings cannot be quantified. Perhaps more importantly, if this monitoring is not performed, it becomes difficult for energy managers to determine whether or not their UTC systems are being operated at their maximum level of effectiveness.

We found that nearly all of our samples had the desire to monitor the performance of their UTC systems. Out of all of our samples, however, only one has actually been able to conduct thorough performance monitoring. This monitoring has been performed at one of our Army installation samples and the research has been conducted by the National Renewable Energy Laboratory (NREL). Preliminary reports had uncovered the need to install a larger fan for the UTC wall in order to reach desired performance levels. This highlights how monitoring not only validates the actual performance of the system, but can help uncover ways to improve performance. A finalized performance report from this location was not available for inclusion in our study.

There are a few challenges that may have to be overcome when establishing a monitoring system for a UTC. As previously mentioned, baseline data may be required to provide a measure of comparison. Also, additional costs may have to be incurred in order to put a measurement system in place. A problem we discovered with one of our cases was that the UTC facility was being heated by a steam plant that was also providing heat for three other buildings. Energy managers were only able to measure the total amount of heat energy being sent to all four facilities, and could not determine the amount of heat that was being used specifically by the UTC facility.

It was noted by another case that there are some difficulties that can arise when UTC systems are installed in conjunction with other energy efficiency projects. This is because the two projects may have interactive effects on energy reduction and it could be difficult to separately measure the performance of each system independently. For example, if a facility that uses electric heat installs a UTC system in conjunction with more energy efficient lighting, it may be difficult to distinguish how much energy is being saved by each project independently.

Recommendation:

In the future, the Air Force should work with organizations such as NREL to monitor how well UTCs are performing. Ideally, performance monitoring mechanisms should be put in place prior to UTC implementation. By monitoring the facility before installation of the UTC, baseline data can be established to allow for proper comparisons between performance with, and without, the UTC in place. Monitoring of UTCs also allows energy managers to determine how operational changes of the system can increase or decrease performance. For example, an energy manager could track how changing a fan's speed or hours of operation could influence energy savings. This could help ensure that UTC systems are operated to their full potential.

### *Additional Comments*

As with other solar energy technologies, not all geographic locations are able to effectively utilize transpired solar collectors. Locations with very low solar radiation exposure may find that the cost of a transpired solar collection system cannot be recouped by the financial benefits over the life of the system. In addition, locations which have very few required heating days may not realize the benefits of the system as much as those with a high number required heating days. This is a limitation that certainly faces many regions of the world. One of the purposes of this research is to recognize these various environmental factors to help determine which Air Force installations would likely, and unlikely, benefit from transpired solar collectors.

Many of the DoD installations which have utilized UTC systems are located in areas that must deal with snow during the winter months. No issues were reported in regards to snow or ice adversely effecting UTC systems, which is not surprising. Since UTC walls are typically completely vertical, snow or ice buildup along the face of the wall is no more prevalent than it would be on any other metal wall. The presence of snow on the ground near UTC walls can actually be a benefit to a UTC system, as the ground reflectance off of the snow can create higher amounts of incident radiation that strike the surface of the collector (Duffie *et al.*, 2006:317). The RETSceen® software cannot reasonably capture this effect and we do not presume that the magnitude is significant enough to influence the overall performance and cost effectiveness of UTC systems.

Recommendation:

UTC systems have the potential to provide greater economic benefits when used for new construction projects rather than retrofit applications. With new construction projects, a UTC system can be incorporated into the original design process to optimize the aesthetics, system performance, and ultimately the economic feasibility of the system. For example, the building can be built so that one of the walls faces at the ideal azimuth for solar radiation collection.

Another benefit of incorporating a UTC system into new construction is that the UTC wall can be treated as the finished outside wall of part of the building. Since the building wall that lies underneath the UTC wall is not visible, it can be left unfinished or may be constructed using cheaper, less visually appealing materials. For this reason, it can be more cost effective to incorporate a UTC system in a new construction project rather than a retrofit project. When deciding to put a UTC wall on a building, new or old, it is important to ensure that the UTC wall is never placed on an existing wall that is covered with paint that contains toxins, such as lead, or is flammable.

The quality and amount of data that we were able to obtain from each installation in our case study analysis was moderately dependent upon whether the participants in our study were involved in the UTC project at its inception. Had we been able to interview all the individuals who led these various UTC projects from their inception, our case study analysis would have provided even greater value. This highlights the importance of ensuring adequate continuity as new energy managers inherit responsibility over UTC systems. Since the useful life of a UTC system typically extends beyond 30 years, there is a high likelihood that multiple individuals will transfer responsibility and oversight over UTC systems.

## Quantitative Assessments

In this section, we will provide the quantitative results of our study and discuss the variety of assumptions and calculations used to arrive at them.

### *Base Selection Summary*

We began our base selection process by compiling a comprehensive list of 81 active duty Air Force bases; 68 located in the U.S. and 13 located overseas. After establishing a list of potential samples, we attempted to pull climate data for every Air Force base location using the RETScreen® climate database. The database had specific climate data available for 60 of the 81 bases. For the remaining 21 locations that were not included in the database, we obtained climate date from the closest available location. Most of these bases are situated within a mile from a location included in the database, with the furthest base being 45 miles from a data location.

After analyzing the climate characteristics for each of the 81 locations, we narrowed the list down to 19 bases with potentially favorable climates for UTC applications. Table 7 provides a list of these 19 bases along with their respective climate characteristics. We included other installations of interest to illustrate how their climate characteristics compare with the samples chosen for our study. We used a heating degree day (HDD) threshold of greater than 4,100 days and an average wind speed of less than 4.4 meters per second for our base selection criteria. The exceptions to this rule were Edwards AFB, which has less than 4,100 HDDs, as well as Minot AFB and Grand Forks AFB, which have average wind speeds slightly greater than 4.5 m/s. We included

Edwards AFB because they have implemented a UTC system in the past and wanted to capture how well the base performs in relation to our other samples. We included Minot AFB and Grand Forks AFB because of the high heating demands at their locations. We felt that even though the higher speeds at these locations may degrade the performance of a UTC system, the high heating requirements may allow a UTC to provide effective results that could still benefit the installations.

**Table 7: Summary of Installation Climate Characteristics**

| Air Force Installation | State or Country | Climate Zone | Average (Annual) | | | |
|---|---|---|---|---|---|---|
| | | | HDD | Solar Radiation (kWh/m$^2$/d) | Air Temp. (F) | Wind Speed (m/s) |
| Edwards AFB* | CA | 3B | 2,618 | 5.36 | 62.4 | 4.3 |
| Andrews AFB | MD | 4A | 4,106 | 3.99 | 56.1 | 3.4 |
| Scott AFB | IL | 4A | 4,359 | 4.07 | 56.0 | 3.0 |
| Kirtland AFB | NM | 4B | 4,243 | 5.57 | 55.9 | 4.1 |
| Kunsan AB | S. Korea | 4 | 4,397 | 4.08 | 55.8 | 3.4 |
| Wright-Patterson AFB | OH | 5A | 5,050 | 3.81 | 52.8 | 3.1 |
| Offutt AFB | NE | 5A | 5,578 | 3.99 | 51.9 | 3.4 |
| Mountain Home AFB | ID | 5B | 5,636 | 4.51 | 50.9 | 3.5 |
| Hill AFB | UT | 5B | 5,780 | 4.67 | 50.7 | 3.7 |
| Buckley AFB* | CO | 5B | 5,830 | 4.58 | 49.8 | 3.3 |
| Air Force Academy | CO | 5B | 6,181 | 4.69 | 48.3 | 4.4 |
| Peterson AFB* | CO | 5B | 6,181 | 4.69 | 48.3 | 4.4 |
| Fairchild AFB | WA | 5B | 6,454 | 3.85 | 47.4 | 3.2 |
| Ellsworth AFB | SD | 6A | 6,636 | 4.06 | 47.7 | 4.3 |
| Malmstrom AFB | MT | 6B | 6,717 | 3.78 | 46.8 | 4.0 |
| Minot AFB | ND | 7 | 8,706 | 3.66 | 41.3 | 4.6 |
| Grand Forks AFB | ND | 7 | 8,794 | 3.67 | 41.3 | 4.7 |
| Elmendorf AFB* | AK | 7 | 10,249 | 2.67 | 36.3 | 2.4 |
| Eielson AFB | AK | 8 | 13,409 | 2.69 | 27.7 | 1.5 |
| Other Installations of Interest | | | | | | |
| Fort Huachuca* | AZ | 3B | 1,394 | 5.41 | 68.9 | 2.8 |
| Norfolk Naval Station* | VA | 4A | 2,857 | 4.18 | 60.9 | 4.2 |
| Fort Lewis* | WA | 4C | 4,830 | 3.36 | 51.2 | 2.4 |
| Fort Carson* | CO | 5B | 6,181 | 4.69 | 48.3 | 4.4 |
| Fort Drum* | NY | 6A | 7,289 | 3.57 | 45.2 | 4.0 |

*Denotes Current UTC User

Out of our chosen sample of 19 installations, only three locations were not included in the RETScreen® database. The U.S. Air Force Academy (USAFA), Kirtland AFB, and Peterson AFB were all excluded from the database. Fortunately, the database did include the cities in which these bases are located. For USAFA and Peterson AFB, we used climate data for Colorado Springs, Colorado. For our analysis of Kirtland AFB, we selected Albuquerque, New Mexico. Since USAFA and Peterson AFB are both using identical climate data, the UTC system performance estimates will be the same for both bases. However, the energy costs associated with each of these bases are different, which will lead to differences in economic performance estimates.

After selecting our sample bases, we discovered a U.S. map which shows expected daily energy savings associated with different regions of the country. After overlaying our selected Air Force bases on the map, we found that the majority of our selected bases were located in regions with moderately high expected savings. This map, created by NREL and included in a briefing by Taylor (2006), can be shown in Figure 19. We used white circles to represent the selected Air Force base locations which have already utilized UTC systems, while all other selected base locations are represented by a black circle.

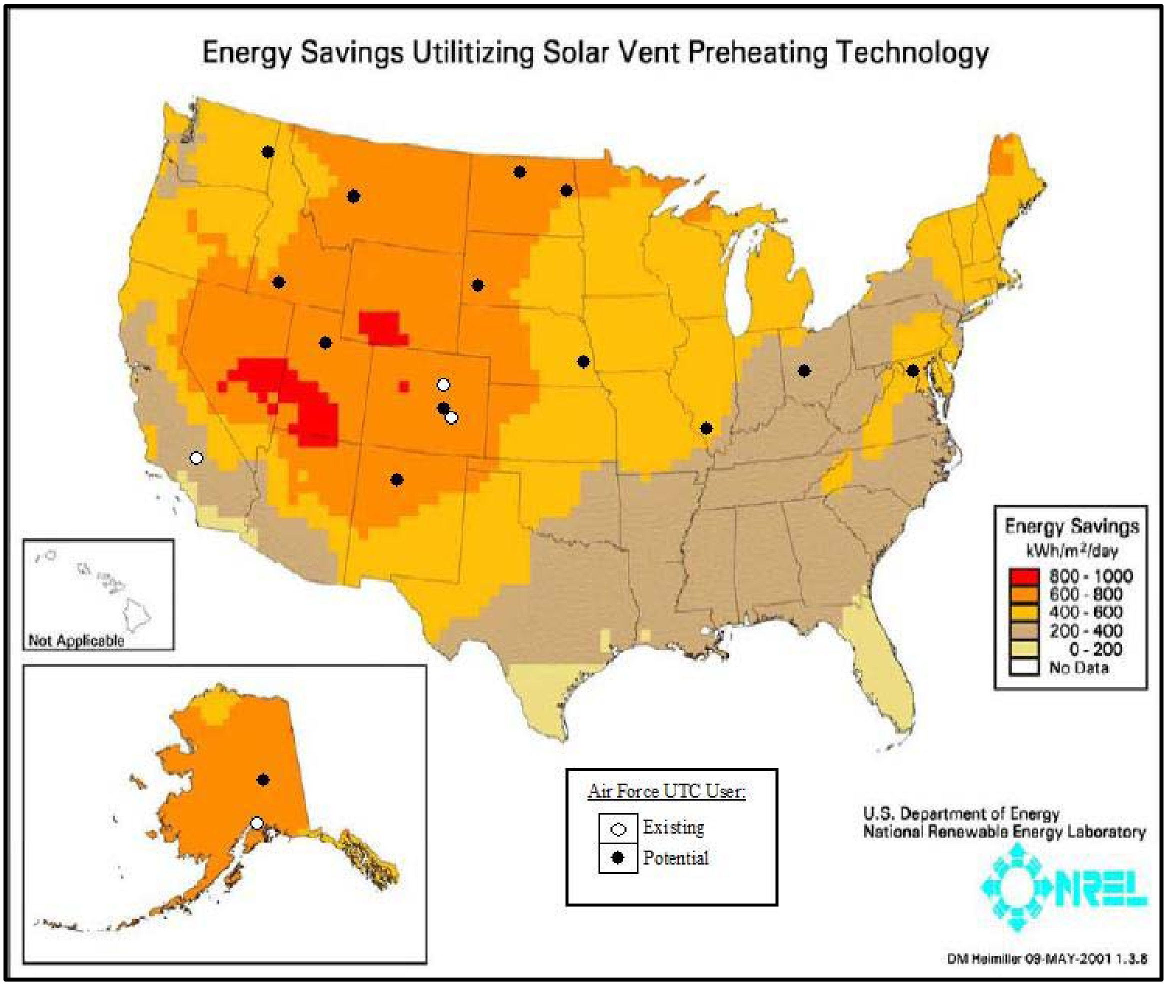



**Figure 19: UTC Energy Savings Map with Selected Air Force Base Locations**
(Source: Taylor, 2006)

### *Assumptions and Calculations*

After developing our list of sample locations, the next step in our assessment was to determine the various assumptions and calculations required to perform our analysis. A summary of these assumptions is shown in Table 8. Our assumptions were formulated based on a number of different sources of information which included, but was not limited to, the following: RETScreen® case study models, ASHRAE energy and ventilation standards, subject matter experts, previously installed UTC system characteristics, literature from past UTC research, and also information gathered from our qualitative analysis. We based our building characteristic assumptions on universal characteristics which we believe can be reasonably generalized across the various installations included in our assessment. The sensitivity analysis portion of our evaluation captures how changes in each individual input assumption can affect the expected performance of a UTC system.

**Table 8: Summary of Facility Assumptions**

| **RETScreen® Inputs** | Hangar | Warehouse | Maintenance Shop |
|---|---|---|---|
| Facility type | Industrial | Industrial | Industrial |
| Air temperature (°F): | | | |
| Indoor | 70.0 | 70.0 | 70.0 |
| Minimum | 50.0 | 50.0 | 50.0 |
| Maximum | 90.0 | 90.0 | 90.0 |
| Building stratification | 10.0 | 8.0 | 6.0 |
| Floor area ($ft^2$) | 80,000 | 40,000 | 25,000 |
| R-Value – roof ($ft^2$ - °F/(Btu/h)) | 19.0 | 19.0 | 19.0 |
| R-Value – wall ($ft^2$ - °F/(Btu/h)) | 13.0 | 13.0 | 13.0 |
| | | | |
| Design objective | Standard Operation | Standard Operation | Standard Operation |
| Design airflow rate (CFM) | 53,333 | 20,000 | 16,667 |
| Operating days per week - weekdays | 5 | 5 | 5 |
| Operating hours per day - weekdays | 8 | 8 | 8 |
| Operating days per week – weekends | 2 | 2 | 2 |
| Operating hours per day – weekends | 8 | 8 | 8 |
| | | | |
| Solar tracking mode | Fixed | Fixed | Fixed |
| Slope (degrees) | 90.0 | 90.0 | 90.0 |
| Azimuth (degrees) | 10.0 | 10.0 | 10.0 |
| | | | |
| Initial cost (CY$08) | $282,333 | $109,000 | $91,667 |
| Solar collector color | Black | Black | Black |
| Solar collector absorptivity | 0.94 | 0.94 | 0.94 |
| Solar collector area ($ft^2$) | 10,667 | 4,000 | 3,333 |
| | | | |
| Heating – fuel type | Natural Gas | Natural Gas | Natural Gas |
| Seasonal efficiency (%) | 75.0 | 75.0 | 75.0 |
| **Additional assumptions used for calculating input parameters** | | | |
| Building height (ft) | 40 | 30 | 20 |
| Complete air exchanges per hour | 1 | 1 | 2 |

We chose to assess three different types of buildings for the initial portion of our quantitative assessment. The first building we chose was an 80,000 square foot hangar with a ceiling height of 40 feet. The second building we chose was a 40,000 square foot warehouse with a ceiling height of 30 feet. Finally, our third building choice was a 25,000 square foot maintenance facility with a ceiling height of 20 feet. Although we refer to these buildings as a "hangar," "warehouse," and "maintenance facility," they can be related to similar sized buildings with similar heating and ventilation requirements. For example, the "hangar" in our analysis could be generalized to closely approximate a large gym at Wright Patterson Air Force Base or a two-acre dining facility at USAFA. The names simply represent the type of facility we are attempting to generalize and provide a basis from which we can derive our assumptions.

We gathered information on various types of U.S. Air Force and military facilities to determine common types of buildings and their design and engineering characteristics. From this research, we discovered that there is a substantial variance in how large Air Force hangars, warehouses, and maintenance facilities can be. We based our assumptions on the most common characteristics we found at buildings across various installations with different sized aircraft and maintenance requirements.

Although the analysis software does not include building height as an input parameter for our models, it was necessary to assume a building height in order to calculate our assumed air flow rate and building stratification. The air flow rate, measured in cubic feet per minute (CFM), was based on the volume of space inside the building and the necessary amount of fresh air exchanges per hour. We consulted several instructors at the Civil Engineering and Services School at the Air Force Institute of

Technology (AFIT) to gain a better understanding of typical ventilation requirements for our three assumed types of facilities. We also reviewed ASHRAE standard 62.1-2007 and consulted the following ASHRAE handbooks: *Fundamentals, HVAC Applications*, and *HVAC Systems and Equipment*. What we discovered was that the nature of these types of facilities makes it extremely difficult to choose assumed ventilation rates. A hangar, for instance, could be used to simply store aircraft and conduct maintenance inspections. This type of hangar would require far less ventilation than a corrosion control hangar used to paint aircraft. We chose to generalize to the former example, which would require a lower rate of ventilation of roughly one air exchange per hour. For our maintenance facility, we chose a higher ventilation rate of two complete air exchanges per hour. We assume that our maintenance facility uses substances that are volatile or health threatening and require more adequate ventilation levels. The following equation was used to calculate the air flow rate for each of our buildings:

$$CFM = \frac{V_{Building}}{H} \times \frac{H}{T_m} \qquad (3)$$

where

$CFM$ = *Airflow rate* ($ft^3/min$)

$V_{Building}$ = *Volume of facility* ($ft^3$)

$H$ = *1 (hr)*

$T_m$ = *Time between complete air exchanges (min)*

An example of how this calculation was used to determine the airflow rate of our hangar facility is shown in Equation 4:

$$53{,}333 = \frac{(80{,}000\ ft^2 \times 40\ ft)}{1\ Hour} \times \frac{1\ Hour}{60\ min} \qquad (4)$$

There are a number of reasons why we selected modest ventilation rates of one and two exchanges per hour. One reason why we selected a lower rate is that it allows for generalization across numerous types of facilities. Large industrial buildings such as gyms, dining facilities, and warehouses have characteristics similar to those of our assumed buildings. Another reason why we assumed a lower rate is because UTC systems are generally more beneficial to users requiring high rates of ventilation. Therefore, if our evaluation indicates that UTC systems would perform well at conservative levels of ventilation, then we could reasonably assume that the potential benefit of utilizing UTC systems can only be greater for those facilities which require higher levels of ventilation. Our attempt is to maintain a consistent theme of being conservatively realistic when determining our assumptions, then capturing the magnitude of potential benefit increases though the use of sensitivity analysis.

We assumed a desired building air temperature of 70 degrees Fahrenheit and a minimum and maximum incoming air temperature of 50 and 90 degrees Fahrenheit, respectively. We based these values on the RETScreen® recommended air temperatures which were as follows: 70 degrees Fahrenheit is the typical building thermostat temperature, 41 to 70 degrees Fahrenheit is the typical minimum delivered air temperature range, and 50 to 140 degrees Fahrenheit is the typical maximum delivered air temperature range (RETScreen®, 2008).

Air stratification values were assumed to be 10 degrees Fahrenheit for our warehouse with a ceiling height of 40 feet, 8 degrees Fahrenheit for our warehouse with a ceiling height of 30 feet, and 6 degrees Fahrenheit for our maintenance facility with a ceiling height of 20 feet. According to the RETScreen® users' guide, buildings with low ceilings, such as warehouses, typically have modest stratification of 2 to 9 degrees Fahrenheit. Buildings with tall ceilings, such as manufacturing facilities, may have significant stratification ranging from 9 to 27 degrees Fahrenheit (RETScreen®).

Another input required to perform our RETScreen® analysis is the R-values for the roof and walls of our model buildings. For our analysis, we used the energy standard R-values provided by ASHRAE 90.1-2007. We assumed an R-value of 19.0 for roofs and 13.0 for walls which corresponds to the minimum R-value for non-residential metal buildings.

Our next set of assumptions includes the assumed operating times for our proposed UTC systems. We assumed that the system would operate seven days per week, for eight hours per day. The RETScreen® software allows us to decide the percent of each month in which the UTC systems are to be utilized. We did not maintain a consistent level of monthly use across every different installation. This is because monthly HDD requirements vary greatly across the different locations selected in our research. Certain locations, such as Eielson AFB and Elmendorf AFB, have fairly high HDD requirements throughout all 12 months of the year. In contrast, five of our proposed locations have few HDD requirements half of the year. A summary of how these differences affected our assumed monthly UTC usage rates can be illustrated in Table 9.

**Table 9: UTC Utilization Rate - Percent of Month Used**

| | Warming | | | | Mixed | | | | | Warming | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| Air Force Academy | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Andrews AFB | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| Buckley AFB | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Edwards AFB | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| Eielson AFB | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Ellsworth AFB | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Elmendorf AFB | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Fairchild AFB | 1 | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 |
| Grand Forks AFB | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Hill AFB | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Kirtland AFB | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| Kunsan AB | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| Malmstrom AFB | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Minot AFB | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Mountain Home AFB | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Offutt AFB | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Peterson AFB | 1 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 1 | 1 | 1 | 1 |
| Scott AFB | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |
| Wright-Patterson AFB | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 |

0=0%, 1=100%

Our assumed slope of 90 degrees corresponds to the angle of the UTC wall relative to complete horizontal, or zero degrees. We assumed that the UTC wall is completely vertical and would be placed parallel on the existing façade of our buildings. The azimuth of 10 degrees means that the UTC wall faces 10 degrees away from true south. The RETScreen® software does not distinguish between whether this is 10 degrees south-west or south-east, only that it is 10 degrees from true south. The RETScreen® user guide states that the preferred orientation should face the equator, which would be zero degrees in the Northern Hemisphere and 180 degrees in the Southern Hemisphere (RETScreen®, 2008). All of the bases involved in our research are located in the Northern Hemisphere. Since most buildings do not have a wall that faces exactly due south, we are assuming that most UTC applications will be close to, but not exactly at, zero degrees. A typical range would be plus or minus 20 degrees from true south and our assumed value of 10 degrees would fall in the middle of that range.

Next, we had to determine the color and size of our proposed UTC walls. We assumed that UTC color selection in most cases will be made to optimize the solar gain for the systems. We chose black since it offers the best rate of absorption at 0.94. The size of the UTC wall was based on our calculated air flow rates. The RETScreen® users' guide provides typical fan flow rates per square foot of UTC wall, shown in Table 10. We used a standard operation nominal rate of 5 cfm/ft$^2$.

**Table 10: Solar Collector Fan Flow Rates for Various Design Objectives**

| Type | Nominal | Range |
|---|---|---|
| High temperature rise | 2 cfm/ft$^2$ | 1 to 3 cfm/ft$^2$ |
| Standard operation | 5 cfm/ft$^2$ | 3 to 6 cfm/ft$^2$ |
| High air volume | 8 cfm/ft$^2$ | 6 to 10 cfm/ft$^2$ |

(Source: RETScreen®, 2008)

We derived our UTC area using the following equation:

$$A = \frac{F}{R} \qquad (5)$$

where:

*A = Solar Collector Area*

*F = Flow rate of incoming air (CFM)*

*R = Rate obtained from Table 10 (cfm/ft$^2$)*

An example of how this calculation was used to determine the solar collector area of our hangar facility is shown in Equation 6:

$$10{,}667 ft^2 = \frac{53{,}333\ cfm}{5\ cfm/ft^2} \quad (6)$$

Using this equation, we determined solar collector areas of 4,000 $ft^2$ for our warehouse and 3,333 $ft^2$ for our maintenance facility.

Once we calculated the area of our solar collectors, we have enough information to estimate the cost of our UTC system. Like many alternative and renewable energy projects, the majority of the LCCs of UTC systems are incurred in its initial costs. The basic costs of a UTC system can be divided into the following categories: design, supply, and installation. The supply costs consist of UTC materials, fans, ducts, and controls. All of these costs are initial costs that must be obligated prior to installation and use of the UTC. We assumed a design cost of $5,000 per UTC system, which was consistent with the design cost experience at Fort Drum. For our supply and installation costs, we assumed a cost of $26 per square foot of UTC wall area, which was also consistent with the cost experience at Fort Drum as well as estimates provided by the manufacturer for budgeting purposes. We found this cost typically falls within the range of $25 to $27 for complete installation, but can fall outside that range depending on the complexity, size, and location of the project. We then calculated the total cost of our UTC system using Equation 7.

$$TC = DC + \$26(A) \quad (7)$$

where

*TC = Total cost of the UTC system*

*DC = Design cost*

*A = Solar Collector Area*

The only other costs associated with the system, which are not to be considered initial, are maintenance costs that occur throughout the life of the system and possible disposal costs when the life of the system has been concluded. For purposes of our analysis, we have made the assumption that maintenance costs for the system are equal to or less than the maintenance costs associated with the ventilation system in which UTCs will be replacing. Therefore, we excluded these costs from our analysis. Concerns over the effect of additional incremental costs, like maintenance, can be still be addressed by reviewing sensitivity analysis results.

In regards to salvage or disposal costs, it is difficult to quantify these costs since the amount of time since UTC technology has been around is far less than the useful lifetime of the UTC systems that have been constructed. In addition, the UTC walls have a long useful life that is comparable with those of the actual buildings they are being built on, and the time of disposal for the UTC walls would likely coincide with the time in which the building is being disposed of. We assume that the disposal costs of the building itself far outweighs the marginal cost increase associated with UTC system disposal. It is also worth noting that the disposal costs would likely occur 30 to 50 years into the future, and after such a significant amount of time has passed, the present value we presume for these costs would be insignificant to our analysis. If a UTC system were removed before the end of its useful life, it would likely have a salvage value which would only increase the cost effectiveness of implementing the technology.

We assumed an incremental fan power of zero for our analysis. The incremental fan power is the amount of fan power above and beyond the fan power for our base case HVAC system. We assumed that either the existing fan can be used as the UTC fan, or that the new replacement fan is similar in design and desired airflow. We also assumed the solar air heating system is well designed, in which case the increase in fan power is negligible (RETScreen®, 2008). Since the electricity rates we obtained for each location were only used to capture additional electricity costs associated with providing incremental fan power, electricity rates did not end up being required for our analysis.

We assumed that the heating system for each base operates using natural gas as a fuel source and operates at a seasonal efficiency of 75 percent. The FY07 Energy Almanac states that natural gas usage and cost profiles are very consistent with one another across the Air Force. In addition, heating fuels cost less per MBTU than electricity (USAF Energy Almanac – Vol.2, 2008:4). This was also the most common source of fuel used across our 19 sample bases, which had reported fuel costs for 17 of 19 samples. For our two samples which did have natural gas, Eielson AFB and Kunsan AB, we used their heating oil costs instead. We maintained a seasonal efficiency of 75 percent across both fuel types.

We assumed a seasonal efficiency of 75 percent based on the typical levels suggested in the Clean Energy Project Analysis Software which are shown in Table 11. Although we believe that 70 percent may be a more representative efficiency value for heating systems being used at the present day, we feel that a higher level should be chosen to reduce the likelihood of overestimating UTC performance. This is because we anticipate that energy efficiency levels will rise in the future as a result of federal government energy efficiency initiatives as well as general advancements in heating technology.

**Table 11: Typical Seasonal Efficiencies of Heating Systems**

| Heating system type | Typical annual heating system seasonal efficiency |
|---|---|
| Standard boiler/furnace (with pilot light) | 55 to 65% |
| Mid efficiency boiler/furnace (spark ignition) | 65 to 75% |
| High efficiency or condensing boiler/furnace | 75 to 85% |

(Source: RETScreen®, 2008)

The natural gas costs obtained from the DUERS database are shown in Table 12. There were two instances in which the natural gas fuel costs were not available, in which case we decided to supplement natural gas heating for fuel oil heating for those two locations, Eielson AFB and Kunsan Airbase.

**Table 12: Summary of FY08 Energy Costs**

| BASE | Natural Gas Cost (per MBTU) | Fuel Oil Cost (per gallon) |
|---|---|---|
| Air Force Academy | $10.68 | N/A |
| Andrews AFB | $12.68 | $2.61 |
| Buckley AFB | $7.92 | N/A |
| Edwards AFB | $9.52 | N/A |
| Eielson AFB | N/A | $2.82 |
| Ellsworth AFB | $6.55 | N/A |
| Elmendorf AFB | $7.90 | N/A |
| Fairchild AFB | $9.79 | N/A |
| Grand Forks AFB | $8.40 | N/A |
| Hill AFB | $6.66 | N/A |
| Kirtland AFB | $8.47 | N/A |
| Kunsan AB | N/A | $2.86 |
| Malmstrom AFB | $8.91 | $2.83 |
| Minot AFB | $6.46 | $1.85 |
| Mountain Home AFB | $7.52 | N/A |
| Offutt AFB | $8.53 | $0.65 |
| Peterson AFB | $7.98 | N/A |
| Scott AFB | $9.81 | N/A |
| Wright-Patterson AFB | $11.88 | $3.04 |

***Financial Analysis Results***

After selecting the installations for our analysis and determining our hypothetical building characteristics, we were able to generate our proposed UTC performance results for each of our sample installations. Table 13 provides a cash flow summary which shows the initial cost and the net annual savings, or cash flows, determined for the various economic measures of this study.

**Table 13: Cash Flow Summary**

| | Hangar | Warehouse | Maintenance |
|---|---|---|---|
| **Initial Cost:** | ($282,333) | ($109,000) | ($91,667) |
| **Net Annual Savings** | | | |
| Eielson AFB | 83,481 | 30,594 | 24,590 |
| Kunsan AB | 58,792 | 21,572 | 17,370 |
| Air Force Academy | 40,588 | 14,930 | 12,072 |
| Fairchild AFB | 36,339 | 13,332 | 10,734 |
| Andrews AFB | 32,336 | 11,859 | 9,541 |
| Elmendorf AFB | 32,255 | 11,807 | 9,472 |
| Peterson AFB | 30,327 | 11,156 | 9,020 |
| Malmstrom AFB | 30,291 | 11,117 | 8,955 |
| Buckley AFB | 30,195 | 11,108 | 8,983 |
| Edwards AFB | 29,414 | 10,830 | 8,769 |
| Grand Forks AFB | 29,056 | 10,665 | 8,595 |
| Offutt AFB | 27,989 | 10,264 | 8,258 |
| Wright-Patterson AFB | 27,931 | 10,223 | 8,200 |
| Kirtland AFB | 27,545 | 10,151 | 8,231 |
| Mountain Home AFB | 27,006 | 9,923 | 8,009 |
| Hill AFB | 24,846 | 9,136 | 7,383 |
| Scott AFB | 24,094 | 8,829 | 7,093 |
| Ellsworth AFB | 22,844 | 8,388 | 6,763 |
| Minot AFB | 22,016 | 8,079 | 6,507 |

A summary of our financial results for each of our three facilities is found in Table 14, Table 15, and Table 16. The results of our UTC hangar facility assessment, shown in Table 14, demonstrate that our proposed UTC would provide solid financial and environmental benefits at each of our selected bases. To reiterate, our summary headings are made up of the Internal Rate of Return (IRR), Simple Payback Period (SPBP), Discounted Payback Period (DPBP), Net Present Value (NPV), Savings-to-Investment Ratio (SIR), annual reduction in Carbon Dioxide ($CO_2$) emissions, and the percent of heat energy produced by the UTC system during operation (%Solar). The UTC system consistently performed better in our proposed hangar scenario than in the warehouse and maintenance facility, although our results indicate that a UTC system shows great promise in all three building types.

**Table 14: Summary of Results – Hangar Facility**

| | Installation | IRR (%) | SPBP (Yrs) | DPBP (Yrs) | NPV ($000) | SIR | $CO_2$ (tons) | Solar (%) |
|---|---|---|---|---|---|---|---|---|
| 1 | Eielson AFB | 29.5 | 3.38 | 3.62 | 1,171 | 5.15 | 339 | 30.7 |
| 2 | Kunsan AB | 20.6 | 4.80 | 5.27 | 741 | 3.63 | 236 | 75.2 |
| 3 | Air Force Academy | 13.8 | 6.96 | 7.92 | 424 | 2.50 | 199 | 70.2 |
| 4 | Fairchild AFB | 12.1 | 7.77 | 8.98 | 350 | 2.24 | 195 | 61.1 |
| 5 | Andrews AFB | 10.5 | 8.73 | 10.28 | 281 | 1.99 | 134 | 66.8 |
| 6 | Elmendorf AFB* | 10.5 | 8.75 | 10.31 | 279 | 1.99 | 214 | 38.1 |
| 7 | Peterson AFB* | 9.7 | 9.31 | 11.08 | 246 | 1.87 | 199 | 70.1 |
| 8 | Malmstrom AFB | 9.7 | 9.32 | 11.10 | 245 | 1.87 | 178 | 53.2 |
| 9 | Buckley AFB* | 9.6 | 9.35 | 11.14 | 243 | 1.86 | 200 | 75.9 |
| 10 | Edwards AFB* | 9.3 | 9.60 | 11.49 | 230 | 1.81 | 122 | 100.0 |
| 11 | Grand Forks AFB | 9.1 | 9.72 | 11.66 | 224 | 1.79 | 181 | 39.8 |
| 12 | Offutt AFB | 8.7 | 10.09 | 12.20 | 205 | 1.73 | 172 | 62.9 |
| 13 | Wright-Patterson AFB | 8.6 | 10.11 | 12.23 | 204 | 1.72 | 123 | 46.0 |
| 14 | Kirtland AFB | 8.5 | 10.25 | 12.43 | 197 | 1.70 | 171 | 96.7 |
| 15 | Mountain Home AFB | 8.2 | 10.45 | 12.73 | 188 | 1.67 | 188 | 71.6 |
| 16 | Hill AFB | 7.3 | 11.36 | 14.10 | 150 | 1.53 | 196 | 74.0 |
| 17 | Scott AFB | 6.9 | 11.72 | 14.66 | 137 | 1.49 | 129 | 58.0 |
| 18 | Ellsworth AFB | 6.4 | 12.36 | 15.68 | 115 | 1.41 | 183 | 55.9 |
| 19 | Minot AFB | 6.0 | 12.82 | 16.43 | 101 | 1.36 | 179 | 39.3 |

*Denotes Current UTC User

Recall from our previous review of ECIP funding requirements that the Savings-to-Investment Ratio (SIR) threshold for funding requests is that the proposed project must yield a predicted SIR greater than 1.25. Our hangar assessment indicates that our UTC system would result in a SIR greater than 1.25 for all 19 bases. The other ECIP requirement is that the Simple Payback Period (SPBP) must be less than 10 years. For our hangar UTC system, 11 of 19 bases would realize a SPBP of less than 10 years, and 15 of 19 bases would realize a SPBP of less than 11 years. Although eight bases would exceed the 10-year SPBP, all 19 bases yield a NPV of greater than $100,000. The lowest

IRR we calculated was six percent at Minot AFB, which is still significantly higher than our discount rate of three percent.

Next, we provide the summary of results for our proposed warehouse facility, shown in Table 15.

**Table 15: Summary of Results – Warehouse Facility**

| | Installation | IRR (%) | SPBP (Yrs) | DPBP (Yrs) | NPV ($000) | SIR | $CO_2$ (tons) | Solar (%) |
|---|---|---|---|---|---|---|---|---|
| 1 | Eielson AFB | 28.0 | 3.56 | 3.83 | 423 | 4.89 | 124 | 30.3 |
| 2 | Kunsan AB | 19.6 | 5.05 | 5.57 | 267 | 3.45 | 87 | 73.0 |
| 3 | Air Force Academy | 13.1 | 7.30 | 8.37 | 151 | 2.39 | 73 | 68.5 |
| 4 | Fairchild AFB | 11.4 | 8.18 | 9.52 | 123 | 2.13 | 71 | 59.7 |
| 5 | Andrews AFB | 9.8 | 9.19 | 10.92 | 97 | 1.89 | 49 | 65.0 |
| 6 | Elmendorf AFB* | 9.8 | 9.23 | 10.97 | 97 | 1.89 | 78 | 37.4 |
| 7 | Peterson AFB* | 9.1 | 9.77 | 11.74 | 85 | 1.78 | 73 | 68.5 |
| 8 | Malmstrom AFB | 9.0 | 9.80 | 11.79 | 86 | 1.78 | 65 | 52.1 |
| 9 | Buckley AFB* | 9.0 | 9.81 | 11.80 | 84 | 1.77 | 74 | 74.0 |
| 10 | Edwards AFB* | 8.7 | 10.06 | 12.16 | 80 | 1.73 | 46 | 100.0 |
| 11 | Grand Forks AFB | 8.5 | 10.22 | 12.39 | 77 | 1.70 | 67 | 39.2 |
| 12 | Offutt AFB | 8.1 | 10.62 | 12.98 | 70 | 1.64 | 63 | 61.3 |
| 13 | Wright-Patterson AFB | 8.0 | 10.66 | 13.04 | 69 | 1.63 | 45 | 45.0 |
| 14 | Kirtland AFB | 7.9 | 10.74 | 13.16 | 68 | 1.62 | 63 | 92.9 |
| 15 | Mountain Home AFB | 7.7 | 10.98 | 13.53 | 64 | 1.59 | 69 | 69.8 |
| 16 | Hill AFB | 6.7 | 11.93 | 14.99 | 50 | 1.46 | 72 | 72.1 |
| 17 | Scott AFB | 6.4 | 12.35 | 15.66 | 45 | 1.41 | 47 | 56.6 |
| 18 | Ellsworth AFB | 5.8 | 12.99 | 16.72 | 37 | 1.34 | 67 | 54.7 |
| 19 | Minot AFB | 5.4 | 13.49 | 17.56 | 32 | 1.29 | 66 | 38.7 |

*Denotes Current UTC User

The economic results from Table 15 show that UTC performance remains strong for our warehouse application, but is slightly reduced from that of our hangar scenario. All 19 bases still yield a SIR greater than 1.25 and positive NPVs; however, the amount of bases with a SPBP of less than 10 years is reduced from 11 to 9.

Table 16 provides a summary of the UTC performance at our maintenance facility which again, performs well, but with slightly lower economic performance results. Minot AFB is the only location that yields an SIR less than 1.25, but it is extremely close at 1.24. The amount of UTC systems which have a SPBP of less than 10 years falls to six bases, while five other bases are below 11 years.

**Table 16: Summary of Results – Maintenance Facility**

| | Installation | IRR (%) | SPBP (Yrs) | DPBP (Yrs) | NPV ($000) | SIR | $CO_2$ (tons) | Solar (%) |
|---|---|---|---|---|---|---|---|---|
| 1 | Eielson AFB | 26.8 | 3.73 | 4.01 | 337 | 4.67 | 100 | 29.7 |
| 2 | Kunsan AB | 18.7 | 5.28 | 5.83 | 211 | 3.30 | 70 | 69.9 |
| 3 | Air Force Academy | 12.5 | 7.59 | 8.75 | 119 | 2.29 | 59 | 66.2 |
| 4 | Fairchild AFB | 10.8 | 8.54 | 10.01 | 95 | 2.04 | 58 | 57.5 |
| 5 | Andrews AFB | 9.3 | 9.61 | 11.51 | 74 | 1.81 | 40 | 62.4 |
| 6 | Elmendorf AFB* | 9.2 | 9.68 | 11.61 | 73 | 1.80 | 63 | 36.5 |
| 7 | Peterson AFB* | 8.6 | 10.16 | 12.31 | 65 | 1.71 | 59 | 66.2 |
| 8 | Malmstrom AFB | 8.5 | 10.24 | 12.41 | 64 | 1.70 | 53 | 50.5 |
| 9 | Buckley AFB* | 8.5 | 10.20 | 12.37 | 65 | 1.71 | 60 | 71.3 |
| 10 | Edwards AFB* | 8.3 | 10.45 | 12.73 | 61 | 1.67 | 38 | 100.0 |
| 11 | Grand Forks AFB | 8.0 | 10.67 | 13.05 | 58 | 1.63 | 54 | 38.3 |
| 12 | Offutt AFB | 7.5 | 11.10 | 13.70 | 52 | 1.57 | 51 | 59.0 |
| 13 | Wright-Patterson AFB | 7.5 | 11.18 | 13.82 | 51 | 1.56 | 36 | 43.6 |
| 14 | Kirtland AFB | 7.5 | 11.14 | 13.76 | 52 | 1.56 | 51 | 90.1 |
| 15 | Mountain Home AFB | 7.2 | 11.45 | 14.23 | 48 | 1.52 | 56 | 67.2 |
| 16 | Hill AFB | 6.3 | 12.42 | 15.77 | 37 | 1.40 | 58 | 69.4 |
| 17 | Scott AFB | 5.9 | 12.92 | 16.60 | 32 | 1.35 | 38 | 54.5 |
| 18 | Ellsworth AFB | 5.4 | 13.55 | 17.66 | 26 | 1.28 | 54 | 53.1 |
| 19 | Minot AFB | 5.0 | 14.09 | 18.59 | 22 | 1.24 | 53 | 37.8 |

*Denotes Current UTC User

Further details on these results, along with rankings of these 19 bases for each economic measure, are shown in Tables 17 through 21 and Figures 20 through 24.

**Table 17: Ranking of Sample Results – Internal Rate of Return (IRR)**

| Installation | | Hangar | Warehouse | Maintenance |
|---|---|---|---|---|
| 1 | EIELSON AFB | 29.5% | 28.0% | 26.8% |
| 2 | KUNSAN AB | 20.6% | 19.6% | 18.7% |
| 3 | AIR FORCE ACADEMY | 13.8% | 13.1% | 12.5% |
| 4 | FAIRCHILD AFB | 12.1% | 11.4% | 10.8% |
| 5 | ANDREWS AFB | 10.5% | 9.8% | 9.3% |
| 6 | ELMENDORF AFB | 10.5% | 9.8% | 9.2% |
| 7 | PETERSON AFB | 9.7% | 9.1% | 8.6% |
| 8 | MALMSTROM AFB | 9.7% | 9.0% | 8.5% |
| 9 | BUCKLEY AFB | 9.6% | 9.0% | 8.5% |
| 10 | EDWARDS AFB | 9.3% | 8.7% | 8.3% |
| 11 | GRAND FORKS AFB | 9.1% | 8.5% | 8.0% |
| 12 | OFFUTT AFB | 8.7% | 8.1% | 7.5% |
| 13 | WRIGHT PATTERSON AFB | 8.6% | 8.0% | 7.5% |
| 14 | KIRTLAND AFB | 8.5% | 7.9% | 7.5% |
| 15 | MOUNTAIN HOME AFB | 8.2% | 7.7% | 7.2% |
| 16 | HILL AFB | 7.3% | 6.7% | 6.3% |
| 17 | SCOTT AFB | 6.9% | 6.4% | 5.9% |
| 18 | ELLSWORTH AFB | 6.4% | 5.8% | 5.4% |
| 19 | MINOT AFB | 6.0% | 5.4% | 5.0% |
| | Min: | 6.0% | 5.4% | 5.0% |
| | Max: | 29.5% | 28.0% | 26.8% |
| | Mean: | 10.8% | 10.1% | 9.5% |

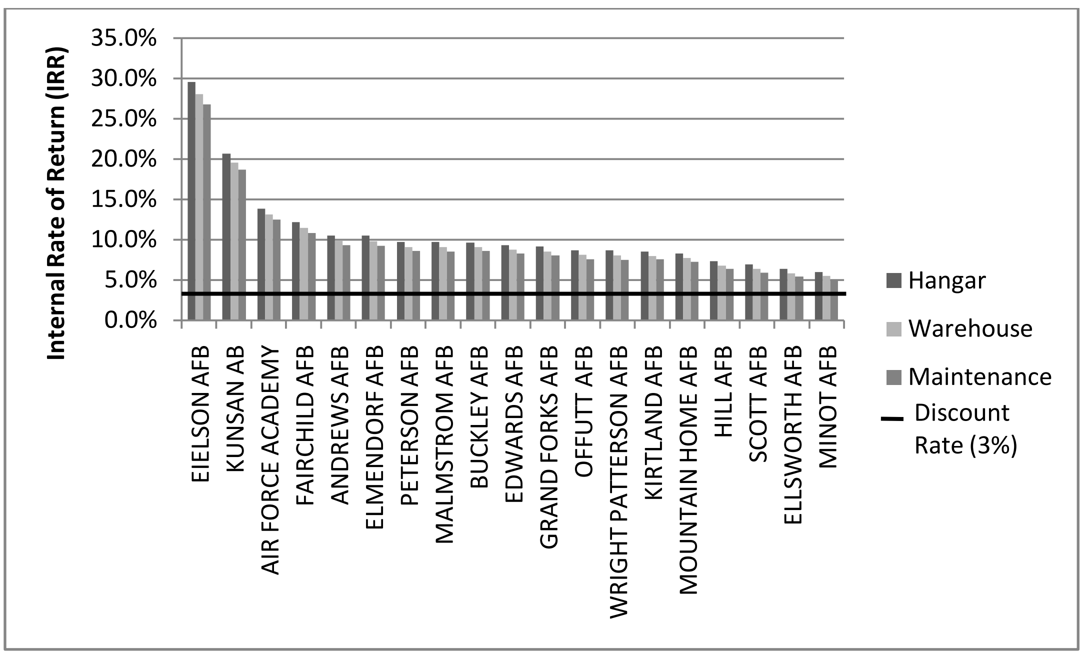



**Figure 20: Internal Rate of Return (IRR) Results**

**Table 18: Ranking of Sample Results - Simple Payback Period (SPBP)**

| | Installation | Hangar | Warehouse | Maintenance |
|---|---|---|---|---|
| 1 | EIELSON AFB | 3.38 | 3.56 | 3.73 |
| 2 | KUNSAN AB | 4.80 | 5.05 | 5.28 |
| 3 | AIR FORCE ACADEMY | 6.96 | 7.30 | 7.59 |
| 4 | FAIRCHILD AFB | 7.77 | 8.18 | 8.54 |
| 5 | ANDREWS AFB | 8.73 | 9.19 | 9.61 |
| 6 | ELMENDORF AFB | 8.75 | 9.23 | 9.68 |
| 7 | PETERSON AFB | 9.31 | 9.77 | 10.16 |
| 8 | MALMSTROM AFB | 9.32 | 9.80 | 10.24 |
| 9 | BUCKLEY AFB | 9.35 | 9.81 | 10.20 |
| 10 | EDWARDS AFB | 9.60 | 10.06 | 10.45 |
| 11 | GRAND FORKS AFB | 9.72 | 10.22 | 10.67 |
| 12 | OFFUTT AFB | 10.09 | 10.62 | 11.10 |
| 13 | WRIGHT PATTERSON AFB | 10.11 | 10.66 | 11.18 |
| 14 | KIRTLAND AFB | 10.25 | 10.74 | 11.14 |
| 15 | MOUNTAIN HOME AFB | 10.45 | 10.98 | 11.45 |
| 16 | HILL AFB | 11.36 | 11.93 | 12.42 |
| 17 | SCOTT AFB | 11.72 | 12.35 | 12.92 |
| 18 | ELLSWORTH AFB | 12.36 | 12.99 | 13.55 |
| 19 | MINOT AFB | 12.82 | 13.49 | 14.09 |
| | Min: | 3.38 | 3.56 | 3.73 |
| | Max: | 12.82 | 13.49 | 14.09 |
| | Mean: | 9.31 | 9.79 | 10.21 |

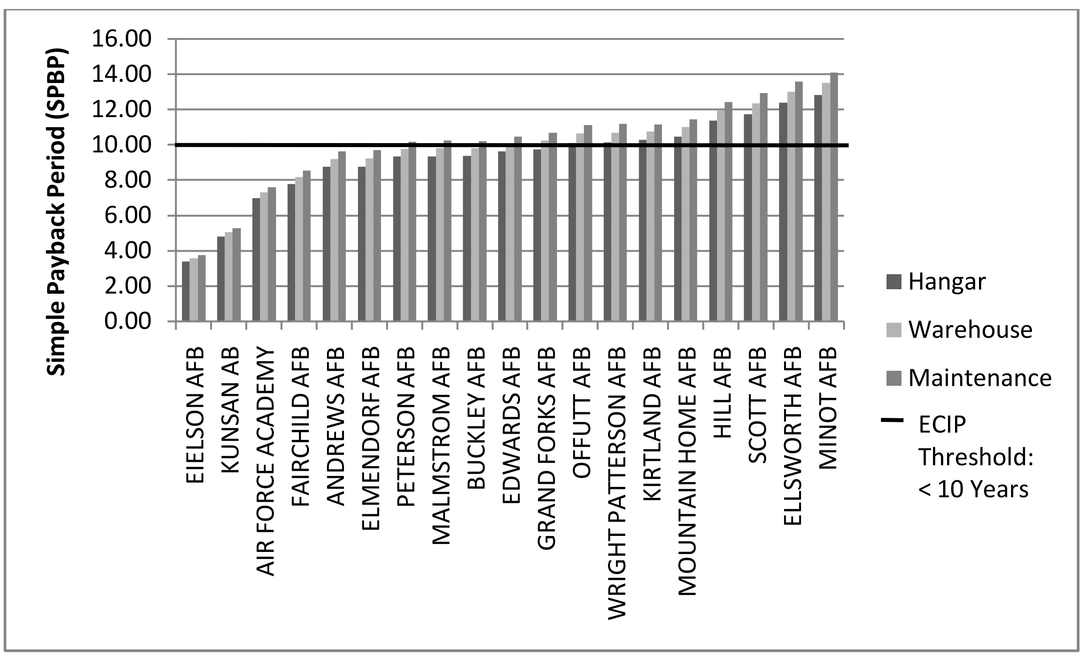



**Figure 21: Simple Payback Period (SPBP) Results**

**Table 19: Ranking of Sample Results - Discounted Payback Period (DPBP)**

| | Installation | Hangar | Warehouse | Maintenance |
|---|---|---|---|---|
| 1 | EIELSON AFB | 3.62 | 3.83 | 4.01 |
| 2 | KUNSAN AB | 5.27 | 5.57 | 5.83 |
| 3 | AIR FORCE ACADEMY | 7.92 | 8.37 | 8.75 |
| 4 | FAIRCHILD AFB | 8.98 | 9.52 | 10.01 |
| 5 | ANDREWS AFB | 10.28 | 10.92 | 11.51 |
| 6 | ELMENDORF AFB | 10.31 | 10.97 | 11.61 |
| 7 | PETERSON AFB | 11.08 | 11.74 | 12.31 |
| 8 | MALMSTROM AFB | 11.10 | 11.79 | 12.41 |
| 9 | BUCKLEY AFB | 11.14 | 11.80 | 12.37 |
| 10 | EDWARDS AFB | 11.49 | 12.16 | 12.73 |
| 11 | GRAND FORKS AFB | 11.66 | 12.39 | 13.05 |
| 12 | OFFUTT AFB | 12.20 | 12.98 | 13.70 |
| 13 | WRIGHT PATTERSON AFB | 12.23 | 13.04 | 13.82 |
| 14 | KIRTLAND AFB | 12.43 | 13.16 | 13.76 |
| 15 | MOUNTAIN HOME AFB | 12.73 | 13.53 | 14.23 |
| 16 | HILL AFB | 14.10 | 14.99 | 15.77 |
| 17 | SCOTT AFB | 14.66 | 15.66 | 16.60 |
| 18 | ELLSWORTH AFB | 15.68 | 16.72 | 17.66 |
| 19 | MINOT AFB | 16.43 | 17.56 | 18.59 |
| | Min: | 3.62 | 3.83 | 4.01 |
| | Max: | 16.43 | 17.56 | 18.59 |
| | Mean: | 11.23 | 11.93 | 12.56 |

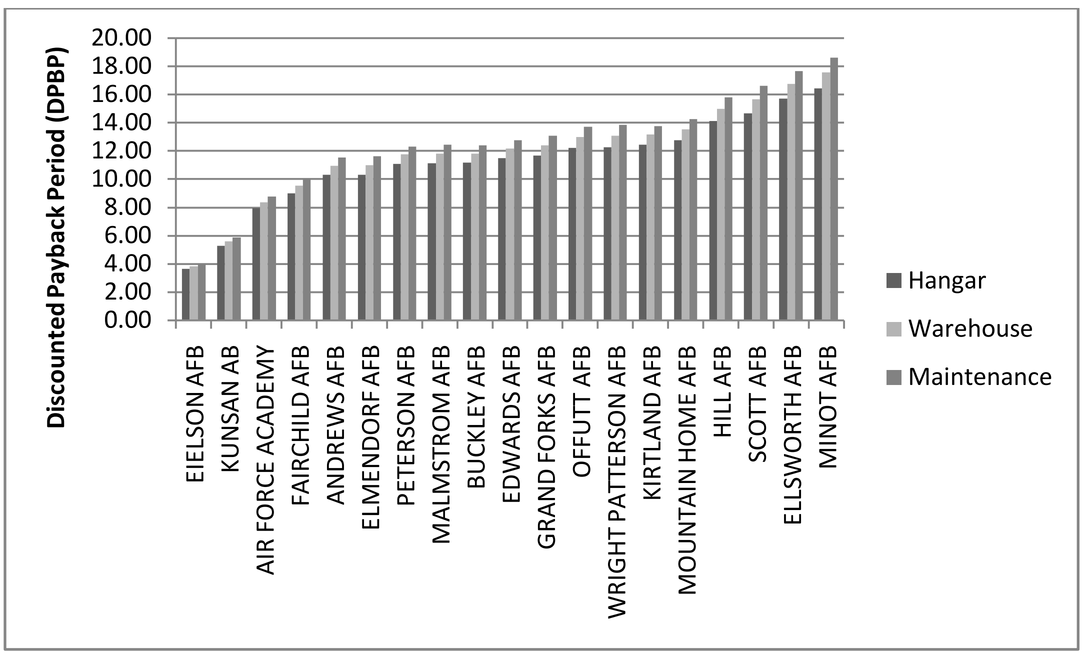



**Figure 22: Discounted Payback Period (DPBP) Results**

**Table 20: Ranking of Sample Results - Net Present Value (NPV)**

| | Installation | Hangar | Warehouse | Maintenance |
|---|---|---|---|---|
| 1 | EIELSON AFB | $1,171,340 | $423,731 | $336,522 |
| 2 | KUNSAN AB | $741,419 | $266,630 | $210,800 |
| 3 | AIR FORCE ACADEMY | $424,423 | $150,986 | $118,550 |
| 4 | FAIRCHILD AFB | $350,451 | $123,153 | $95,238 |
| 5 | ANDREWS AFB | $280,733 | $97,497 | $74,478 |
| 6 | ELMENDORF AFB | $279,333 | $96,604 | $73,277 |
| 7 | PETERSON AFB | $245,748 | $85,259 | $65,405 |
| 8 | MALMSTROM AFB | $245,136 | $84,584 | $64,276 |
| 9 | BUCKLEY AFB | $243,462 | $84,431 | $64,751 |
| 10 | EDWARDS AFB | $229,865 | $79,581 | $61,027 |
| 11 | GRAND FORKS AFB | $223,621 | $76,716 | $57,993 |
| 12 | OFFUTT AFB | $205,045 | $69,730 | $52,127 |
| 13 | WRIGHT PATTERSON AFB | $204,027 | $69,021 | $51,119 |
| 14 | KIRTLAND AFB | $197,305 | $67,756 | $51,665 |
| 15 | MOUNTAIN HOME AFB | $187,928 | $63,793 | $47,793 |
| 16 | HILL AFB | $150,313 | $50,095 | $36,897 |
| 17 | SCOTT AFB | $137,224 | $44,734 | $31,852 |
| 18 | ELLSWORTH AFB | $115,449 | $37,069 | $26,106 |
| 19 | MINOT AFB | $101,037 | $31,677 | $21,641 |
| | Min: | $101,037 | $31,677 | $21,641 |
| | Max: | $1,171,340 | $423,731 | $336,522 |
| | Mean: | $301,782 | $105,423 | $81,132 |

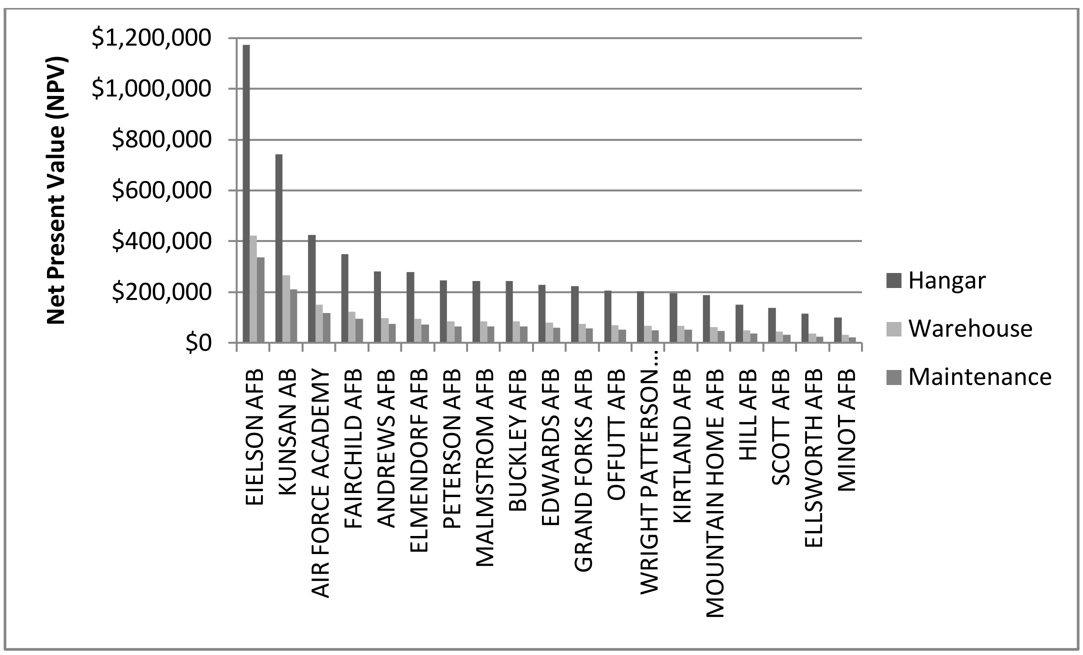



**Figure 23: Net Present Value (NPV) Results**

**Table 21: Ranking of Sample Results - Savings-to-Investment Ratio (SIR)**

| | Installation | Hangar | Warehouse | Maintenance |
|---|---|---|---|---|
| 1 | EIELSON AFB | 5.15 | 4.89 | 4.67 |
| 2 | KUNSAN AB | 3.63 | 3.45 | 3.30 |
| 3 | AIR FORCE ACADEMY | 2.50 | 2.39 | 2.29 |
| 4 | FAIRCHILD AFB | 2.24 | 2.13 | 2.04 |
| 5 | ANDREWS AFB | 1.99 | 1.89 | 1.81 |
| 6 | ELMENDORF AFB | 1.99 | 1.89 | 1.80 |
| 7 | PETERSON AFB | 1.87 | 1.78 | 1.71 |
| 8 | MALMSTROM AFB | 1.87 | 1.78 | 1.70 |
| 9 | BUCKLEY AFB | 1.86 | 1.77 | 1.71 |
| 10 | EDWARDS AFB | 1.81 | 1.73 | 1.67 |
| 11 | GRAND FORKS AFB | 1.79 | 1.70 | 1.63 |
| 12 | OFFUTT AFB | 1.73 | 1.64 | 1.57 |
| 13 | WRIGHT PATTERSON AFB | 1.72 | 1.63 | 1.56 |
| 14 | KIRTLAND AFB | 1.70 | 1.62 | 1.56 |
| 15 | MOUNTAIN HOME AFB | 1.67 | 1.59 | 1.52 |
| 16 | HILL AFB | 1.53 | 1.46 | 1.40 |
| 17 | SCOTT AFB | 1.49 | 1.41 | 1.35 |
| 18 | ELLSWORTH AFB | 1.41 | 1.34 | 1.28 |
| 19 | MINOT AFB | 1.36 | 1.29 | 1.24 |
| | Min: | 1.36 | 1.29 | 1.24 |
| | Max: | 5.15 | 4.89 | 4.67 |
| | Mean: | 2.07 | 1.97 | 1.89 |

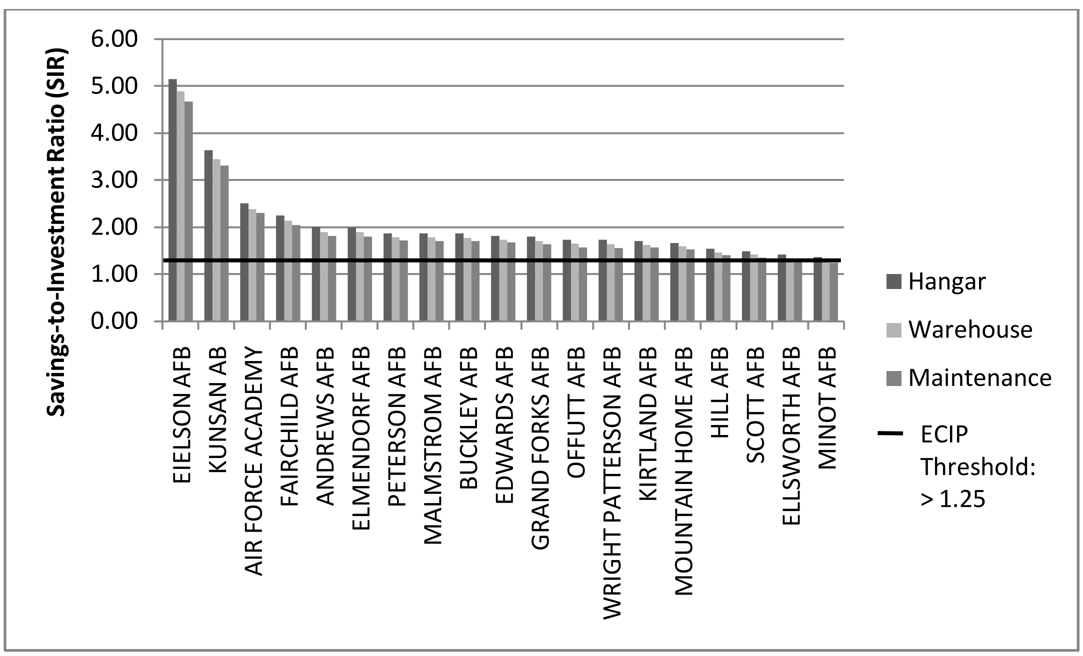



**Figure 24: Savings-to-Investment Ratio (SIR) Results**

The results of our financial analysis indicate that UTC implementation has the potential to be economically beneficial across all of our 19 sample bases. In addition, preliminary estimates from this study indicate that numerous locations may be competitive candidates for obtaining ECIP funding. In the next section, we will provide the results from our environmental analysis.

***Greenhouse Gas (GHG) Emission Results***

The results of our analysis indicated that the use of UTC systems would result in GHG emission reductions ranging from 45 to 339 tons of $CO_2$ annually. If we expand these reduction figures across a 25-year time horizon, the range converts to 1,125 to 8,475 tons of $CO_2$. Table 22 provides a ranking of our sample installations based on the estimated annual GHG emission reduction amounts.

**Table 22: Ranking of Sample Results - GHG Emission Reductions (tCO2)**

| | Installation | Hangar | Warehouse | Maintenance |
|---|---|---|---|---|
| 1 | EIELSON AFB | 339 | 124 | 100 |
| 2 | KUNSAN AB | 236 | 87 | 70 |
| 3 | ELMENDORF AFB | 214 | 78 | 63 |
| 4 | BUCKLEY AFB | 200 | 74 | 60 |
| 5 | AIR FORCE ACADEMY | 199 | 73 | 59 |
| 6 | PETERSON AFB | 199 | 73 | 59 |
| 7 | HILL AFB | 196 | 72 | 58 |
| 8 | FAIRCHILD AFB | 195 | 71 | 58 |
| 9 | MOUNTAIN HOME AFB | 188 | 69 | 56 |
| 10 | ELLSWORTH AFB | 183 | 67 | 54 |
| 11 | GRAND FORKS AFB | 181 | 67 | 54 |
| 12 | MINOT AFB | 179 | 66 | 53 |
| 13 | MALMSTROM AFB | 178 | 65 | 53 |
| 14 | OFFUTT AFB | 172 | 63 | 51 |
| 15 | KIRTLAND AFB | 171 | 63 | 51 |
| 16 | ANDREWS AFB | 134 | 49 | 40 |
| 17 | SCOTT AFB | 129 | 47 | 38 |
| 18 | WRIGHT PATTERSON AFB | 123 | 45 | 36 |
| 19 | EDWARDS AFB | 122 | 46 | 38 |
| | Min: | 122 | 45 | 36 |
| | Max: | 339 | 124 | 100 |
| | Mean: | 186 | 68 | 55 |

Figure 25 provides a graphical representation of the annual tons of $CO_2$ reductions resulting from using our proposed UTCs at each base location.

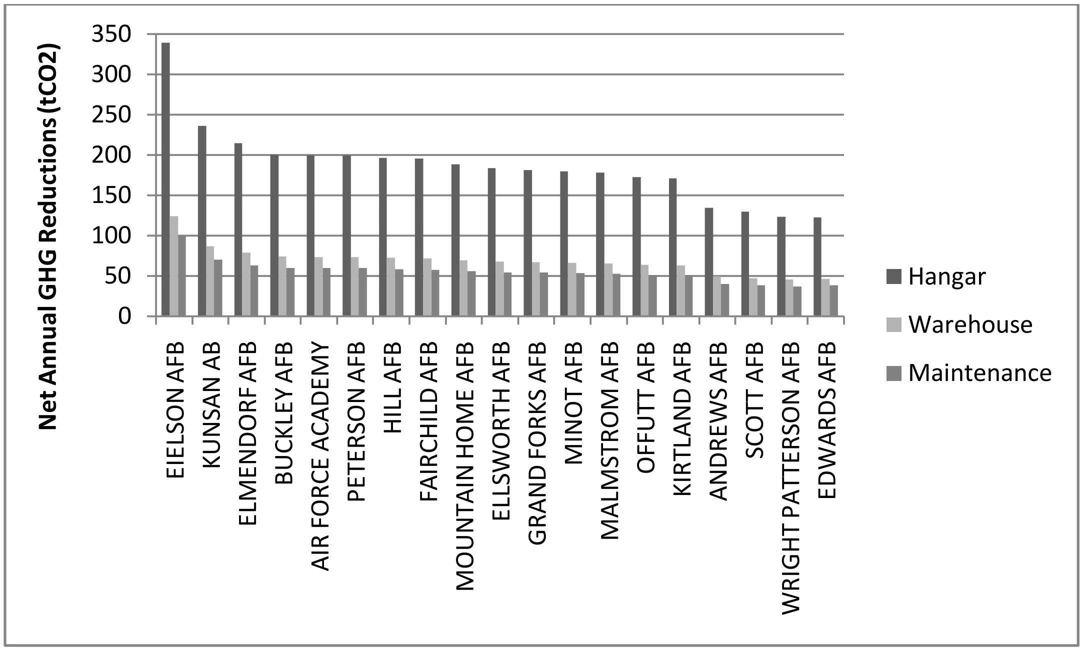



**Figure 25: Summary of GHG Emission Reductions (Tons of CO2 per year)**

To provide a better understanding of the magnitude of these emission reduction amounts, Table 23 provides a conversion chart to illustrate the equivalence of reducing $CO_2$ emissions by one ton. We note that these conversion values are based on North American energy use patters (RETScreen, 2008).

**Table 23: Equivalence of Reducing 1 Ton of $CO_2$ Emissions**

| | | |
|---|---|---|
| **1 ton of $CO_2$ =** | 107.342 | Gallons of gasoline not used |
| | | or |
| | 2.0764 | Barrels of crude oil not consumed |
| | | or |
| | 1 | Person reducing energy consumption by 20% |
| | | or |
| | 0.85 | Acres of forest absorbing carbon |
| | | or |
| | 0.2033 | Cars and light trucks not used |

(Source: RETScreen®, 2008)

Using GHG emission reduction quantities for Hill AFB as an example, we will illustrate, in Table 24, the impact that a UTC on a hangar can potentially have in reducing GHG emissions at Hill AFB. We extrapolated the annual reduction amounts to 25, 30, and 35 years to highlight the total reductions that could be realized over the useful life of a UTC system.

**Table 24: Equivalence of GHG Reduction Amounts at Hill AFB (Hangar)**

| **Hill Air Force Base** | **Years** | | | |
|---|---|---|---|---|
| | **1** | **25** | **30** | **35** |
| **GHG Reduction amount (tons of CO2)** | **196** | **4,900** | **5,880** | **6,860** |
| *Which is equivalent to* | | | | |
| Gallons of gasoline not used: | 21,039 | 525,976 | 631,171 | 736,366 |
| Barrels of crude oil not consumed: | 407 | 10,174 | 12,209 | 14,244 |
| People reducing energy use by 20%: | 196 | 4,900 | 5,880 | 6,860 |
| Acres of forest absorbing carbon: | 167 | 4,165 | 4,998 | 5,831 |
| Cars and light trucks not used: | 40 | 996 | 1,195 | 1,395 |

The results of our calculated "%Solar" variable at each of our sample locations are shown in Figure 26. The variable, %Solar, represents the percent of heating demands being met by the UTC during the time in which it is being operated.

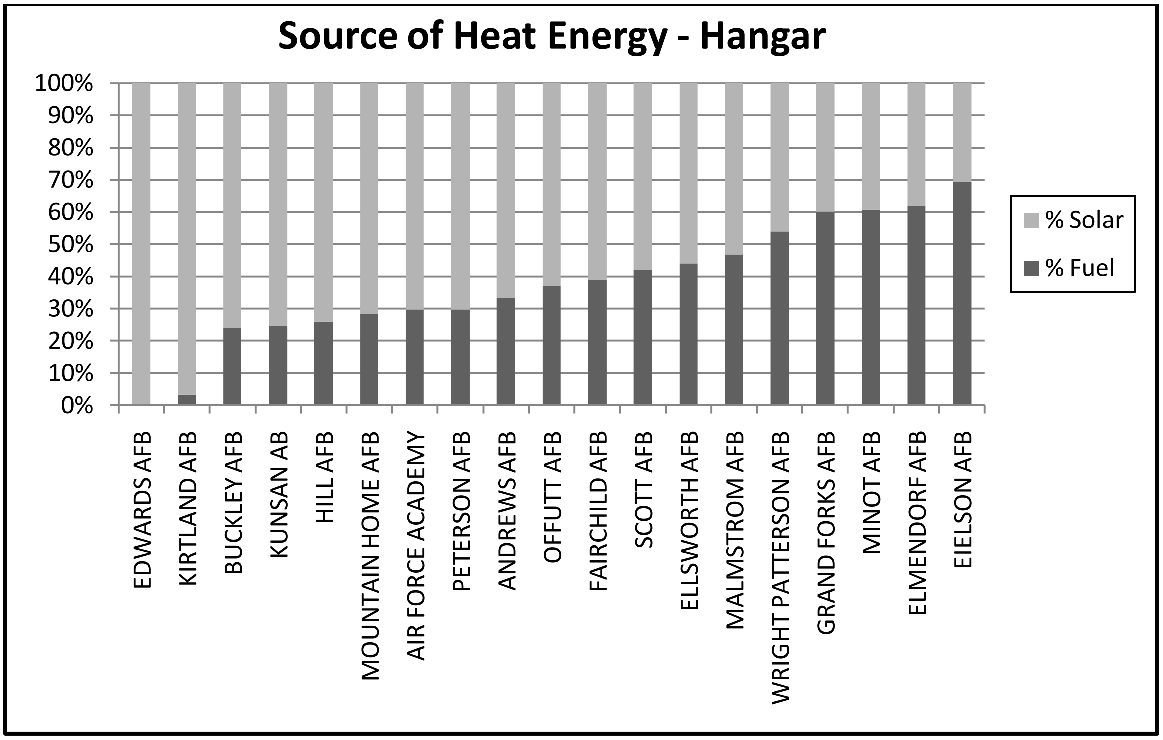



**Figure 26: Source of Heat Energy during UTC Operation**

Our results indicated that during periods of UTC operation, the UTC system would provide more than 50 percent of the hangar facility heat needed for 14 out of 19 bases. The UTC system would be able to meet all of the hangar facility heating demands at Edwards AFB, and over 95 percent of the heating demands at Kirtland AFB.

The buildings modeled at the two sample bases located in Alaska, Elmendorf and Eielson AFB, would still utilize their fuel source to meet over 60 percent of heating demands. We expect that a location such as Alaska, which has winters with very low levels of solar radiation and incredibly high amounts of HDDs, would receive most of its heating energy from the fuel source during the winter months. The UTC system would likely be most beneficial to these bases during the summer months, when there are still HDD requirements and the daylight hours are substantially longer.

### *Analysis of UTC Performance Drivers*

We attempted to perform an evaluation of UTC systems that can be generalized across various Air Force bases. In doing so, we chose our hypothetical facility types and UTC characteristics to try to represent scenarios that we felt had the highest likelihood of being found at each location. Just like cost estimates for complex programs, however, the probability that our scenario estimates are 100 accurate is unlikely. We acknowledge that our scenarios are only pre-feasibility estimates, and that actual facility and UTC system characteristics will be slightly different in real world applications. In an attempt to gain a better understanding of how these differences can change the performance of a UTC system, we performed sensitivity analysis.

We chose to perform a sensitivity analysis on ten different input variables on our hangar example. These variables are then adjusted within an upper and lower boundary to demonstrate the corresponding change in each of our performance measures. These boundaries were set at plus or minus 20 percent, with the exception of solar collector absorptivity. Solar collector absorptivity had an upper boundary of 0.94, which is our base case assumption corresponding to a black UTC wall. We set a lower boundary of 0.85, which corresponds to the lowest level of absorptivity that has been used by DoD installations in the past. We selected climate data from Colorado Springs, CO. A summary of our sensitivity analysis inputs is shown in Table 25.

**Table 25: Summary of Sensitivity Analysis Inputs**

| RETScreen® Inputs | Base case Values (Hangar) | Lower Boundaries (-20%) | Upper Boundaries (+20%) |
|---|---|---|---|
| Building air temperature stratification(°F): | 10.0 | 8.0 | 12.0 |
| Floor area ($ft^2$) | 80,000 | 64,000 | 96,000 |
| R-Value – roof ($ft^2$ - °F/(Btu/h)) | 19.0 | 15.2 | 22.8 |
| R-Value – wall ($ft^2$ - °F/(Btu/h)) | 13.0 | 10.4 | 15.6 |
| | | | |
| Design airflow rate (CFM) | 53,333 | 42,666 | 64,000 |
| | | | |
| Initial cost (CY$08) | $282,333 | $225,866 | $338,800 |
| Natural gas fuel cost ($/MBtu) | $8.00 | $6.40 | $9.60 |
| | | | |
| Solar collector absorptivity | 0.94 | 0.85 | 0.94 |
| Solar collector area ($ft^2$) | 10,667 | 8,534 | 12,800 |
| | | | |
| Heating – fuel type | Natural Gas | Natural Gas | Natural Gas |
| Seasonal efficiency (%) | 75.0 | 62.4 | 90.0 |

We then produced tornado diagrams to illustrate the sensitivity of each of these variables on each performance measure. Tornado diagrams allow us to compare one-way sensitivity analysis for multiple input variables at once. They indicate which variables we need to consider more closely when making UTC assumptions and help us determine which variables drive UTC performance. The width of each bar represents the extent to which each performance measure is sensitive to each variable, captured as a percent change in the value of the base case performance value. This percent change is quantified on the x-axis of each tornado diagram. The variables with the widest bars are located at the top of the diagram and represent the variables that are most sensitive (Clemen *et al.*, 2001:180). A ranking of variable sensitivity for each measure can be found in Table 26.

**Table 26: Ranking of Variable Sensitivity by Measure**

| Variable | Measure | | | | | | |
|---|---|---|---|---|---|---|---|
| | IRR | SPBP | DPBP | NPV | SIR | tCO2 | %Solar |
| Fuel cost | 3 | 1 | 1 | 2 | 3 | * | * |
| Initial cost | 1 | 2 | 2 | 4 | 1 | * | * |
| Seasonal efficiency | 2 | 3 | 3 | 1 | 2 | 1 | 3 |
| Collector area | 4 | 4 | 4 | 3 | 4 | 2 | 2 |
| Airflow rate | 5 | 5 | 5 | 5 | 5 | 3 | 1 |
| UTC solar absorptivity | 6 | 6 | 6 | 6 | 6 | 4 | 4 |
| Stratification | 7 | 7 | 7 | 7 | 7 | 5 | 5 |
| R-value: wall | * | * | * | * | * | * | * |
| R-value: roof | * | * | * | * | * | * | * |
| Floor area | * | * | * | * | * | * | * |

*Little to no sensitivity to measure

Fuel cost, collector area, airflow rate, UTC solar absorptivity, and stratification all have a positive relationship with our economic measures. We note that for SPBP and DPBP, lower values are desired, which is contrary to IRR, NPV, and SIR. This accounts for why the relationships for SPBP and DPBP appear opposite to the other measures in Table 27. These relationships determined from our analysis confirm our presumed relationships uncovered in previous UTC literature and design guides.

**Table 27: Relationship between Variables and Measures**

| Variable | Measure | | | | | | |
|---|---|---|---|---|---|---|---|
| | IRR | SPBP | DPBP | NPV | SIR | tCO2 | %Solar |
| Fuel cost | + | - | - | + | + | NA | NA |
| Initial cost | - | + | + | - | - | NA | NA |
| Seasonal efficiency | - | + | + | - | - | - | + |
| Collector area | + | - | - | + | + | + | + |
| Airflow rate | + | - | - | + | + | + | - |
| UTC solar absorptivity | + | - | - | + | + | + | + |
| Stratification | + | - | - | + | + | + | + |

"+" = Positive Relationship
"-" = Negative Relationship
"NA" = Not Applicable (no relationship)

It is important to note that for our analysis, the ends of each bar in the tornado diagrams can represent either the upper or lower boundary from the sensitivity analysis. If the variable has a negative relationship with the measure, then the lower boundary will be located on the right end of the bar while the upper boundary will be located at the left end of the bar. For positive relationships, the upper boundary will be located on the right end of each bar, while the lower boundary will be located on the left end.

Our results indicate that fuel cost, initial cost, and seasonal efficiency variables have the greatest sensitivity to our economic measures. Collector area, airflow rate, absorptivity, and stratification are also sensitive to our economic measures, but to a lesser degree. The R-value of the wall and roof, as well as the size of the floor area, has very little sensitivity across all measures. The tornado diagrams for the economic measures can be found in Figures 27 through 31.

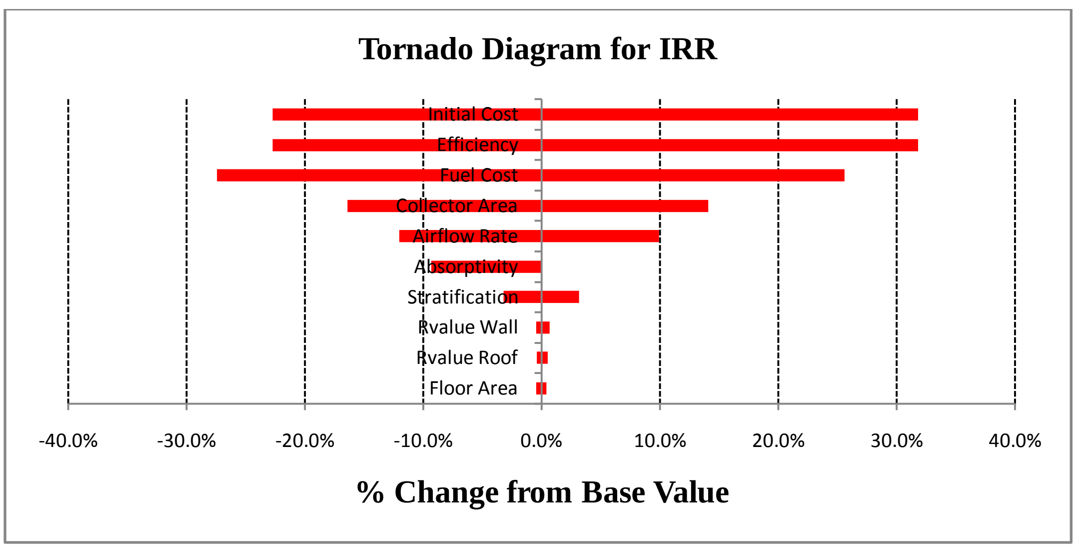



**Figure 27: Tornado Diagram for IRR**

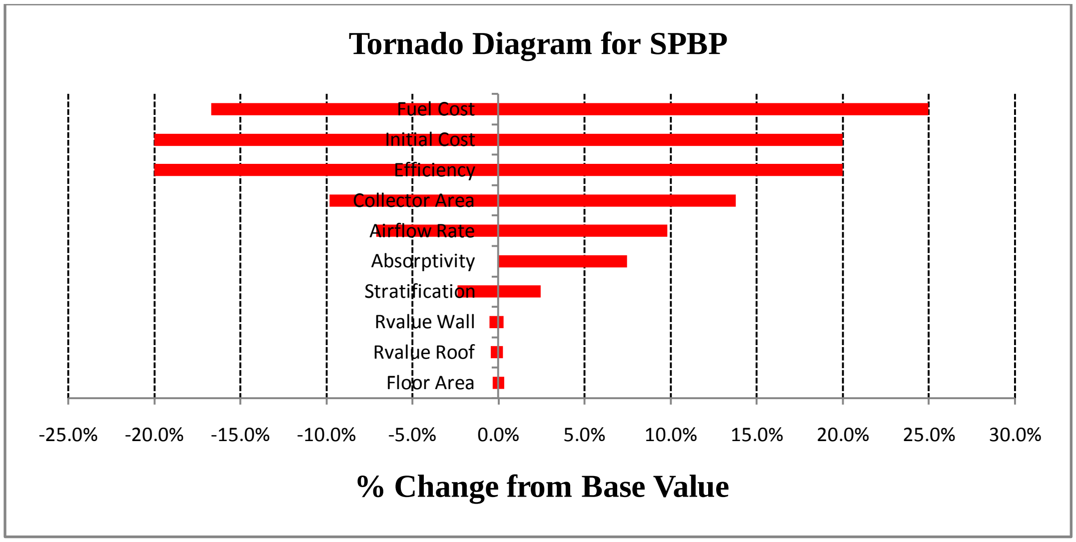



**Figure 28: Tornado Diagram for SPBP**

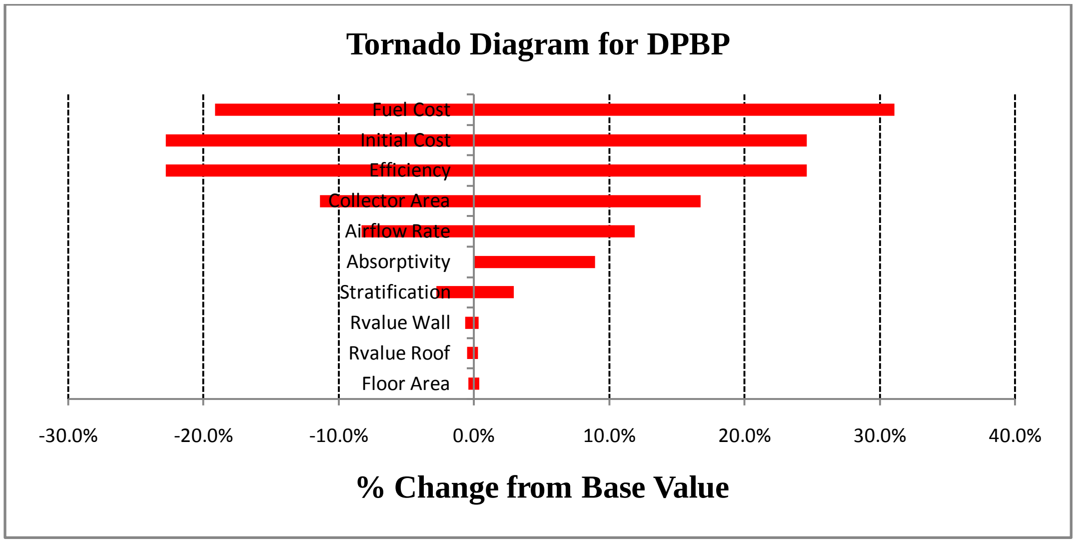



**Figure 29: Tornado Diagram for DPBP**

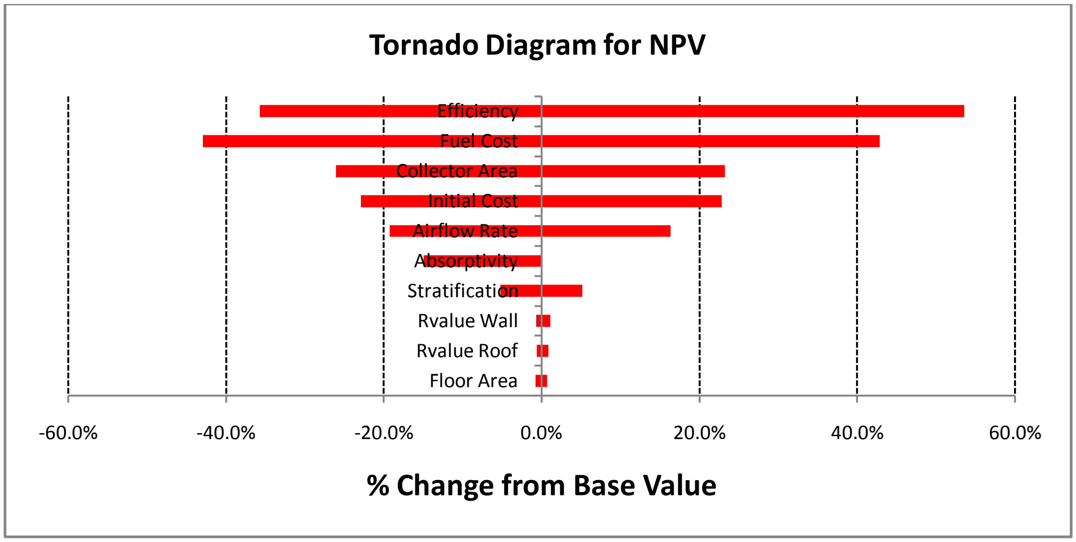



**Figure 30: Tornado Diagram for NPV**

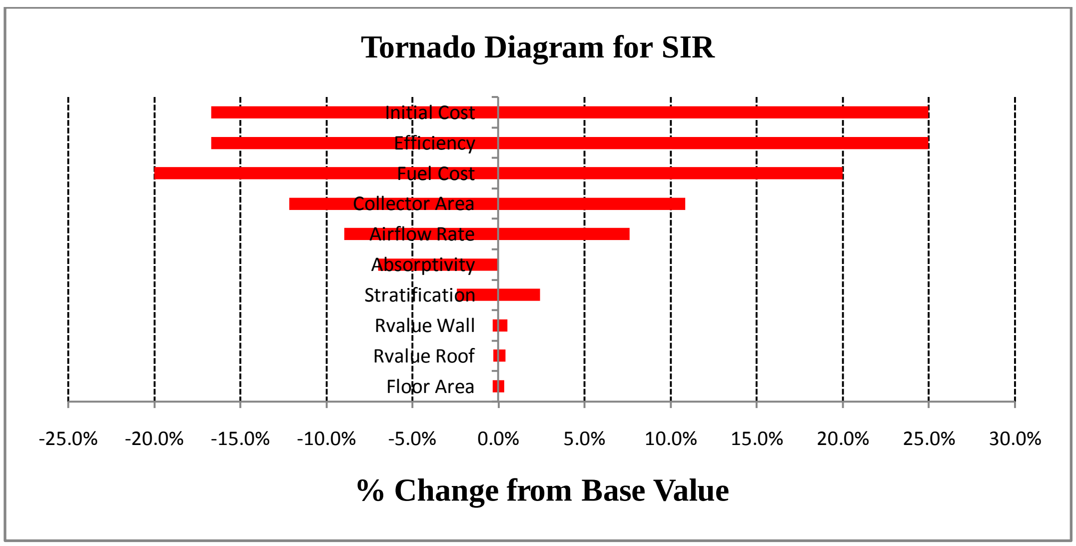



**Figure 31: Tornado Diagram for SIR**

The costs associated with the UTC system have no effect on the amount of $CO_2$ emission reductions and the percent of energy being provided by the UTC system. Collector area, airflow rate, seasonal efficiency, absorptivity, and stratification are all sensitive to our non-economic variables, tCO2 and %Solar. The tornado diagrams for tCO2 and %Solar can be found in Figure 32 and Figure 33, respectively.

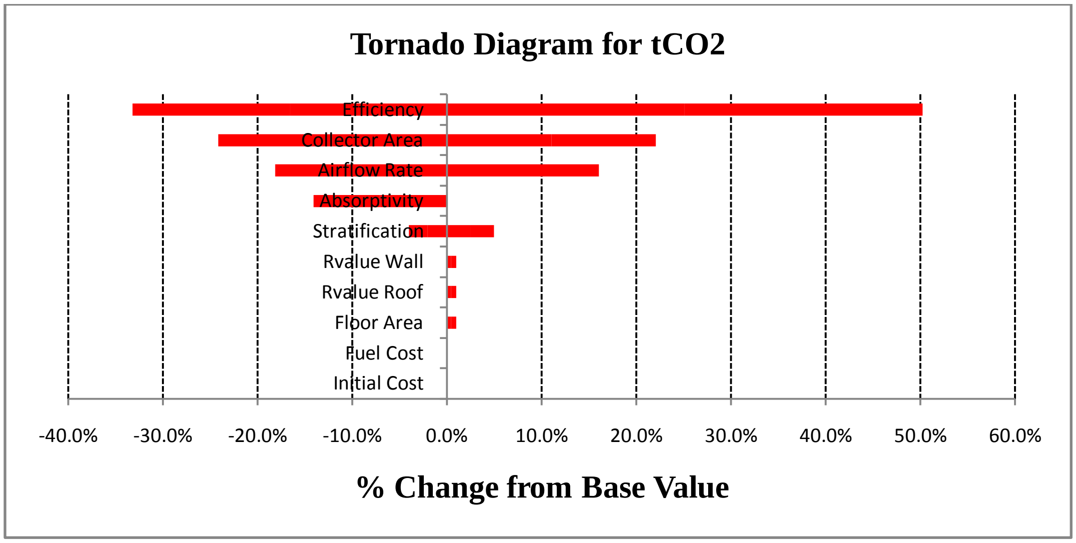



**Figure 32: Tornado Diagram for $tCO_2$**

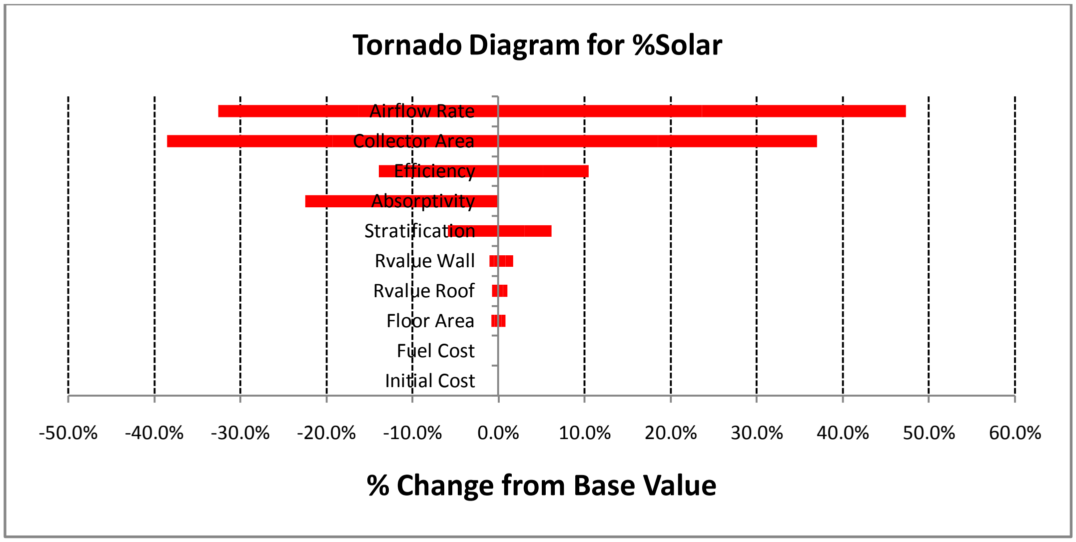



**Figure 33: Tornado Diagram for %Solar**

Further detail of our sensitivity analysis results can be found in Appendix E. We included a comprehensive one-way and two-way sensitivity analysis. An example of how a two-way analysis could be useful is shown in Table 28. In this example, we show how simultaneous changes in our assumptions can affect the economic performance measures for our proposed hangar at Minot AFB, our weakest performing location. The two-way analysis in Table 28 shows how the most sensitive factors for each performance measure can lead to substantial differences in the performance of the UTC system.

**Table 28: Two-way Sensitivity Example - Minot AFB**

**IRR**

| Initial Cost | Efficiency 60% | Efficiency 75% | Efficiency 90% |
|---|---|---|---|
| $225,866 | 11.36 | 8.47 | 6.40 |
| $282,333 | 8.47 | 5.97 | 4.14 |
| $338,800 | 6.40 | 4.14 | 2.48 |

**NPV**

| Fuel Cost | Efficiency 60% | Efficiency 75% | Efficiency 90% |
|---|---|---|---|
| $5.17 | $101,192 | $24,487 | ($26,650) |
| $6.46 | $196,888 | $101,043 | $37,148 |
| $7.75 | $292,584 | $177,601 | $100,945 |

**SPBP**

| Initial Cost | Fuel Cost $5.17 | Fuel Cost $6.46 | Fuel Cost $7.75 |
|---|---|---|---|
| $225,866 | 12.82 | 10.26 | 8.55 |
| $282,333 | 16.05 | 12.82 | 10.69 |
| $338,800 | 19.23 | 15.39 | 12.83 |

**SIR**

| Initial Cost | Efficiency 60% | Efficiency 75% | Efficiency 90% |
|---|---|---|---|
| $225,866 | 2.12 | 1.70 | 1.41 |
| $282,333 | 1.70 | 1.36 | 1.13 |
| $338,800 | 1.41 | 1.13 | 0.94 |

Notice that the UTC system performs best during less than ideal conditions. If fuel costs rise, which would be undesirable from the Air Force's perspective, the UTC system would provide a better Net Present Value (NPV) and a shorter simple payback period (SPBP). We feel that these results demonstrate how UTCs could be a desirable investment for risk-averse decision-makers who are concerned with potential increases in energy costs in the future.

# V. Conclusions and Future Research

The purpose of this research effort was to evaluate the suitability of utilizing Unglazed Transpired Collector (UTC) technology in the Air Force. This research serves as a stepping stone for individuals trying to gain a better understanding of UTC technology and its potential use moving forward. Our pre-feasibility study helped identify strong candidates for future UTC project implementation across the Air Force. In addition, this research quantified the potential cost and environmental savings that could be realized from various applications of UTC use. This evaluation also provided a consolidated source of lessons learned from the various military installations which have already utilized UTC systems. This information can help Air Force leaders and future UTC program managers implement more effective and successful UTC programs.

## Review

Balance of power with foreign nations, energy security, pollution, unpredictable and rising energy costs, and the need for less dependency on foreign sources of oil all provide justification for the aggressive energy goals set forth by the Federal Government. The Air Force has not only recognized the numerous reasons why the pursuit of alternative forms of energy is critical to the U.S., but has already begun doing something about it. The Air Force, as a whole, is one of the leading users of alternative energy in the world. Our research highlighted just one of the many technologies in use today that can further assist the Air Force in accomplishing energy goals by reducing demand for non-renewable sources of energy.

In addition to conducting a thorough review of literature on UTC systems, we performed a site visit to Fort Drum, New York, to gain a better understanding of UTC technology and the various ways in which it can be implemented. With a sound understanding of the technology, we were then able to perform a case study analysis across the various UTC users in the DoD. The information gathered from our case study analysis can provide valuable lessons for future managers of UTC programs.

Our quantitative analysis identified 19 active duty Air Force installations which could all benefit from the use of UTC technology in the future. Four of these installations have already implemented UTC projects, and this research confirms that all four have strong climate characteristics for UTC use. This analysis was performed by modeling three likely UTC applications; a hangar, warehouse, and maintenance facility. Using RETScreen®'s Clean Energy Project Analysis Software, we calculated potential energy savings that could be realized from utilizing these three UTC systems at each Air Force base location. Further analysis determined how variations in our assumptions could affect the expected performance of proposed UTCs.

**Recommendations and Conclusion**

The Air Force needs to welcome alternative energy ideas, like UTCs, but must also commit to testing these technologies thoroughly before accepting or condemning them. More monitoring needs to be performed on UTC systems across the DoD. We feel that the magnitude of the cost savings uncovered in this study more than justify the additional costs that would be associated with implementing more monitoring systems in the future.

Energy managers who are thinking of implementing a UTC should consult previous users to avoid "reinventing the wheel". Although this research attempted to uncover many of the lessons that can be learned from previous UTC users in the DoD, it cannot fully replace the wealth of knowledge that can be gained from actual users, nor can it answer every question that a potential user may have. We feel that this research would serve well as a guide, to be used in conjunction with knowledge obtained from actual users.

To address our central research question, we concluded that the Air Force should further pursue UTC implementation. As a pre-feasibility study, the results of our three different industrial building models demonstrate that all of our 19 bases could potentially benefit from utilizing UTC systems. Our GHG emission analysis reveals that UTCs may be a viable option for Air Force bases that are pursuing different means to reduce the amount of GHG emissions they produce. UTC projects could serve as an excellent means to reach many of the aggressive energy and environmental goals facing energy managers across the Air Force and Federal Government.

**Limitations**

Our research only analyzed three specific types of facilities which we determined could be reasonably generalized across our 19 sample bases. We did not select our assumptions for these buildings based on optimal building characteristics and ventilation requirements for a UTC system, which could have resulted in better results.

The software used in our analysis precluded us from being able to capture the benefits of pre-cooling facilities at night during warm months of the year, when UTC systems remain inoperable during the day. The software also does not take into account potential savings during the warmer months when the UTC wall can act as a passive sunscreen.

We did not factor in energy cost escalation rates in this analysis, which may surpass our discount rate of three percent in the future. Increasing rates of growth for energy costs, however, would lead to a corresponding higher economic advantage in utilizing a UTC system. From our sensitivity analysis, we determined that rising costs in energy could lead to significant increases in the economic performance of a UTC system.

**Future Research**

Our research only focused on a limited number of active duty Air Force installations. An extension of this research could be performed to account for other active duty, National Guard, or Air Reserve installations. A similar assessment could also be performed across other organizations within the DoD or U.S. Government.

Another great opportunity for future research would be to use a similar methodology to assess UTC application at a specific Air Force base. By narrowing the scope of this research, modeling could be performed on real-world buildings and if the results are favorable, they could be used to apply for funding through programs such as ECIP.

## Appendix A: National Ambient Air Quality Standards - Tolerance Levels

The purpose of the "primary standards" is to protect public health. In particular, primary standards are in place to protect those more vulnerable to the harmful effects of pollutants such as children, asthmatics, and the elderly. The purpose of the "secondary standards" is to set limits to protect public welfare. This includes, but is not limited to, protection against decreased visibility, damage to animals, crops, vegetation, and buildings (EPA – NAAQS, 2008).

**Table 29: National Ambient Air Quality Standards**

| | **Primary Standards** | | **Secondary Standards** | |
|---|---|---|---|---|
| **Pollutant** | **Level** | **Averaging Time** | **Level** | **Averaging Time** |
| Carbon Monoxide | 9 ppm (10 $mg/m^3$) | 8-hour(1) | None | |
| | 35 ppm (40 $mg/m^3$) | 1-hour(1) | | |
| Lead | 1.5 $\mu g/m^3$ | Quarterly Average | Same as Primary | |
| Nitrogen Dioxide | 0.053 ppm (100 $\mu g/m^3$) | Annual (Arithmetic Mean) | Same as Primary | |
| Particulate Matter ($PM_{10}$) | 150 $\mu g/m^3$ | 24-hour(2) | Same as Primary | |
| Particulate Matter ($PM_{2.5}$) | 15.0 $\mu g/m^3$ | Annual(3) (Arithmetic Mean) | Same as Primary | |
| | 35 $\mu g/m^3$ | 24-hour(4) | Same as Primary | |
| Ozone | 0.075 ppm (2008 std) | 8-hour(5) | Same as Primary | |
| | 0.08 ppm (1997 std) | 8-hour(6) | Same as Primary | |
| | 0.12 ppm | 1-hour(7) (Applies only in limited areas) | Same as Primary | |
| Sulfur Dioxide | 0.03 ppm | Annual (Arithmetic Mean) | 0.5 ppm (1300 $\mu g/m^3$) | 3-hour(1) |
| | 0.14 ppm | 24-hour(1) | | |

(Source: EPA – NAAQS, 2008)

[(1)] Not to be exceeded more than once per year.

[(2)] Not to be exceeded more than once per year on average over 3 years.

[(3)] To attain this standard, the 3-year average of the weighted annual mean PM2.5 concentrations from single or multiple community-oriented monitors must not exceed 15.0 µg/m3.

[(4)] To attain this standard, the 3-year average of the 98th percentile of 24-hour concentrations at each population-oriented monitor within an area must not exceed 35 µg/m3 (effective December 17, 2006).

[(5)] To attain this standard, the 3-year average of the fourth-highest daily maximum 8-hour average ozone concentrations measured at each monitor within an area over each year must not exceed 0.075 ppm. (effective May 27, 2008)

[(6)] (a) To attain this standard, the 3-year average of the fourth-highest daily maximum 8-hour average ozone concentrations measured at each monitor within an area over each year must not exceed 0.08 ppm.

(b) The 1997 standard—and the implementation rules for that standard—will remain in place for implementation purposes as EPA undertakes rulemaking to address the transition from the 1997 ozone standard to the 2008 ozone standard.

[(7)] (a) The standard is attained when the expected number of days per calendar year with maximum hourly average concentrations above 0.12 ppm is $\leq$ 1.

(b) As of June 15, 2005 EPA revoked the 1-hour ozone standard in all areas except the 8-hour ozone nonattainment Early Action Compact (EAC) Areas.

(Source: EPA – NAAQS, 2008)

## Appendix B: U.S. Air Force Alternative Energy Initiatives

In Appendix B we provide further information on various types of alternative energy initiatives that have been performed by the U.S. Air Force. We provide this information to provide readers with a better understanding of other types of alternative energy technology used by the Air Force in hopes of providing a better understanding of the role that UTCs could play in the overall Air Force energy program.

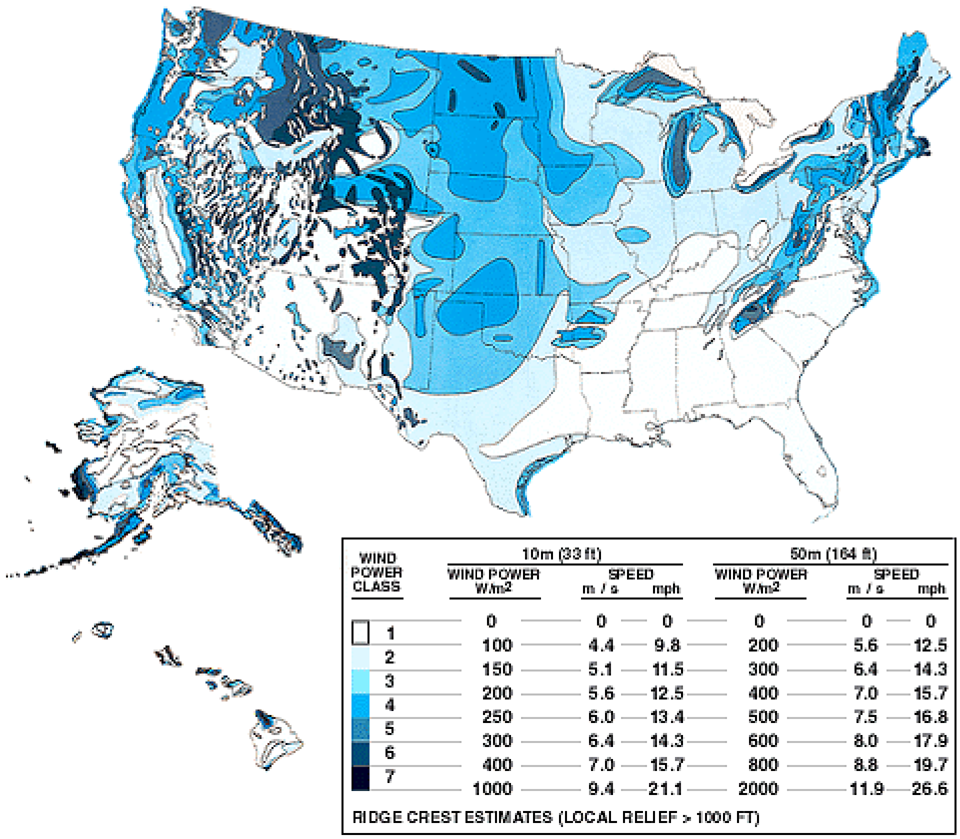
### Wind

Wind power is currently the leading provider of renewable energy for the U.S. Air Force. Dyess AFB, located in Abilene, Texas, entered into a substantial wind energy contract on 1 January 2003 to become the single largest consumer of renewable energy at any single site in the country. The supply contract was issued by the Defense Energy Support Center (DESC) and the wind energy is provided by TXU Energy. Six wind farms are used to capture enough wind energy to provide 100 percent of the electricity demand of the base. At the time, the purchase was large enough to make up 20 percent of the overall renewable energy used by the Federal government and allowed the entire Air Combat Command (ACC) to meet the requirements set forth in EO 13123 (Dyess, 2003:1). In addition, Dyess AFB became the first Air Force Base to enter the EPA's Green Power Partnership. After entering into the wind power contract, the base became the largest site in the partnership to be completely powered by renewable energy sources in 2003 (Dyess, 2003:1).

Fairchild AFB in Spokane, Washington, is another Air Force installation which is fully committed to wind energy. In 2004, Fairchild AFB began purchasing 100 percent of its power from renewable energy sources. Wind power provides 99 percent of this energy, while small hydro provides the remaining 1 percent. Minot AFB has also recently been able to obtain 100 percent renewable energy through the use of wind farms. Senator Byron Dorgan of North Dakota was a strong proponent of wind energy use for Minot AFB and said that the project was an important step "toward realizing North Dakota's potential as the Saudi Arabia of wind energy" (Dorgan, 2002). While this statement may seem somewhat exaggerated, some studies have demonstrated otherwise. In 1991, Pacific Northwest Laboratory conducted a study to assess the wind availability across the United States. In their study, they determined that wind turbines in North Dakota could produce 1.2 billion kilowatt-hours of electricity annually. In 1990 levels, this equates to enough energy to supply more than 14,000 times the demand of North Dakota, and enough to provide 36 percent of U.S. energy consumption (Wind, 2000). This highlights the potential impact that wind resources can provide for the U.S.

Although Dyess, Fairchild, and Minot AFB are the only three installations to be 100 percent wind powered, initiatives have been made at a number of other bases across the DoD to take advantage of the wind's renewable energy. A 2.7 megawatt wind farm on the Ascension Island in the South Atlantic Ocean provides roughly 4,600 megawatt hours of electrical power annually for the installation. A 1.3 megawatt wind farm at F.E. Warrant AFB in Wyoming is capable of generating 4.4 million kilowatt hours per year, which is enough energy to power 520 households (U.S. Air Force Energy Program).

There are limitations of wind energy which keep the technology from being a viable option for many installations. The most apparent characteristic which determines the feasibility of utilizing wind energy at a particular location is the amount of wind resources available there. Wind power is classified on a scale of class 1 to class 7, with class 7 representing the greatest amount of wind power present. Generally, class 4 and above are considered adequate wind resources where large wind turbines could be a viable option (Combs, 2005). Figure  shows the areas of the U.S. which would be both poor and excellent candidates for wind energy generation.



| WIND POWER CLASS | 10m (33 ft) WIND POWER W/m2 | 10m SPEED m/s | 10m SPEED mph | 50m (164 ft) WIND POWER W/m2 | 50m SPEED m/s | 50m SPEED mph |
|---|---|---|---|---|---|---|
| | 0 | 0 | 0 | 0 | 0 | 0 |
| 1 | 100 | 4.4 | 9.8 | 200 | 5.6 | 12.5 |
| 2 | 150 | 5.1 | 11.5 | 300 | 6.4 | 14.3 |
| 3 | 200 | 5.6 | 12.5 | 400 | 7.0 | 15.7 |
| 4 | 250 | 6.0 | 13.4 | 500 | 7.5 | 16.8 |
| 5 | 300 | 6.4 | 14.3 | 600 | 8.0 | 17.9 |
| 6 | 400 | 7.0 | 15.7 | 800 | 8.8 | 19.7 |
| 7 | 1000 | 9.4 | 21.1 | 2000 | 11.9 | 26.6 |

RIDGE CREST ESTIMATES (LOCAL RELIEF > 1000 FT)

**Figure 34: Map of U.S. Wind Resources**

(Source: NREL, 1986)

Another limitation of wind turbines is that the power generation that is created is intermittent in nature. Even if the wind turbine is located in an area with exceptionally high wind speeds, there are times during the year when no wind is present, making it impossible for the turbine to generate electricity. This situation requires that additional sources of power be available to meet energy demands during these time periods or periods of peak demand. The other option would be to store excess energy created by wind turbines through the use of batteries, which is a fairly difficult option given the battery technology currently available. This is a harsh reality faced by wind turbine users that cannot be understated.

Combs (2005) details a number of environmental disadvantages of wind energy to include bird and avian issues, electromagnetic interference, visual and noise issues, and flora and fauna issues (Combs, 2005). Bird and bat deaths caused by wind turbines have received a lot of attention and have been an ongoing concern for some of the critics of wind turbines. Although it is undeniable that wind turbines have caused the death of avian animals, studies have shown that the amount of bird deaths caused by other man-made objects such as motor vehicles, tall buildings, communications towers, windows, airplanes, and overhead electrical lines are far greater. A study released by the National Wind Coordinating Committee found that only a fraction of one percent of avian collision mortality in the U.S. is caused by wind energy production; roughly 1 out of every 5,000 to 10,000 collision fatalities. Overall, the amount of deaths per wind turbine site has been minimal, and has provided a solid indication that the small quantity of fatalities is not simply the product of a correspondingly low quantity of wind turbines in the U.S. (Erickson, 2001).

Efforts should still be made in the planning and design of wind farms to avoid unnecessary bird and bat deaths. Designing turbine towers that birds cannot form nests on and placing wind turbines away from migratory paths and areas densely populated with avian prey are just two examples of how wind turbine users attempt to avoid unnecessary death caused by wind turbines. There is also a balance that should be considered when critiquing avian issues: more wind turbines means less electricity that is instead being generated by power plants burning harmful fossil fuels, which may help lead to a greater good for wildlife and natural habitats.

Another environmental concern over wind turbines is the electromagnetic interference. Like other modes of electrical power generation, wind turbines create electromagnetic fields during operation. The potential for radar interference created by these electromagnetic fields is of particular concern to the Air Force. Unwanted interference could potentially disrupt ground and aircraft radar systems, which could impede training missions or disrupt critical early warning radar stations. On July 12, 2002, Air Force concerns of radar interference were enough to abruptly cancel a 130 million dollar Nevada Test Site wind farm project located atop the Shoshone Mountain (Rogers, 2002). On the contrary, in 2007 there was debate over whether a proposed wind farm in the Nantucket Sound would interfere with the U.S. Air Force Space Command's PAVE PAW radar station in Sagamore, Massachusetts. Studies performed by the DoD indicated that the proposed wind farm would have no adverse effects on PAVE PAWS (Salters, 2007). There are many wind turbine sites located near airfields where no significant difficulties have occurred (Twindell, 2007). Still, careful placement and design of wind turbines must be made to ensure that electromagnetic interference does not adversely impact aviation and military operations. In addition, TV and FM radio can also be affected by electromagnetic interference which must be taken into consideration as well (REW, 2007).

Other disadvantages of wind turbines include aesthetic, noise, and flora and fauna issues. Wind turbines are often hundreds of feet tall with very large blades which can be an overpowering sight. In addition, the noise caused by the electric motor and blade tips can be fairly loud and disruptive to those nearby. The impact that these turbines have on local surface animals and species must also be taken into account. These issues can create resistance by local residents towards building wind turbines near their homes and places of leisure. Although many individuals may support the intentions of using renewable forms of energy such as wind turbines, the “not in my backyard” effect is difficult reality that must be overcome by wind turbine developers.

Despite the aforementioned, the DOE states that all of these problems have been resolved or significantly mitigated through technology advancements or by properly locating wind plants (DOE – Advantages, 2008). The research of Combs (2005) validates this DOE claim.

**Solar**

There are four main types of solar energy technologies: photovoltaic (PV) systems, concentrating solar power (CSP) systems, solar water heating systems, and transpired solar collectors. All four of these types of solar energy have been utilized by the Air Force. It is useful to understand the differences between the different types of technology and how they are each able to harness renewable energy from the sun. UTCs would be considered a transpired solar collector and will be discussed in further detail in a later section.

***Photovoltaic (PV) Systems***

PV systems work by converting the suns energy into electrical energy through the use of PV cells. These cells are comprised of semiconducting materials, typically silicone. When photons from the sun's energy are absorbed by the PV cells, they free electrons from the PV cell which allows them to flow and create an electric current. This process allows for the direct transfer of the sun's rays into electricity.

PV use has a number of advantages. A PV system requires very little maintenance over its life cycle. Aside from any pollution generated in the manufacturing of PV cells, PV systems create no pollution or waste, qualifying it as a form of energy which can be used in support of the federal energy policies mentioned. The pollution created in making PV systems is generally recovered in 1 to 2.7 years. This time period, referred to as energy payback time (EPT) is the amount of time it takes for the pollution savings from the system's use to surpass the amount of pollution created in manufacturing and putting the system in place. Another advantage is that the useful life of a well designed PV system can exceed 30 years, and only have an efficiency degradation of less than one percent per year (DOE – Solar, 2008). PV systems generate the greatest energy gains during the hours of 1000 to 1400. In hot climates, this time period of the day correspond to the peak energy load times due to demand from air conditioning units. Therefore, PV systems provide an excellent way to help alleviate the added burden on existing energy grids. PV systems are also modular in nature, which makes it easy to expand and contract the size of the system based on the needs of the user.

PV systems also provide added security to the user. They provide security in terms of shielding against rising energy prices, since they alleviate the need to purchase energy from other sources. For military users especially, PV systems provide added security benefits because they can be placed within the secure compounds of a base. This would help protect the base from threats against energy supply sources. These security benefits can be applied across all four categories of solar energy, as all of these systems shield against changes in energy prices and can be adapted within the confines of an Air Force installation.

There are a number of limitations and challenges that PV systems face as well. The most obvious, and limiting factor, of PV systems are that they can only produce electricity during daylight hours and rely completely on the sun's energy. Energy storage systems or additional sources of energy are required to provide power during the night or during time periods in which inadequate amounts of sunlight are striking the PV panels. From an economic perspective, PV systems typically have a higher initial cost than many other forms of renewable energy with a correspondingly longer payback period. Federal and state incentives such as tax credits are typically used to make PV systems more competitive from this standpoint. Ignoring these incentives, the environmental benefits, and security benefits, PV technology must still make significant advancements in efficiency before they can truly be competitive with existing, nonrenewable, sources of energy. Still, PV systems are in high demand, and the PV industry has been receiving a great deal of attention over the past few years.

Nellis AFB, located just outside of Las Vegas, Nevada, has recently constructed the largest PV solar array in North America. The solar panels are equipped with trackers which allow the panels to follow the sun's path in the sky, increasing the amount of solar energy that can be captured on a daily basis. The solar panels cover 140 acres of land and have the capacity to generate 14.2 megawatts of electricity, enough to meet over 25 percent of the base's energy needs while saving the Air Force an estimated one million dollars in energy costs. The massive project contains 72,416 solar panels, 5,821 trackers, and a total of 5,891,328 solar cells. The total cost of the project totaled roughly $100 million which was financed by MMA Renewable Ventures, LLC, which owns and operates the system (Nellis fact sheet).

***Concentrated Solar Power (CSP) Systems***

A similar system, known as concentrated Solar Power (CSP), attempts to maximize use of the sun's rays through the use of mirrors and tracking systems to concentrate the sun's energy. The sun's rays can then be used to generate immense amounts of heat, which can then be used to create steam in a turbine which creates electricity. This method of CSP is referred to as concentrating solar thermal (CST). The other form of CSP is similar to traditional PV systems with the only difference being that mirrors are used to increase the amount of sunlight striking the solar cells. This allows for greater gains in efficiency over fixed panel PV systems that do not utilize mirrors or tracking systems. These systems do, however, require additional costs associated with the mirrors, tracking equipment, and possible personnel needed to operate and monitor the tracking equipment.

One of the advantages of CST systems is their ability to provide energy during non-solar periods of the day. Through the use of heat storage mediums such as molten-salt, excess heat during solar periods is captured and then released later in the day when solar energy is no longer being captured. This can extend the daily utilization time period of other solar systems such as PV. As heat storage technology advances, the efficiency of CST systems will increase and the costs per kilowatt-hour should decrease substantially (TroughNet, 2008).

One of the disadvantages that CSP users face is mirror breakage. Although it is a rare occurrence, when mirrors do break the replacement mirrors are very costly. As a result, a number of alternative mirror concepts are under development to try to reduce cost, increase performance, and increase resilience form breaking (TroughNet, 2008).

Another challenge faced by CSP users is that in order to maximize the efficiency of the system, the mirrors must be periodically cleaned. Depending on the size of the system, this can take a great deal of time and money to complete. This issue can be mitigated if the land that is being used to host the CSP systems is also used for farming purposes. Often, the ideal locations for CSP use are abnormally sunny and hot. In these environments, it is often difficult to plant crops because it would require a great deal of irrigated water to help the plants survive. One way to mitigate this issue is to create an irrigation system that can serve as a source of water to clean the mirrors and also provide a convenient water source for crops.

***Solar Water Heating***

Solar water heating is another method which uses solar radiation to assist in meeting water heating demands. This method is very similar to UTCs because it is using the sun’s energy to assist in decreasing the amount of energy needed to meet heating demands, rather than increasing electricity supply by converting the sun’s energy into electricity. Heating water accounts for approximately 18 percent of energy use at residential buildings and 4 percent of energy use at commercial buildings (Walker, 2008).

Tyndall Air Force base successfully implemented three concentrated solar-collection systems in 2007 by entering into an ESPC with Honeywell Company. These systems utilize reflective dishes which track the sun's path and concentrate the sun's energy onto a solar collector. The collector is made up of a series of copper tubes which continuously cycle water through them. The concentrated solar radiation heats these copper tubes, which in turn heat the water.

Perhaps a more interesting form of solar air water heating technology that has potential for DOD use is solar evacuated-tube collectors. These collectors consist of glass tubes that have had air removed from them, a term referred to as "evacuated". Inside the evacuated glass tubes are an evacuated copper tube that contains a liquid, commonly water or glycol. The purpose behind the glass tube being evacuated is that it allows the copper tube inside it to be free from heat loss due to convection and radiation. This condition allows the surface of the copper tube to heat rather quickly once exposed to sunlight. Due to the ultra-low pressure found within the copper tube, the liquid inside boils to a vapor at a much lower temperature than it would at normal atmospheric pressures. The hot vapor from within the copper tube rises to the top of the collector, which contains a small exposed bulb that protrudes out of the glass tube. The water source that ultimately needs to be heated flows through a pipe, or header, which these bulbs are placed into. Once the heat from the bulb is absorbed by the water, the vapor cools and condenses which re-starts the cycle.

These collectors may be an excellent option in producing hot water in expeditionary environments where an abundance of sunlight is present. The challenge in using the technology, however, is that they are fairly expensive and the glass tubes may not be rugged enough to survive in a deployed environment. In addition, evacuated-tube collectors' unit area costs are roughly twice that of traditional flat-plate collectors (EPA – Solar, 2006). Despite these challenges, the potential benefits justify further research into possible applications in the Air Force and DoD.

**Geothermal Energy**

Geothermal energy is another form of alternative energy which harnesses energy from the heat of the earth, rather than the sun. There are three main systems which can be used to capture geothermal energy. The first type of system is geothermal power plants which consist of deep wells which are drilled a mile or more into the earth's surface. The wells attempt to tap into underground reservoirs containing very hot water. The steam or hot water from these reservoirs is then used to drive electricity generators (DOE – Geothermal, 2008).

The second type of system is direct heating using geothermal energy. This type of system takes the hot water from underground reservoirs and pumps it directly into facilities. This hot water can then be utilized in numerous ways, such as heating buildings or pumping hot water near the surface of sidewalks in the winter to melt ice and snow (DOE – Geothermal, 2008) .

The third use of geothermal energy is geothermal heat pumps. Geothermal heat pumps use shallow ground energy to heat and cool buildings. Throughout most areas of the world, the upper ten feet of the earth's surface maintains a constant temperature range between 50 and 60 degrees Fahrenheit. A geothermal heat pump system consists of pipes which are buried into the ground near the building which will utilize the system. A heat exchanger is the other main component of the system, along with the ductwork needed to connect the system with the rest of the building. During the cool months of the year, the system draws the heat from the ground through the heat exchanger to provide warm air for the building. During the warmer months of the year, the system pulls warm air into the ground and heat exchanger to cool the air for the building. In addition, the heat loss from air can be captured and used to assist in warming the water to be used by the building (DOE – Geothermal, 2008).

Geothermal energy use has been utilized across the DoD and Air Force. Starting in 1997, Tyndall AFB, Florida, began utilizing geothermal heat pumps. The base now utilizes geothermal at five different facilities as well as 75 housing units. Due to the salt-corrosive environment of being located so close to the ocean, Tyndall AFB benefits particularly well from the use of geothermal technology. This is because a geothermal system is located underground and is not nearly as exposed to this harsh environment. The estimated length of time that a traditional air conditioning unit remains serviceable at the base is only seven to ten years, while the estimated life of a geothermal system exceeds 25 years (Ferrell, 2006).

In 2004, at Offutt AFB in Bellevue, Nebraska, geothermal heat pumps were installed for three dormitories which total 440,000 $ft^2$ of living space (Nebraska, 2004). The pumps save an estimated 21 percent of the costs that would have been incurred had a new conventional boiler/chiller system been installed instead (Rosine, 2006). This translates to an estimated 2,760 megawatt hours of energy savings per year (Renewable, 2008). The following year, Charleston AFB, South Carolina, initiated a geothermal heat pump program that is estimated to save over two million dollars in savings for annual electric, water, and energy costs over the life of the 19-year contract (Rosine, 2006).

These initiatives all demonstrate the success that geothermal systems have had across the Air Force. In addition to being cost effective and increasing energy efficiency, Geothermal provides the key security benefits mentioned earlier. Geothermal systems can be located within the confines of the base, below ground, providing excellent defense against natural disasters or enemy attacks. In addition, the benefits associated with the system are less reliant upon natural variances beyond human control, i.e. wind velocity and available sunlight.

The disadvantages of geothermal energy are that they are not suitable at all locations. Site surveys to locate ideal locations for geothermal systems can be costly and take a great deal of time to complete. In addition, it may be difficult to properly drill the deep holes needed for geothermal power plants and direct heating systems due to the type of rock located at the site. It is also possible that harmful gases and liquids can be emitted from the ground, creating handling and disposal challenges. Finally, it is possible that the steam generated from the ground can run out for extended periods of time.

**Bio and Synthetic Fuels**

As mentioned earlier, the cost of jet fuel required to keep the Air Force fleet in the air is nontrivial. Over 80 percent of the Air Force’s annual $7 billion energy bill goes towards paying for airplane fuel (Aimone, 2007). In an effort to explore alternative forms of jet fuel, the Air Force has been testing a 50-50 blend of synthetic and petroleum gases on B-1B, B-52, C-17, and F-22 aircraft. The goal is to have every aircraft in the inventory use synthetic fuel blends by 2011 and that at least half of these fuels be produced domestically (Eggers, 2008:17). Although cost and environmental factors play a major role in this push towards synthetic fuel use, security concerns are the driving force. The primary concern is "to find a source of domestically produced, assured fuels, which would be sufficient for the Air Force to perform its national defense mission if current, overseas petroleum sources are threatened" (Eggers, 2008:17).

In addition to dealing with possible threats overseas, the U.S. has already had to deal with major domestic shocks to supply as well. During the 2005 hurricane season, the Gulf of Mexico suffered severe damage, causing a substantial shutdown of 25 percent of the U.S. domestic oil production. This shock to supply ultimately required the U.S. to loan 9.8 million barrels and sell an additional 11 million barrels of crude oil reserves. The loans were given to six different refiners who had scheduled deliveries that had been disrupted by the hurricane while the 11 million barrels were sold to five companies who successfully submitted offers to the DOE (DOE – Releasing Crude, 2008).

In response to the energy burden created by this hurricane season, the Secretary of the Air Force, the honorable Michael W. Wynne, issued a letter to all USAF Airmen to instill the energy conservation goals of the Air Force. In addition, he directed Dr. Ron Sega, the Undersecretary of the Air Force, to initiate an aggressive new energy strategy. Dr. Sega immediately went on to form the Senior Focus Group on energy to address the Secretary's concerns (Aimone, 2007). In fiscal year 2006, efforts created by this group went on to save the Air Force $100 million and 3.3 trillion Btu in energy savings (FEMP, 2007:15). The outstanding achievements of the group were recognized by President

Bush, and the focus group was awarded the 2007 Presidential Award for Leadership in Federal Energy Management for outstanding performance.

One of the most important concerns that the Senior Focus Group on energy is trying to address is the challenge of creating synthetic fuels for our aircraft and automobiles.  The Air Force is the largest consumer of fuel across among the major military branches.  The percent of fuel use for each of the different branches of the DoD can be shown in Figure 34.

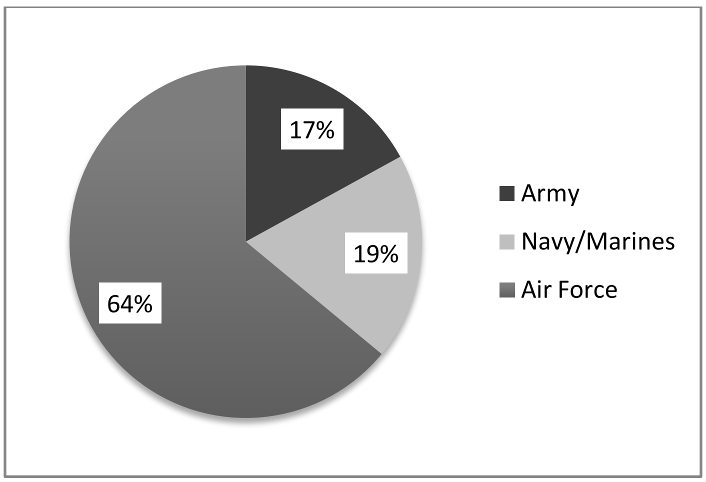



**Figure 34:  U.S. Armed Forces Fuel Utilization**
(Source: Energy Strategy, 2008)

In addressing ground fuel, the Air Force is in the process of converting infrastructure to support E85 ethanol gasoline and B20 diesel fuel.  E85 ethanol gasoline consists of 85 percent ethanol and 15 percent gasoline.  B20 diesel fuel is a combination of 80 percent conventional diesel and 20 percent bio-fuel.  In 2007, 58 Air Force bases were supplying B20 and 16 bases were providing E85.  In addition, plans have been made to build another 26 biofuel infrastructure projects.  The Air Force has also increased its use of Low Speed Vehicles, which are electrically powered and require no fuel. These Low Speed Vehicles will make up 30 Percent of all newly purchased vehicles by the Air Force (Aimone, 2007).

Despite the challenges associated with creating synthetic jet fuel, the Air Force has made admiral progress. The Air Force has successfully tested and implemented the use of a 50-50 blend of traditional crude-oil based fuel and a Fischer-Tropsch fuel derived from natural gas (Woodbury, 2006). In his address to the Senate Committee on Finance, Mr. Aimone brought up an important point in regards to this fuel blend. He mentioned the fact that the Air Force's current synthetic blend does not reduce dependence on foreign oil. This is because domestic natural gas production is still insufficient to meet U.S. needs, therefore using the blend will not meet the desired energy independence goals of the Air Force (Aimone, 2007). Regardless, the Air Force is moving in the right direction towards following its energy strategy and further research is still underway to try to create synthetic jet fuel from alternative sources.

**Biomass**

Energy can also be harnessed from biodegradable waste and plant matter. Decaying waste in landfills emits large quantities of methane ($CH_4$) and carbon dioxide ($CO_2$) which are damaging to air quality. At the very least, these gases must be flared at the source to reduce GHG emissions and the toxicity of the gas (Chen, 2003:viii). What is certainly an even better alternative to simply burning the gas at the source is harnessing these gases to produce electricity. This process is referred to as landfill-gas energy (LFGE). The basic process is that the methane gas is first captured at the landfill by using gas wells and collection systems. Once collected, the methane gas is piped to a processing center and is then converted to electricity using a gas engine or turbine.

In 2004, the Air Force established its first landfill gas project at Hill AFB, Utah. The 1.3 megawatt station produces enough electricity to power approximately 700 homes on a continual basis. The $5 million in initial funding to complete the project was paid for by Energy Service Company (ESCO) on a performance based contract. During the payback period of 10 years, the costs savings created by the project will be paid to ESCO to reimburse their initial funding (Abbuehl, 2005). After that time period, the costs savings will be realized by Hill AFB throughout the life of the system.

## Appendix C: Solar Absorptivity of Various SolarWall® Colors

Table 30 provides a list of UTC colors available through SolarWall® and the corresponding levels of solar absorption for each color option.

**Table 30: Solar Absorptivity of Various SolarWall® Colors**

| Color Name | Solar Absorptivity |
|---|---|
| Black | 0.94 |
| Classic Bronze | 0.91 |
| Chocolate Brown | 0.90 |
| Hartford Green | 0.90 |
| Med. Bronze | 0.89 |
| Boysenberry | 0.86 |
| Rocky Grey | 0.85 |
| Regal Blue | 0.85 |
| Forest Green | 0.84 |
| Hemlock Green | 0.82 |
| Slate Blue | 0.80 |
| Redwood | 0.79 |
| Teal | 0.79 |
| Slate Grey | 0.79 |
| Patina Green | 0.77 |
| Mint Green | 0.71 |
| Dove Grey | 0.69 |
| Siam Blue | 0.69 |
| Mission Red | 0.69 |
| Sierra Tan | 0.65 |
| Bright Red | 0.59 |
| Rawhide | 0.57 |
| Sandstone | 0.54 |
| Silversmith | 0.53 |
| Coppertone | 0.51 |
| Concord Cream | 0.45 |
| Ascot White | 0.40 |
| Bone White | 0.30 |

## Appendix D: Case Study Interview Questions

1. When were the SolarWalls® installed?
2. How many walls? What is the configuration? (Preheated air directly into building, or sent to existing HVAC system?)
3. What type of building(s) are they being used for?
4. What was the source of funding that paid for the SolarWalls®? What FY$ was used? What tool was used to model the estimates needed to secure ECIP funding? (if applicable)
5. What was the installation experience like? What was the installation timeframe? Any installation issues? Were there any challenges accommodating existing doors or windows on the walls which the SolarWalls® were installed on?
6. What types of issues, if any, were brought up during the design/approval phase?
7. Any issues with the architectural theme? Were colors chosen more to optimize solar gain or to create the best "look" of the building?
8. How has the SolarWall(s)® held up to the elements? Wind, hail, etc?
9. Have any measurement methods been put in place to measure the effectiveness of SolarWall(s)®? If so, how has it performed?
10. Were there any major pitfalls in using the system that occurred without warning? Any issues that the vendor neglected to mention?
11. What has the maintenance record been like on the system (walls, fans, ducts, etc)? Have you come across any major issues or problems?

12. Has there been feedback from the users (those working in the buildings)? Any complaints or compliments? How do you think it has affected their working environment?

13. Are silencers being used on the fans? What has the experience been like using the control systems?

14. Are the fans being used to pre-cool buildings at night during cooling days?

15. Are there any recommendations or pieces of advice you would like to share with potential future users to help ensure smoother and more effective implementation?

16. In your judgment, what conditions or factors would describe an "optimum" candidate/s for a SolarWall® installation?

17. Ideally, what would the system controls be capable of doing?

18. In retrospect/looking forward, are there any specific "cost savers" that might have been used/worked for you in carrying out a SolarWall® installation?

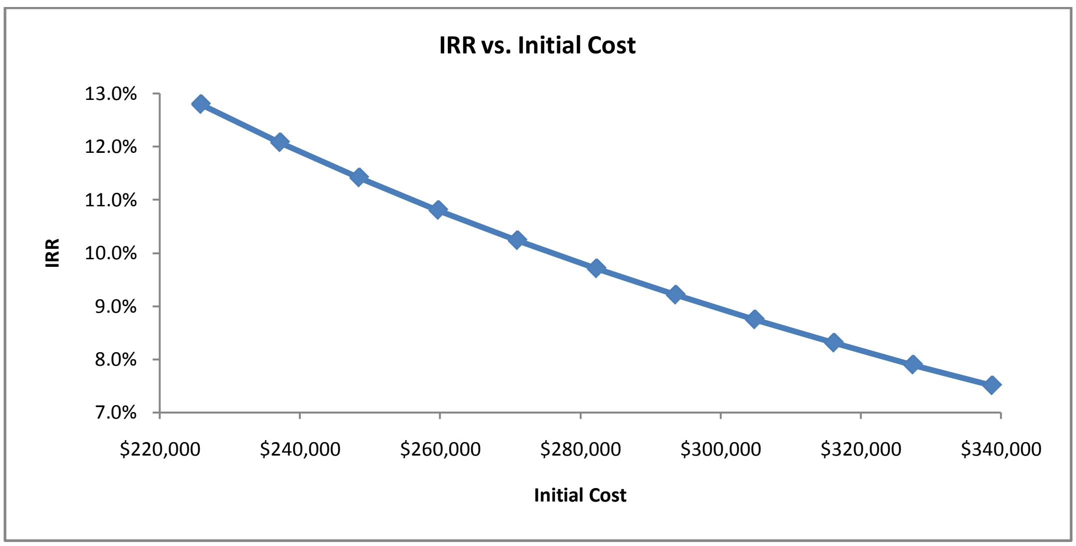
19. Additional Comments

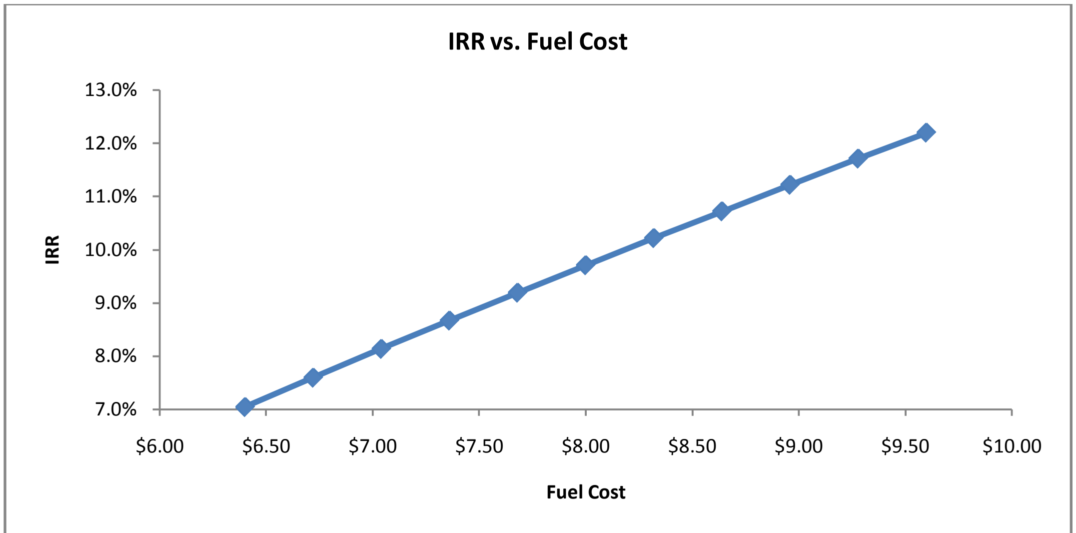
## Appendix E: Sensitivity Analysis

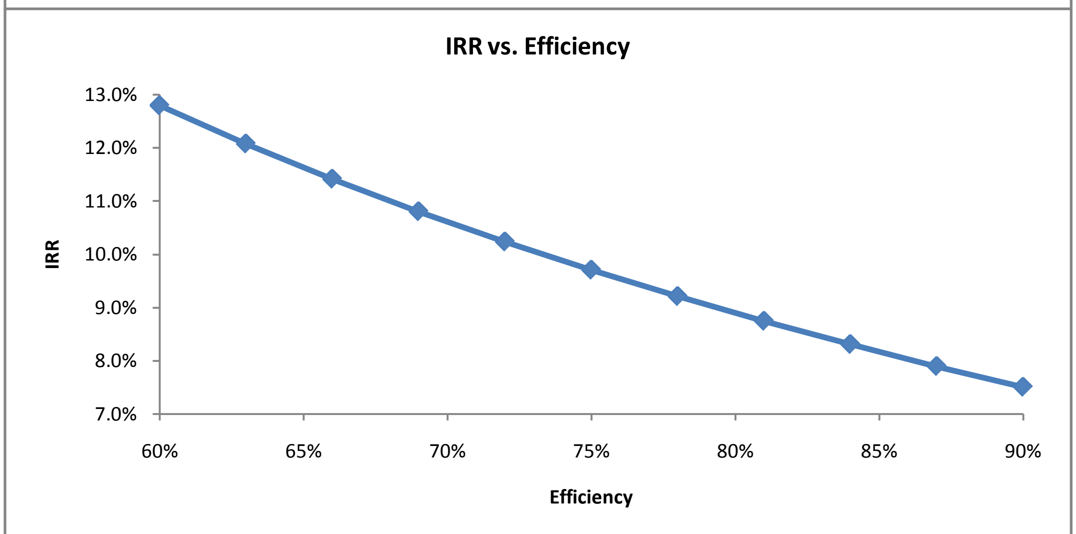
In this section we included sensitivity analysis results from our quantitative assessment. This analysis helps provide a better understanding of how changes to our assumptions can affect the expected performance results for our UTC system. The first section provides one-way sensitivity analysis for each performance measure, which includes the input variables that were revealed to be significant, based on our tornado diagrams. We present these variables in descending order of their sensitivity. The second section includes a two-way sensitivity analysis which illustrates how simultaneous changes in two factors can affect each measure of our analysis.

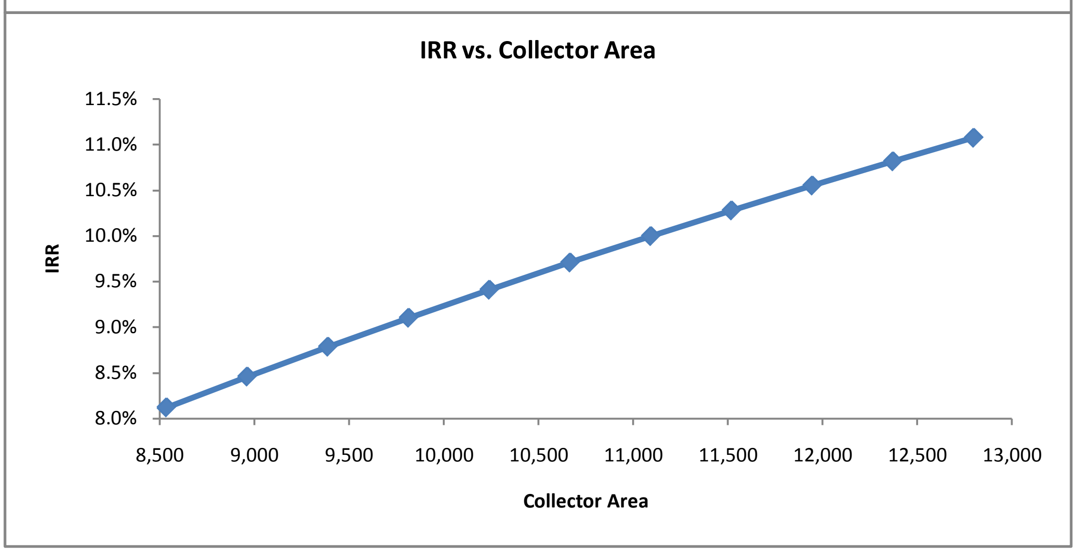
### One-Way Sensitivity Analysis

#### *Internal Rate of Return (IRR)*




IRR vs. Fuel Cost
IRR
13.0%
12.0%
11.0%
10.0%
9.0%
8.0%
7.0%
$6.00
$6.50
$7.00
$7.50
$8.00
$8.50
$9.00
$9.50
$10.00
Fuel Cost


IRR vs. Efficiency
IRR
13.0%
12.0%
11.0%
10.0%
9.0%
8.0%
7.0%
60%
65%
70%
75%
80%
85%
90%
Efficiency


IRR vs. Collector Area
IRR
11.5%
11.0%
10.5%
10.0%
9.5%
9.0%
8.5%
8.0%
8,500
9,000
9,500
10,000
10,500
11,000
11,500
12,000
12,500
13,000
Collector Area

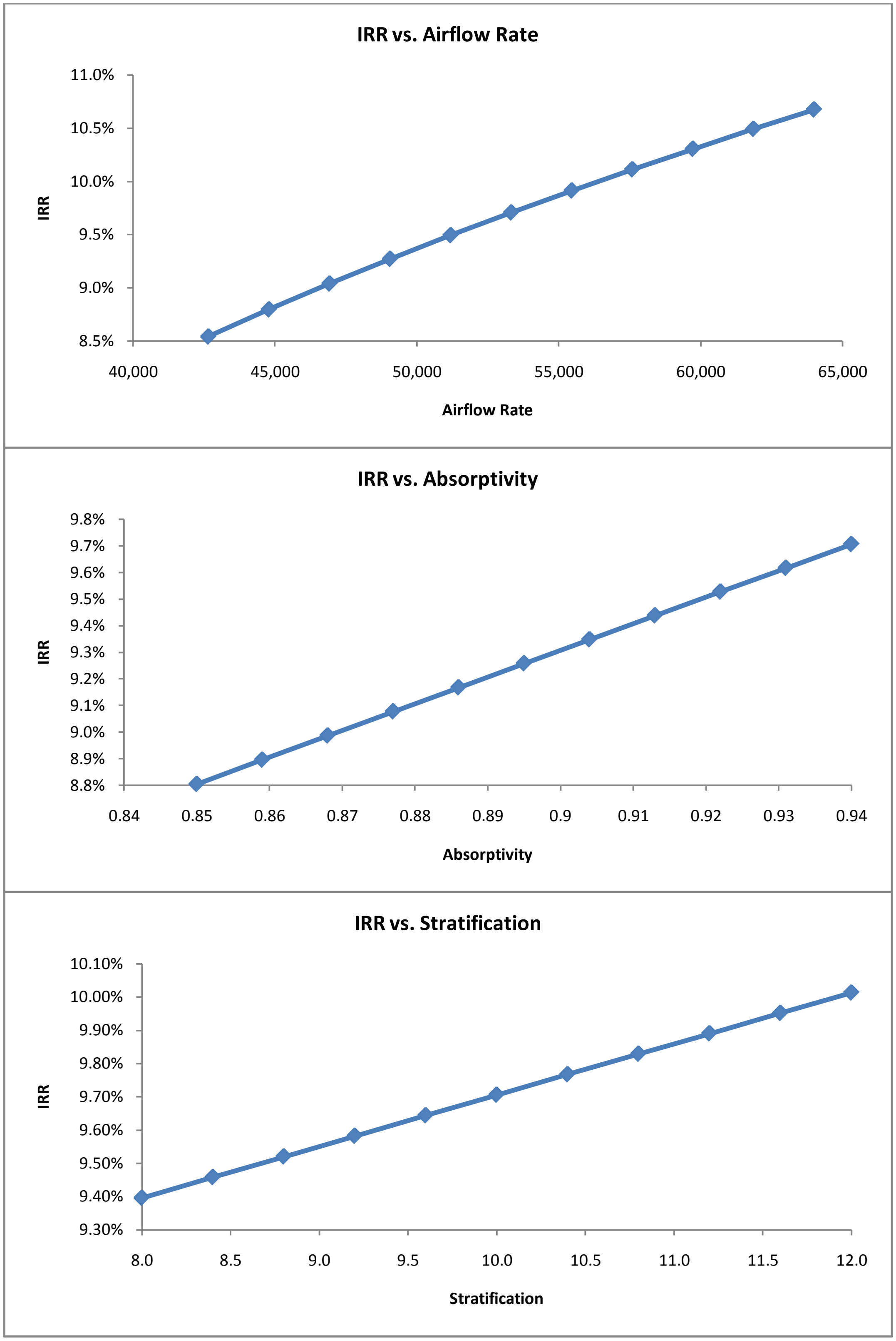
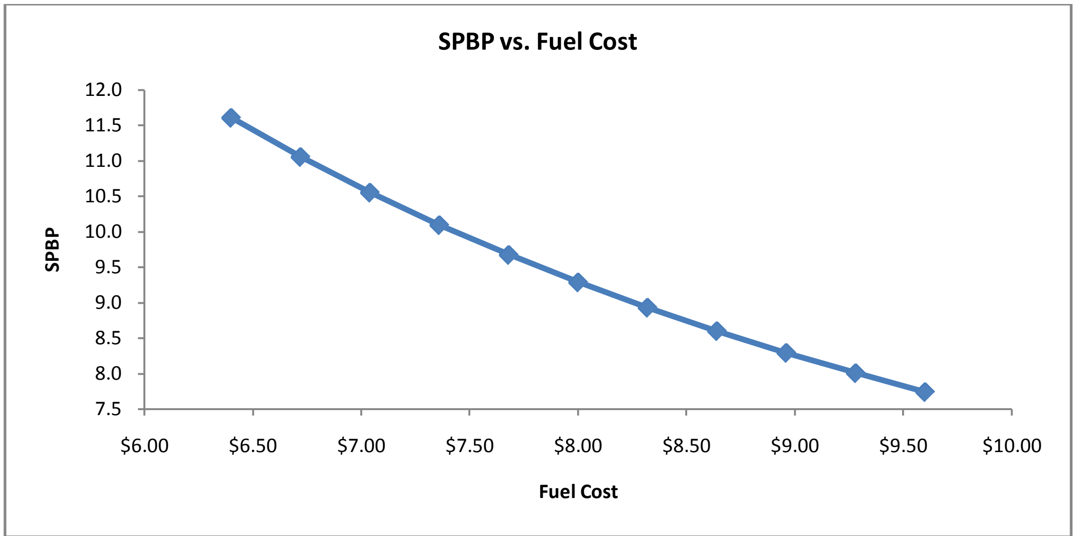
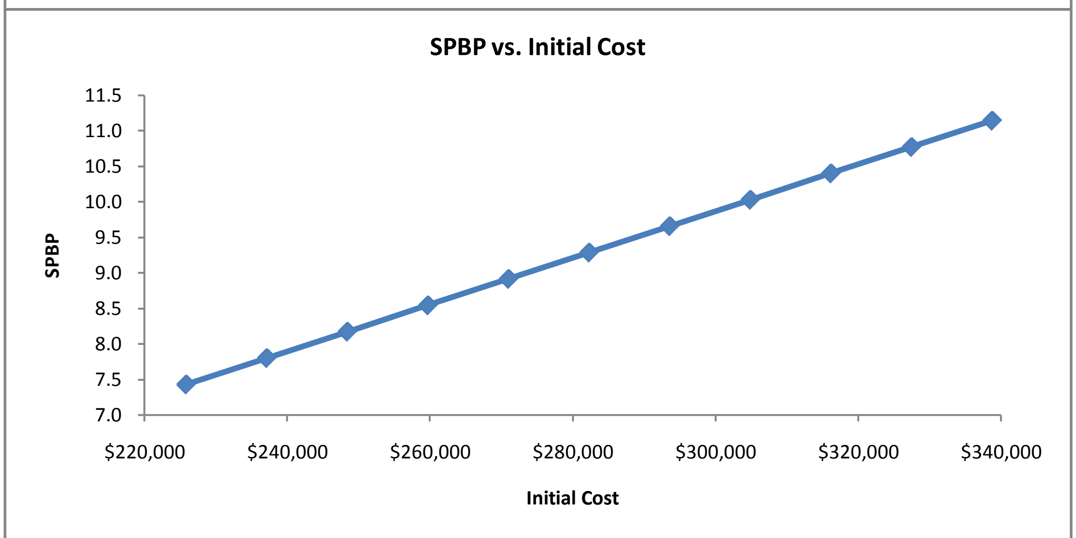
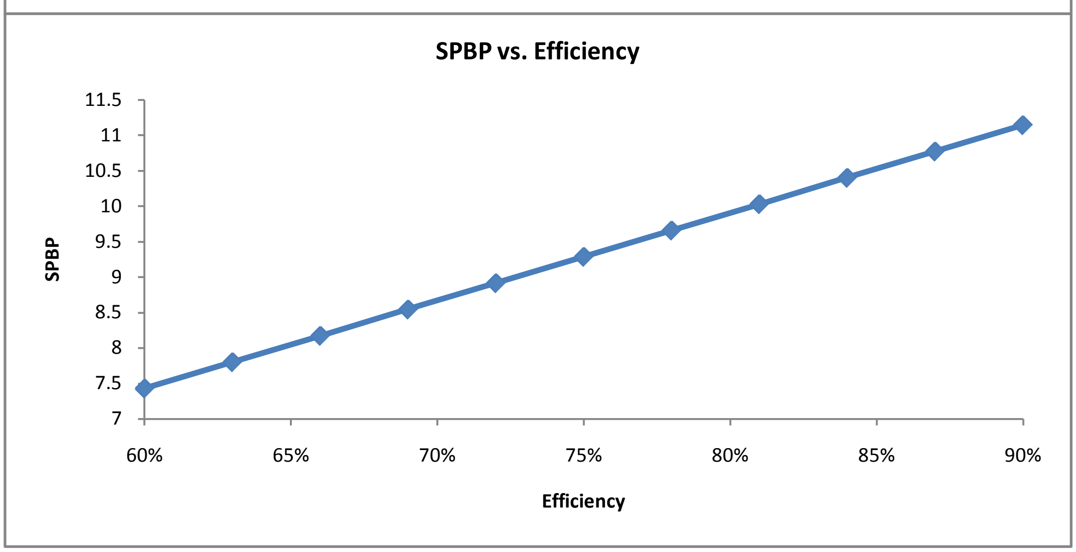


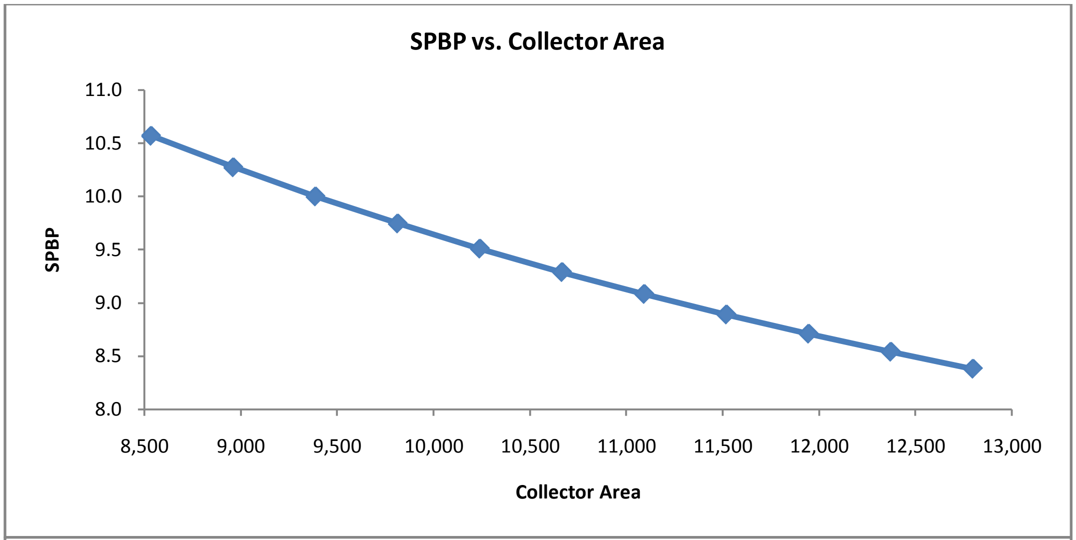

**Figure 35: Sensitivity Analysis (IRR)**

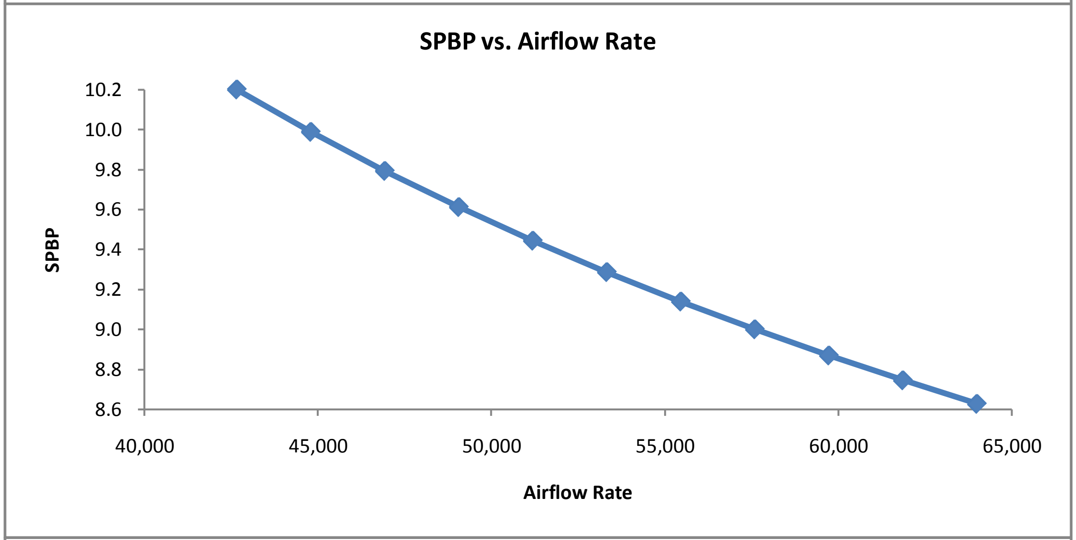
### *Simple Payback Period (SPBP)*

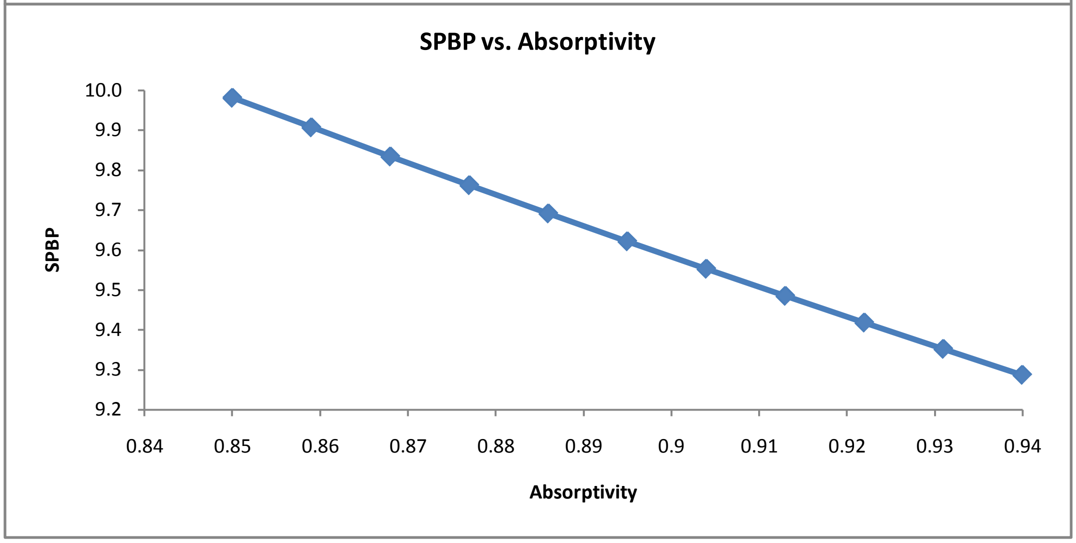



SPBP vs. Collector Area
SPBP
11.0
10.5
10.0
9.5
9.0
8.5
8.0
8,500
9,000
9,500
10,000
10,500
11,000
11,500
12,000
12,500
13,000
Collector Area


SPBP vs. Airflow Rate
SPBP
10.2
10.0
9.8
9.6
9.4
9.2
9.0
8.8
8.6
40,000
45,000
50,000
55,000
60,000
65,000
Airflow Rate


SPBP vs. Absorptivity
SPBP
10.0
9.9
9.8
9.7
9.6
9.5
9.4
9.3
9.2
0.84
0.85
0.86
0.87
0.88
0.89
0.9
0.91
0.92
0.93
0.94
Absorptivity

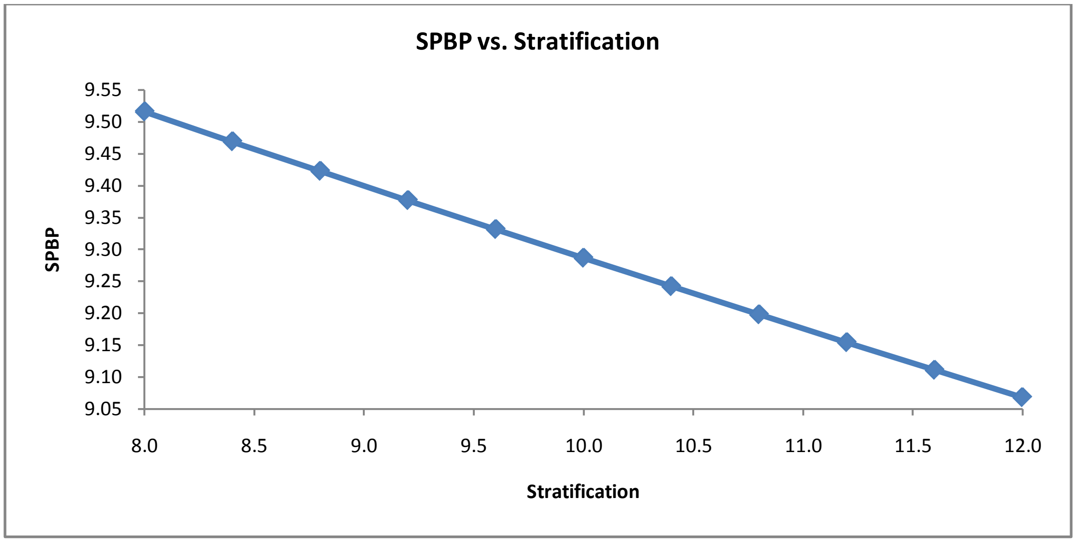
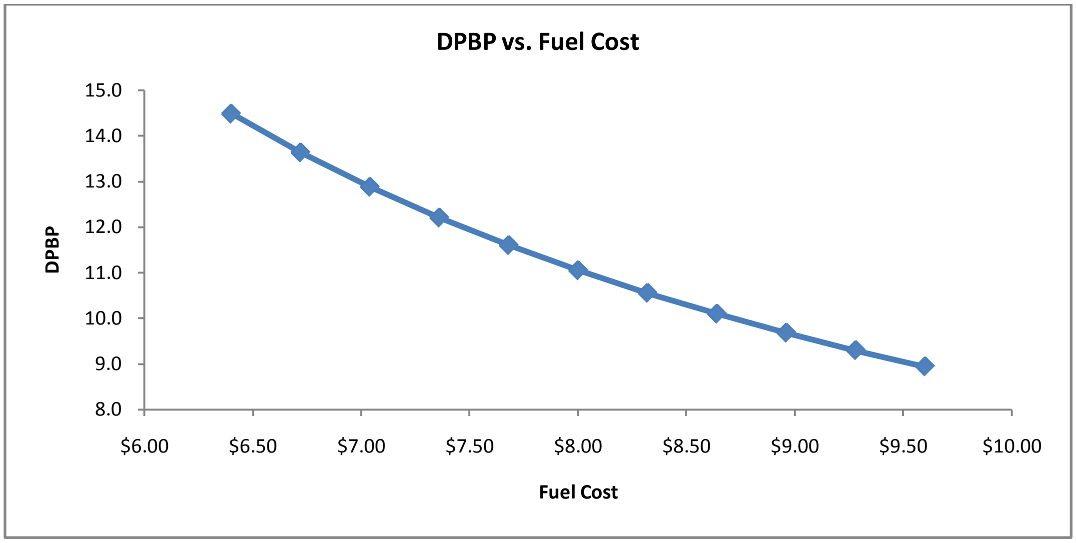
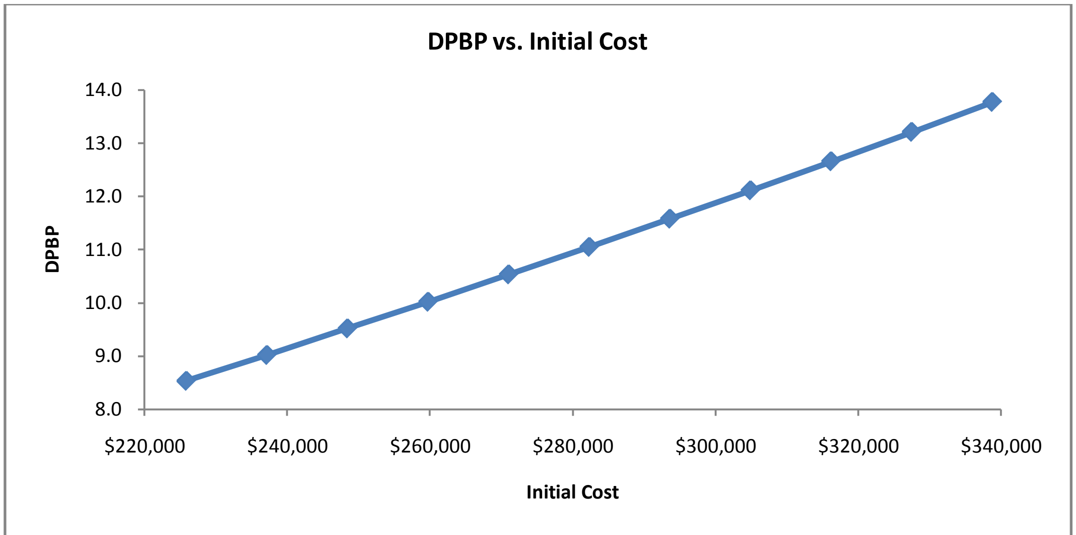
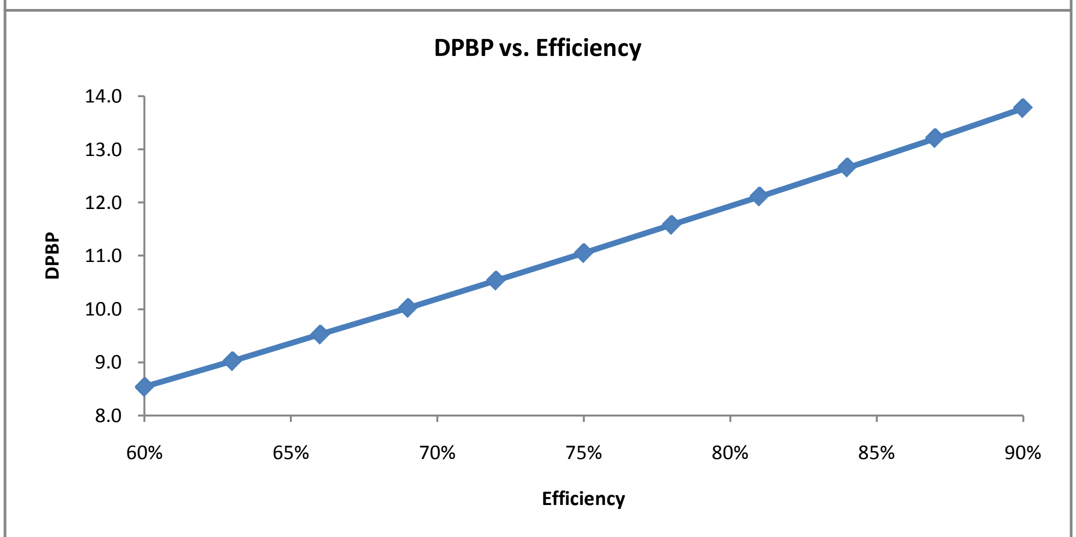


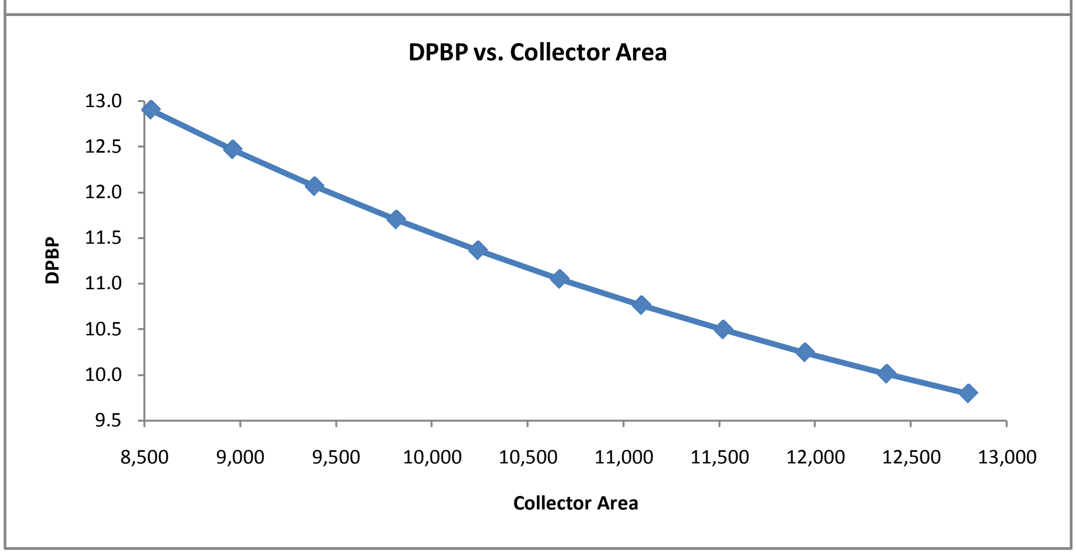

**Figure 36: Sensitivity Analysis (SPBP)**

### *Discounted Payback Period (DPBP)*




DPBP vs. Initial Cost
DPBP
14.0
13.0
12.0
11.0
10.0
9.0
8.0
$220,000
$240,000
$260,000
$280,000
$300,000
$320,000
$340,000
Initial Cost


DPBP vs. Efficiency
DPBP
14.0
13.0
12.0
11.0
10.0
9.0
8.0
60%
65%
70%
75%
80%
85%
90%
Efficiency


DPBP vs. Collector Area
DPBP
13.0
12.5
12.0
11.5
11.0
10.5
10.0
9.5
8,500
9,000
9,500
10,000
10,500
11,000
11,500
12,000
12,500
13,000
Collector Area

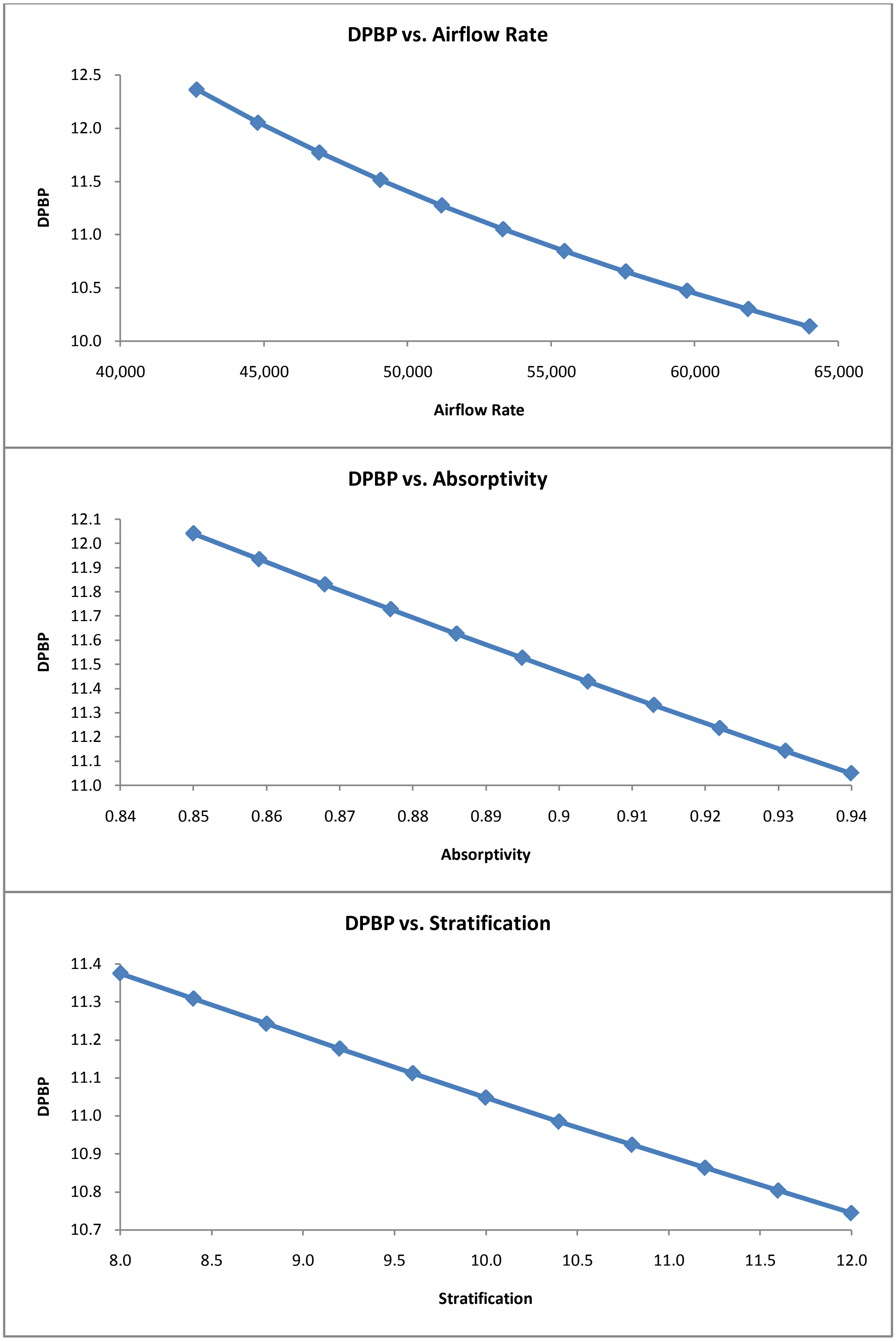
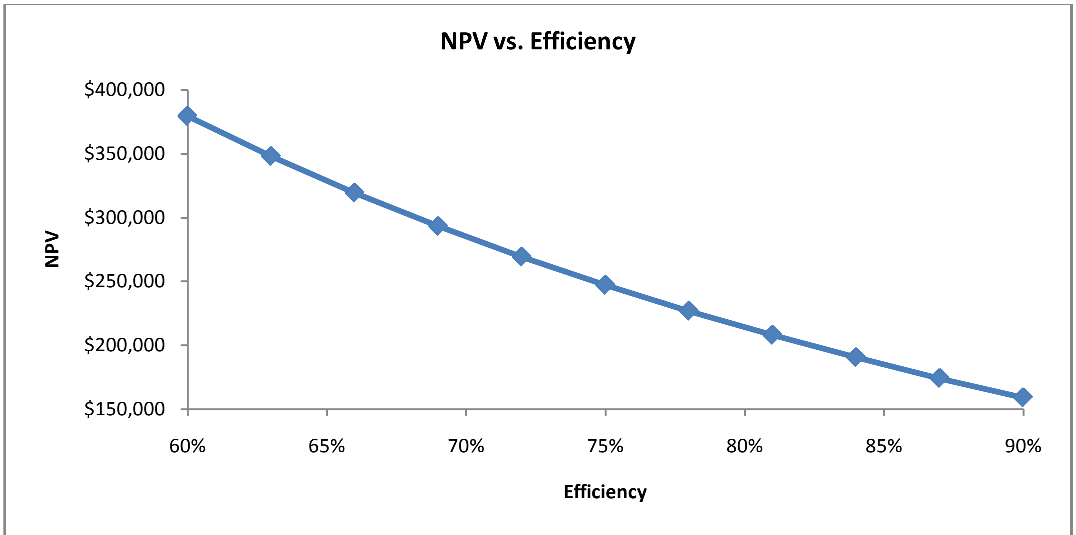
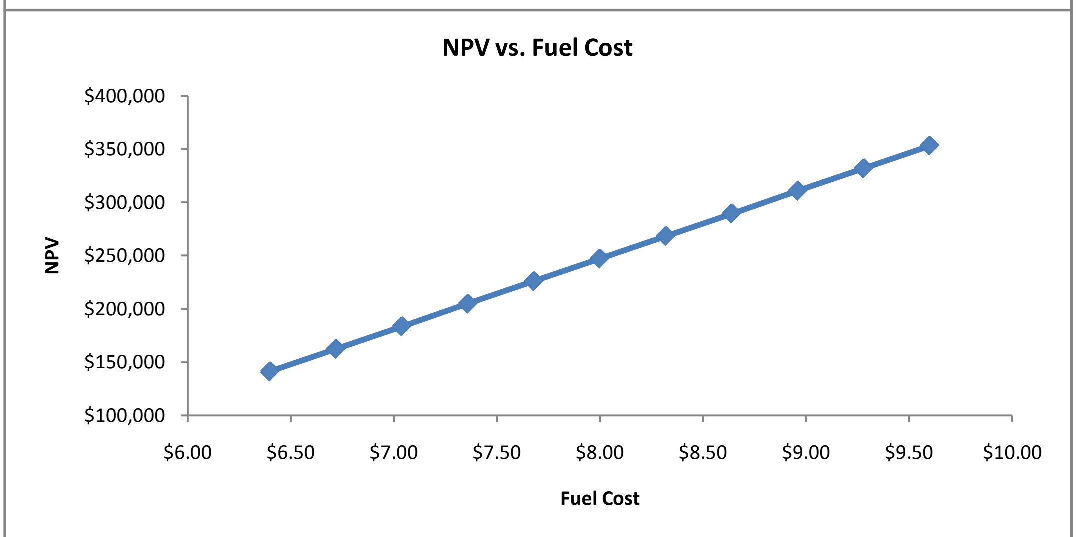
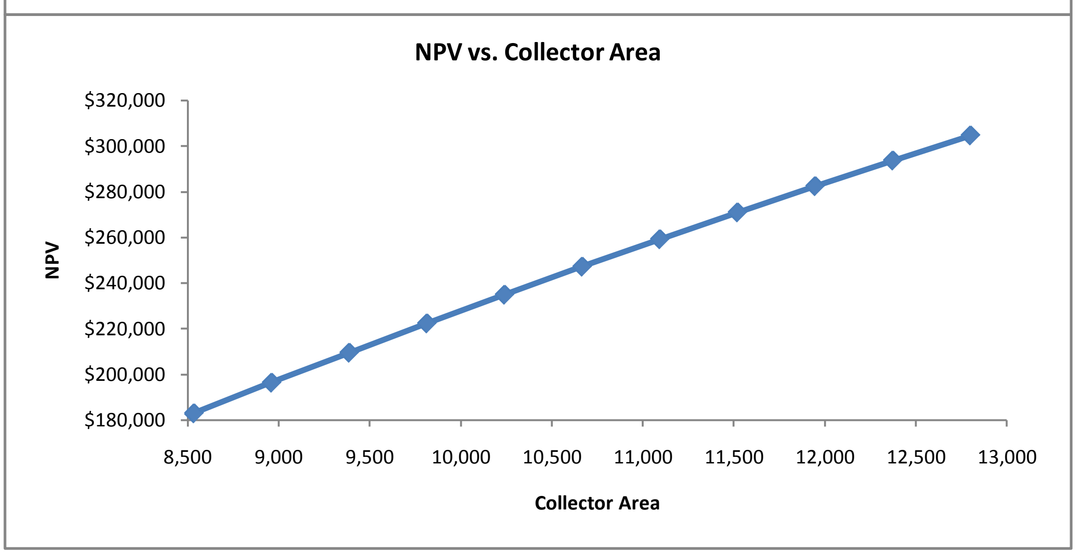


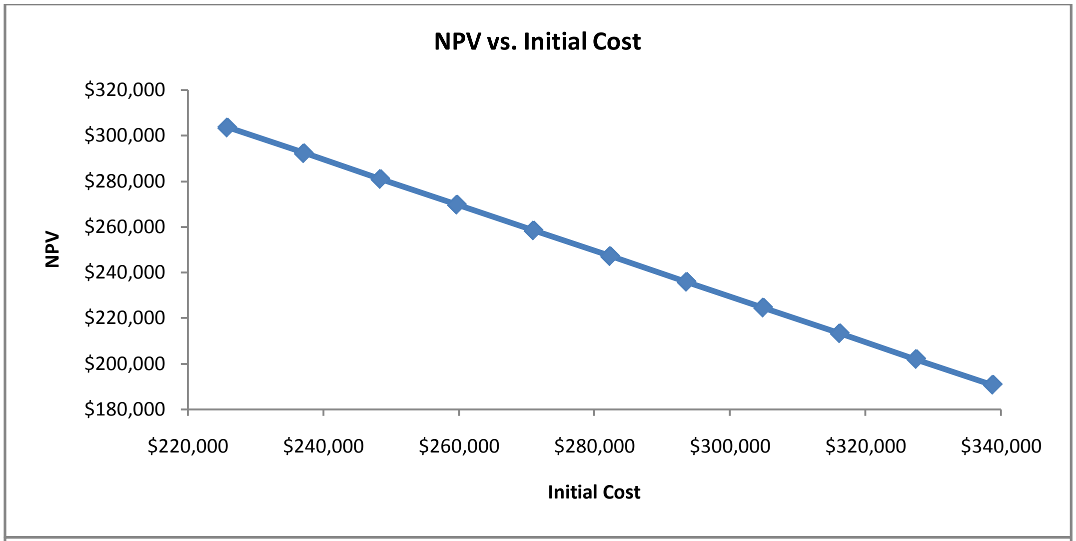

**Figure 37: Sensitivity Analysis (DPBP)**

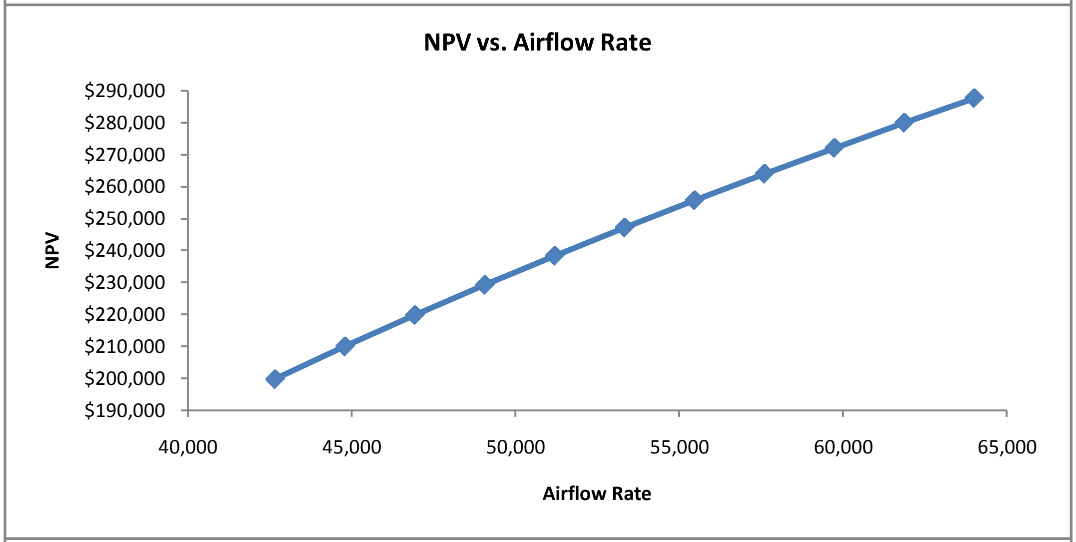
*Net Present Value (NPV)*

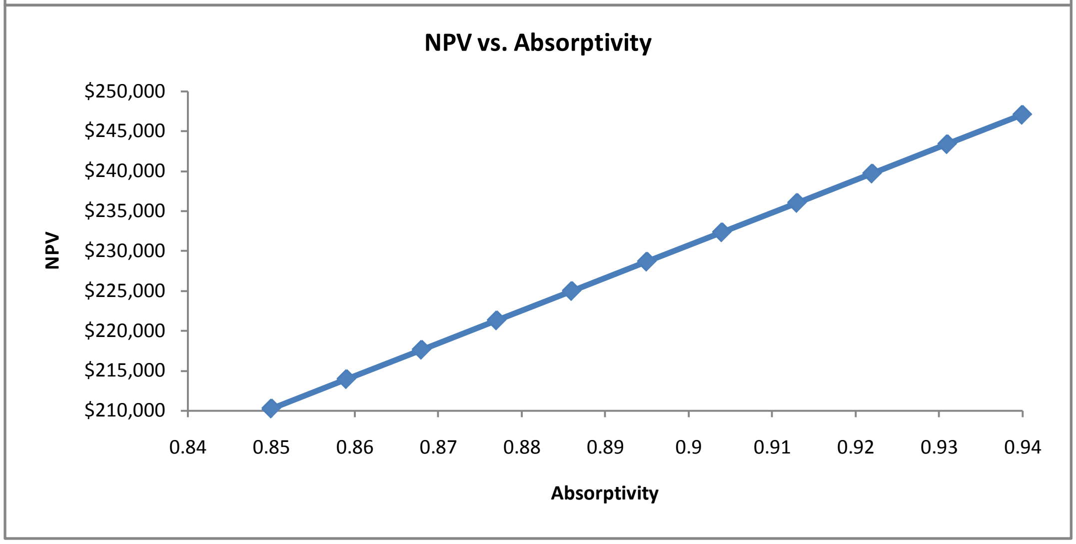



NPV vs. Initial Cost
NPV
$320,000
$300,000
$280,000
$260,000
$240,000
$220,000
$200,000
$180,000
$220,000
$240,000
$260,000
$280,000
$300,000
$320,000
$340,000
Initial Cost


NPV vs. Airflow Rate
NPV
$290,000
$280,000
$270,000
$260,000
$250,000
$240,000
$230,000
$220,000
$210,000
$200,000
$190,000
40,000
45,000
50,000
55,000
60,000
65,000
Airflow Rate


NPV vs. Absorptivity
NPV
$250,000
$245,000
$240,000
$235,000
$230,000
$225,000
$220,000
$215,000
$210,000
0.84
0.85
0.86
0.87
0.88
0.89
0.9
0.91
0.92
0.93
0.94
Absorptivity

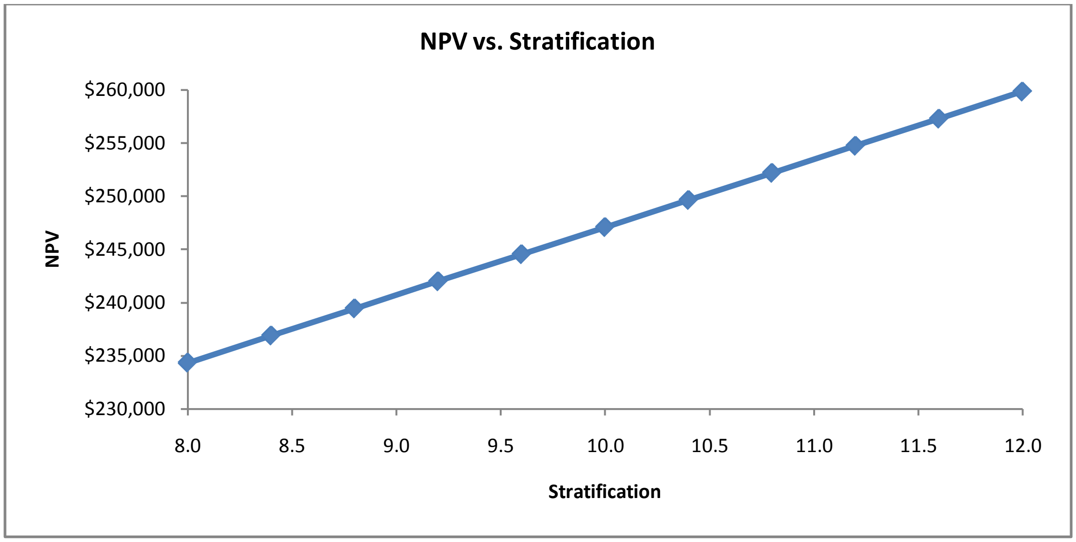
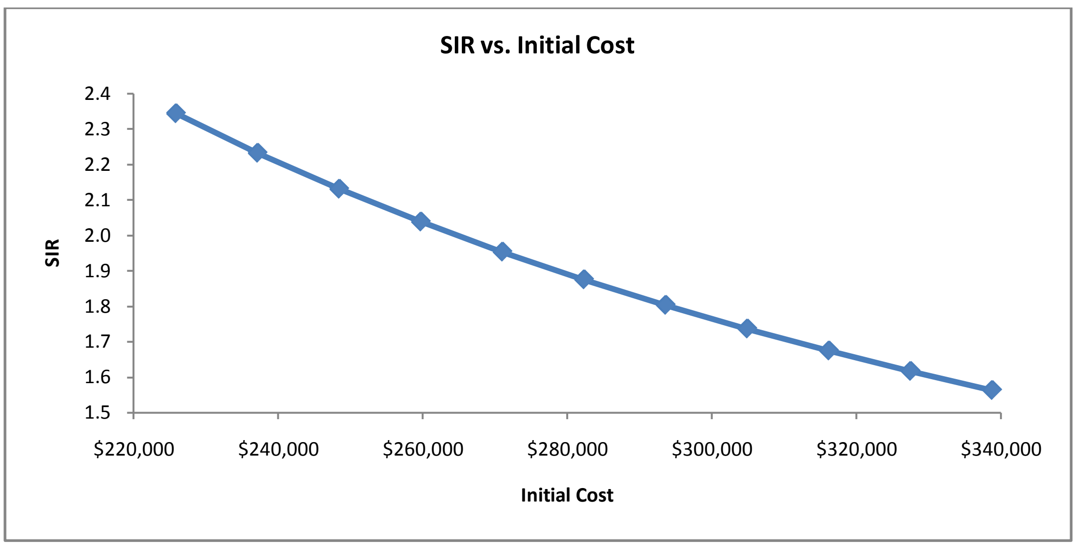
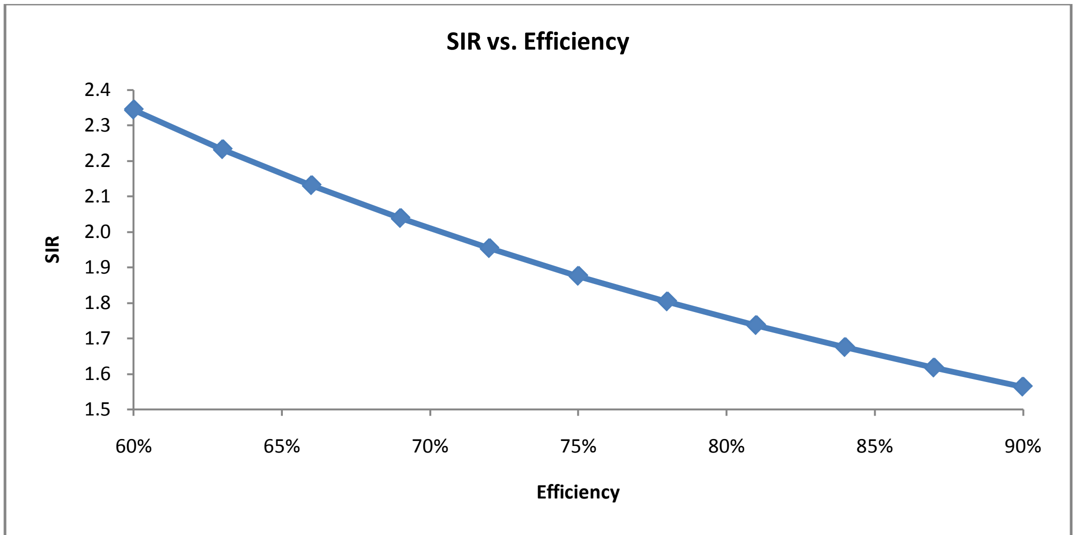
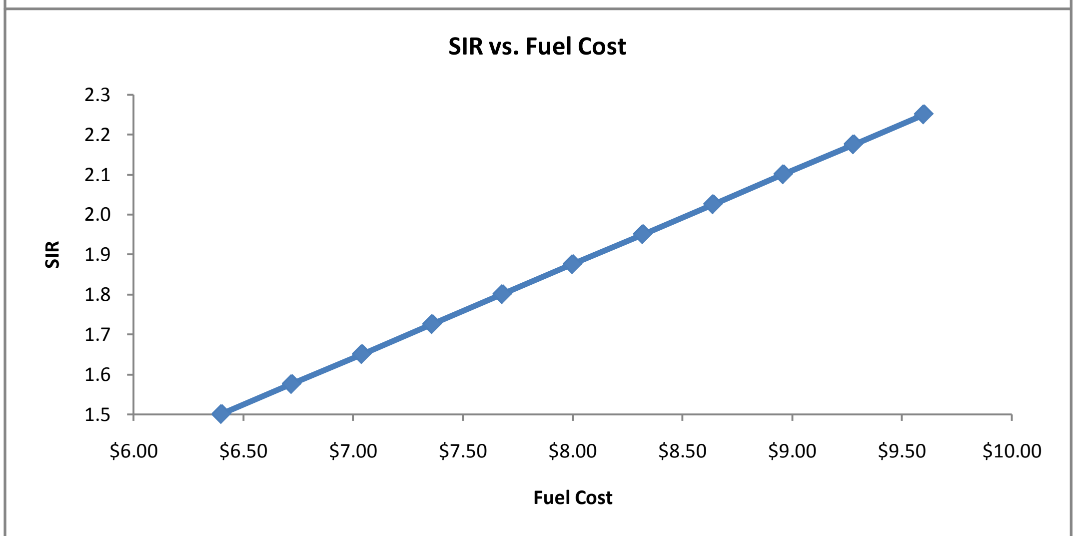


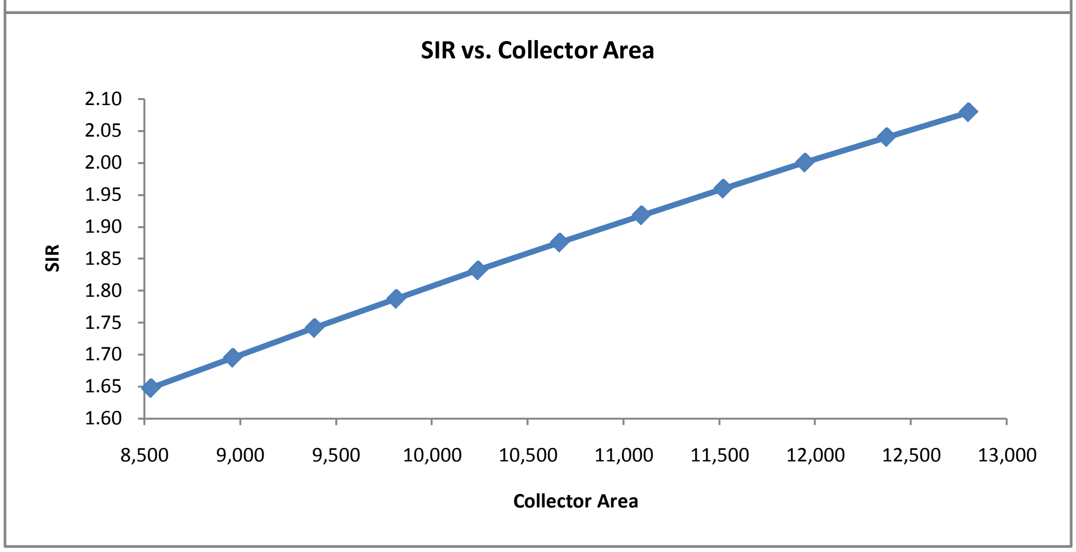

**Figure 38: Sensitivity Analysis (NPV)**

***Savings-to-Investment Ratio (SIR)***




SIR vs. Efficiency
SIR
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
60%
65%
70%
75%
80%
85%
90%
Efficiency


SIR vs. Fuel Cost
SIR
2.3
2.2
2.1
2.0
1.9
1.8
1.7
1.6
1.5
$6.00
$6.50
$7.00
$7.50
$8.00
$8.50
$9.00
$9.50
$10.00
Fuel Cost


SIR vs. Collector Area
SIR
2.10
2.05
2.00
1.95
1.90
1.85
1.80
1.75
1.70
1.65
1.60
8,500
9,000
9,500
10,000
10,500
11,000
11,500
12,000
12,500
13,000
Collector Area

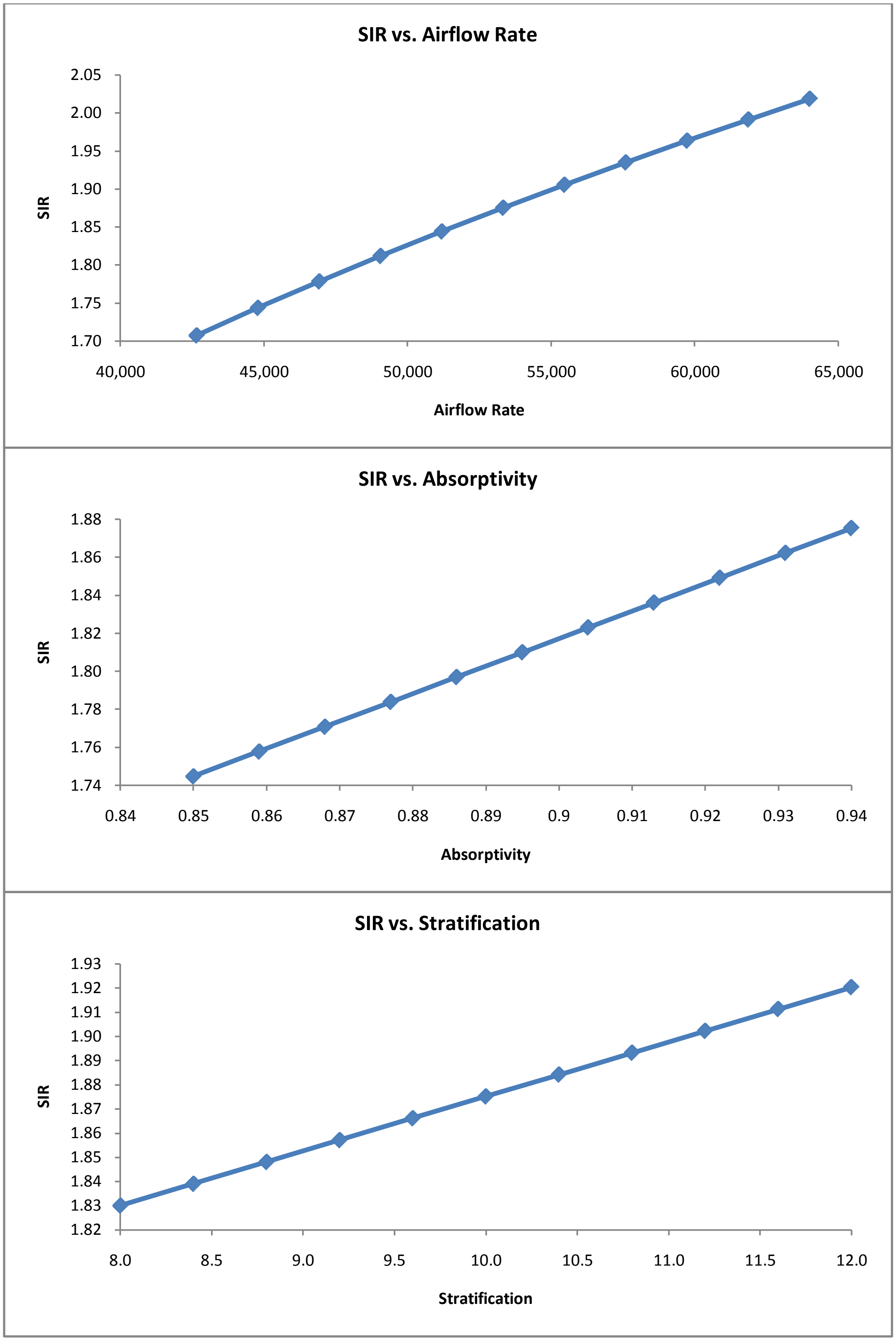
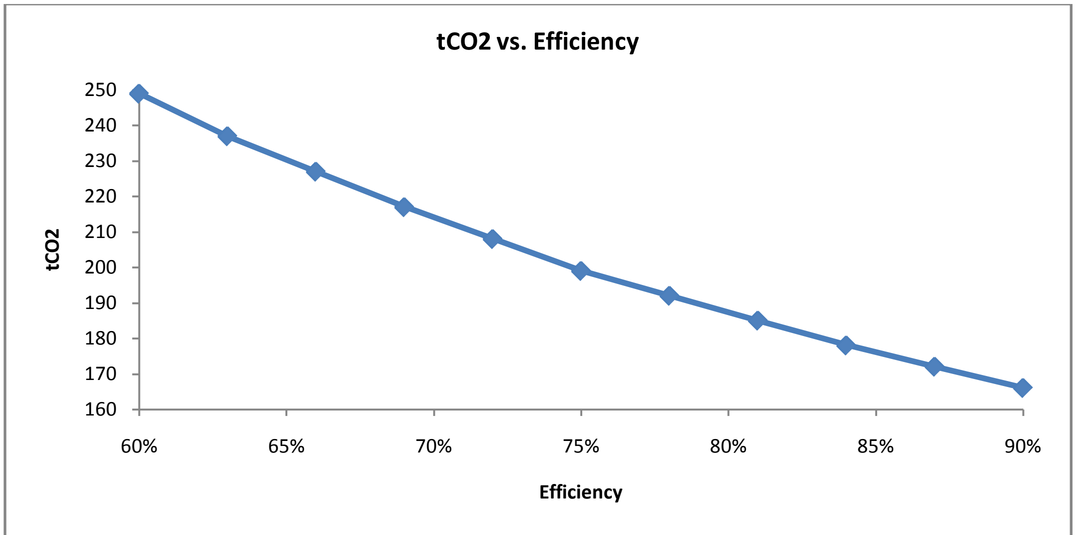
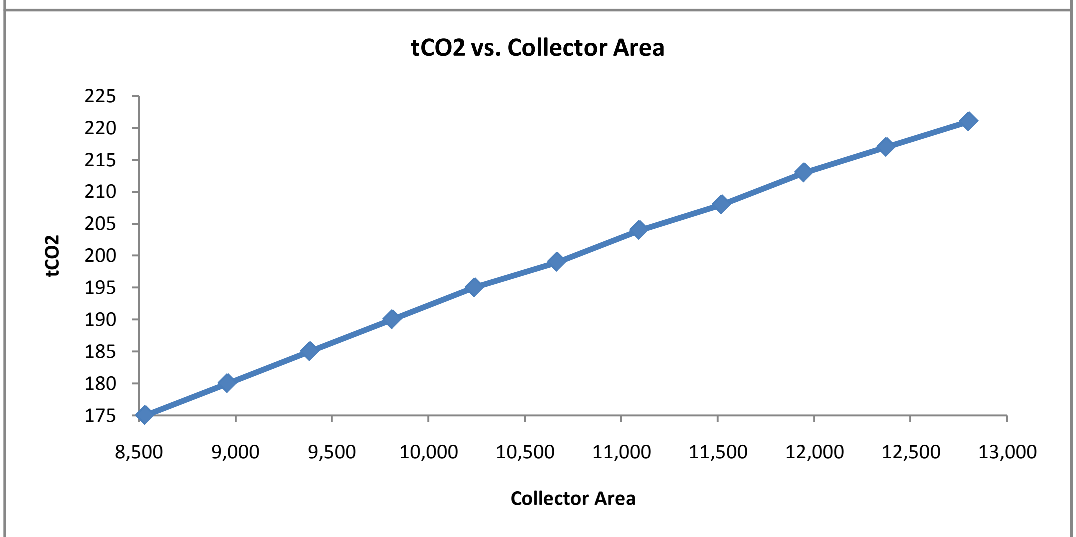
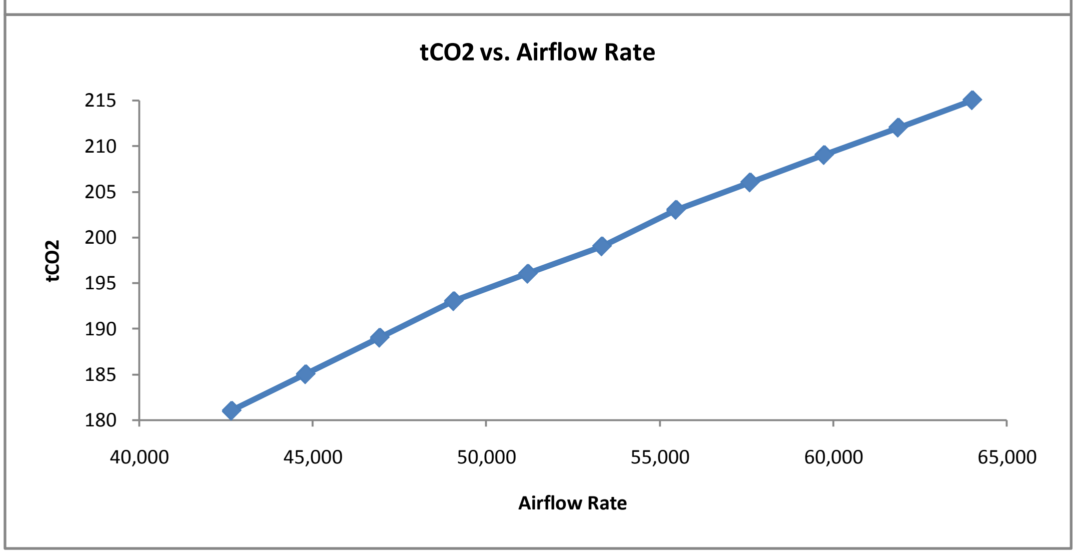



**Figure 39: Sensitivity Analysis (SIR)**

### *Tons of $CO_2$ Emissions Reduced (tCO2)*



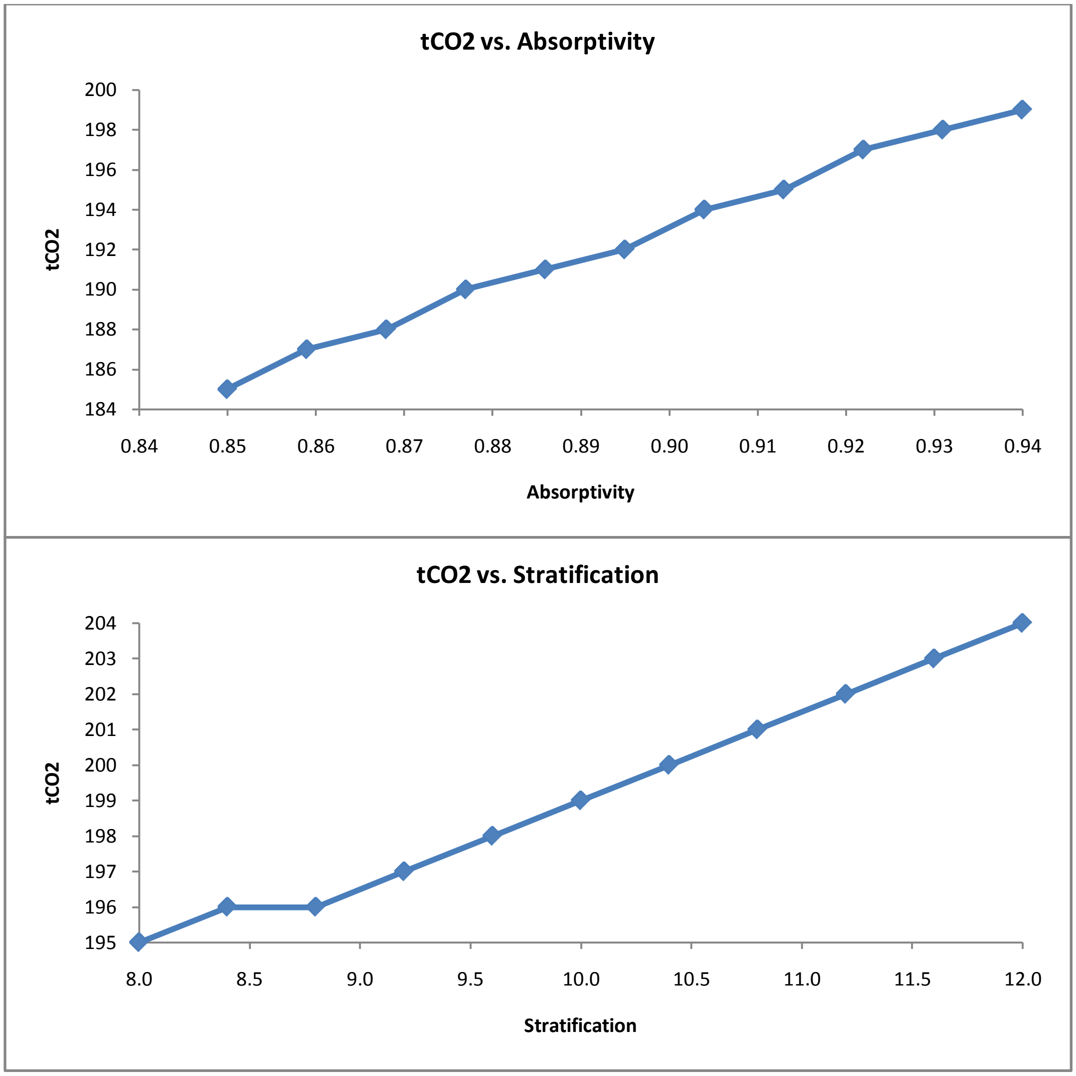
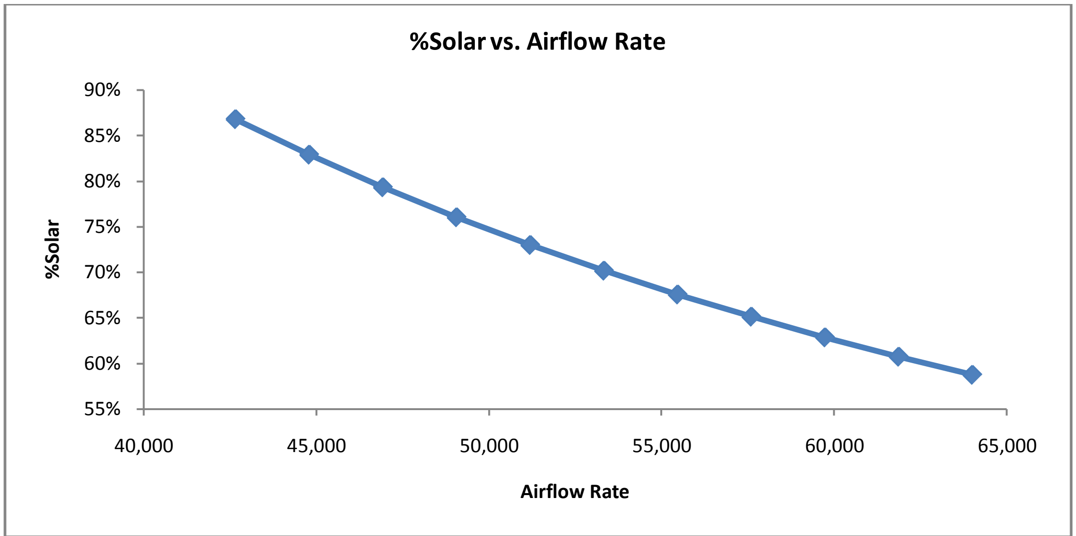
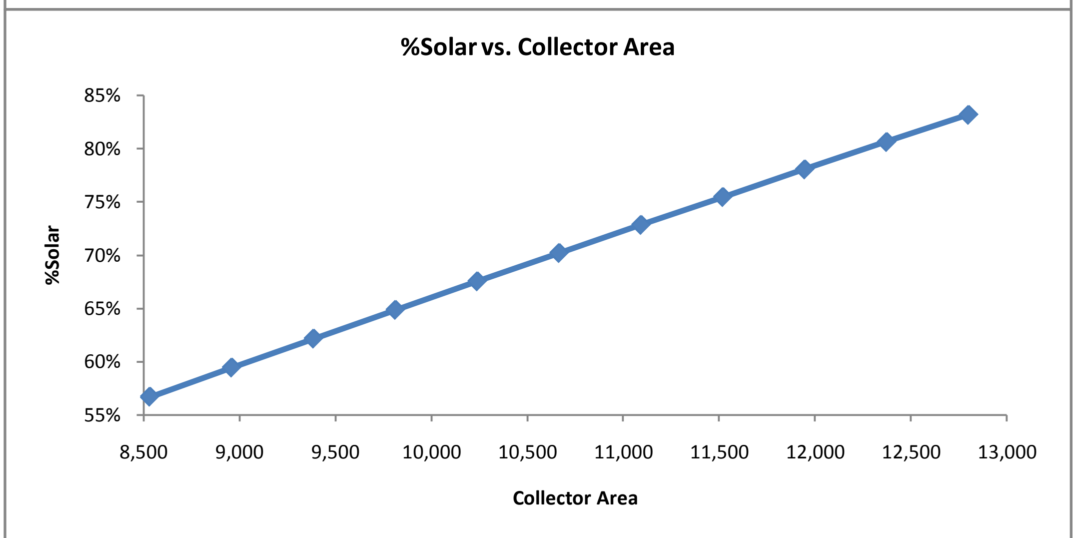
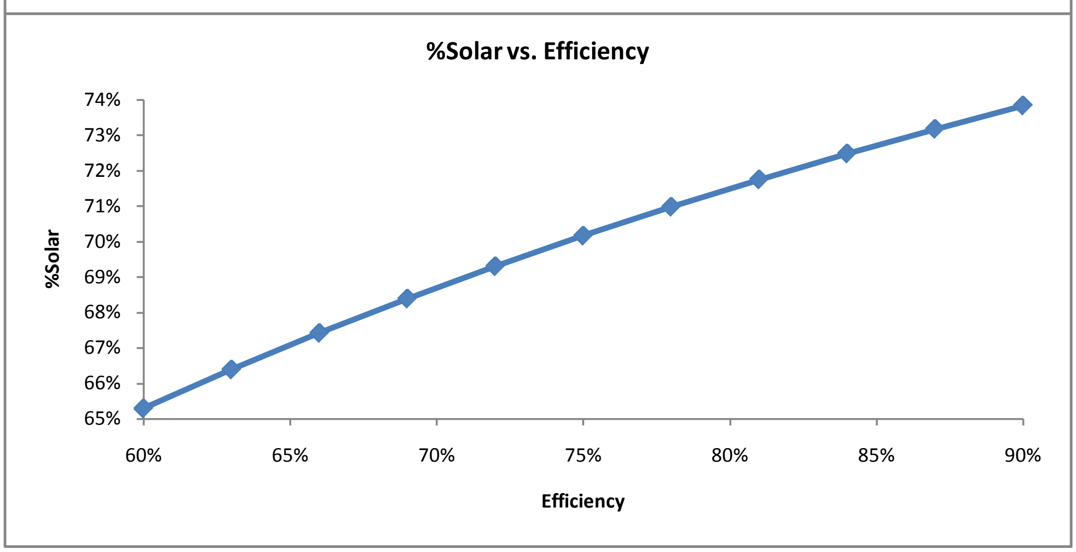



**Figure 40: Sensitivity Analysis ($tCO_2$)**

*Percent of Heat Energy Requirement Provided by UTC (%Solar)*



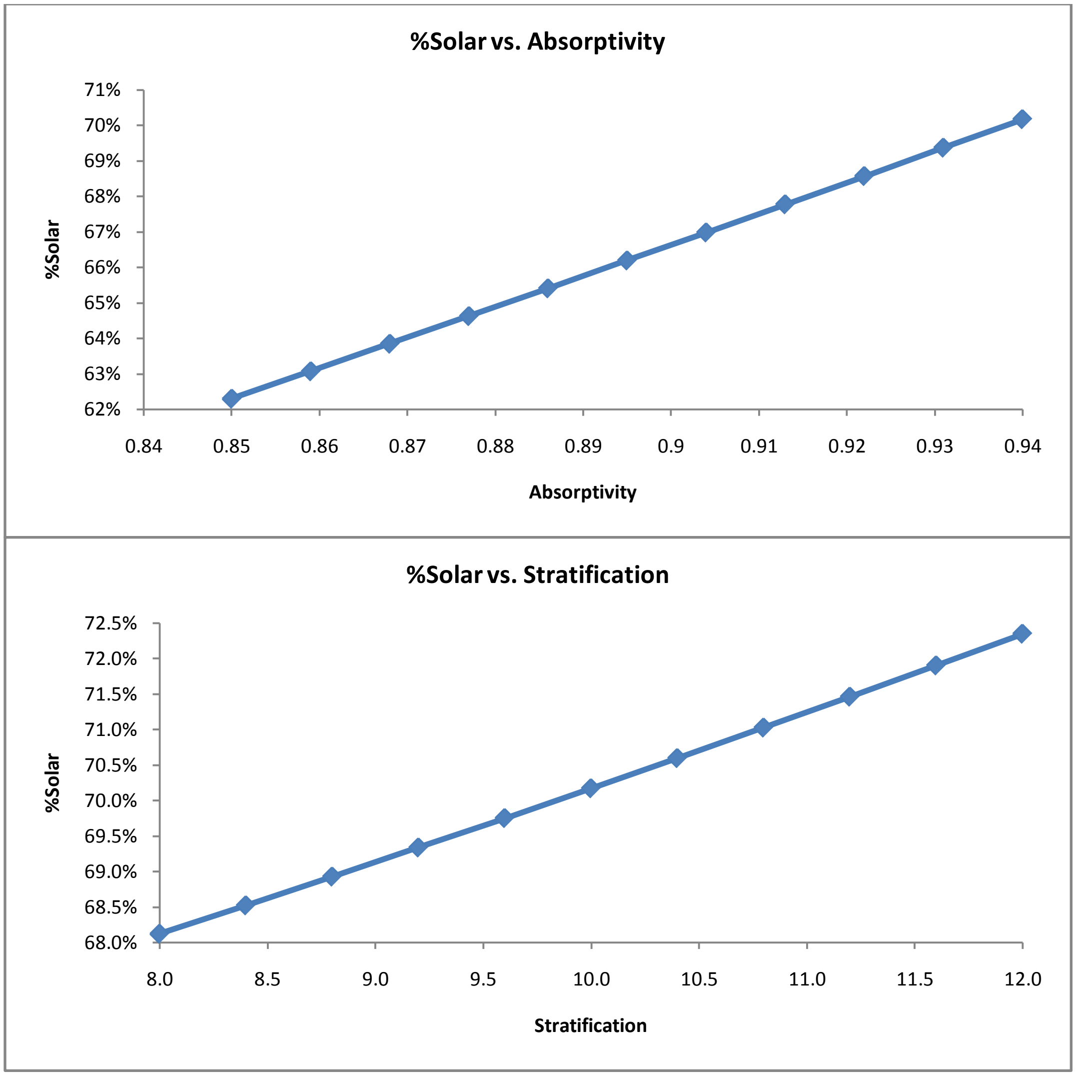



**Figure 41: Sensitivity Analysis (%Solar)**

**Two-Way Sensitivity Analysis**

**Table 31: Two-Way Analysis of Initial Cost vs Fuel Cost**

**IRR**

| Initial Cost | Fuel Cost $6.40 | Fuel Cost $8.00 | Fuel Cost $9.60 |
|---|---|---|---|
| $225,866 | 9.71% | 12.80% | 15.73% |
| $282,333 | 7.04% | 9.71% | 12.19% |
| $338,800 | 5.12% | 7.50% | 9.71% |

**NPV**

| Initial Cost | Fuel Cost $6.40 | Fuel Cost $8.00 | Fuel Cost $9.60 |
|---|---|---|---|
| $225,866 | $197,665 | $303,547 | $409,430 |
| $282,333 | $141,198 | $247,080 | $352,963 |
| $338,800 | $84,731 | $190,613 | $296,496 |

**SPBP**

| Initial Cost | Fuel Cost $6.40 | Fuel Cost $8.00 | Fuel Cost $9.60 |
|---|---|---|---|
| $225,866 | 9.29 | 7.43 | 6.19 |
| $282,333 | 11.61 | 9.29 | 7.74 |
| $338,800 | 13.93 | 11.14 | 9.29 |

**SIR**

| Initial Cost | Fuel Cost $6.40 | Fuel Cost $8.00 | Fuel Cost $9.60 |
|---|---|---|---|
| $225,866 | 1.88 | 2.34 | 2.81 |
| $282,333 | 1.50 | 1.88 | 2.25 |
| $338,800 | 1.25 | 1.56 | 1.88 |

**DPBP**

| Initial Cost | Fuel Cost $6.40 | Fuel Cost $8.00 | Fuel Cost $9.60 |
|---|---|---|---|
| $225,866 | 11.05 | 8.53 | 6.95 |
| $282,333 | 14.49 | 11.05 | 8.94 |
| $338,800 | 18.31 | 13.77 | 11.05 |

tCO2
(Not Applicable)

%Solar
(Not Applicable)

**Table 32: Two-Way Analysis of Initial Cost vs Seasonal Efficiency**

**IRR**

| Initial Cost | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| $225,866 | 16.45% | 12.80% | 10.24% |
| $282,333 | 12.80% | 9.71% | 7.50% |
| $338,800 | 10.24% | 7.50% | 5.53% |

**NPV**

| Initial Cost | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| $225,866 | $435,901 | $303,547 | $215,312 |
| $282,333 | $379,434 | $247,080 | $158,845 |
| $338,800 | $322,967 | $190,613 | $102,378 |

**SPBP**

| Initial Cost | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| $225,866 | 5.94 | 7.43 | 8.91 |
| $282,333 | 7.43 | 9.29 | 11.14 |
| $338,800 | 8.91 | 11.14 | 13.37 |

**SIR**

| Initial Cost | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| $225,866 | 2.93 | 2.34 | 1.95 |
| $282,333 | 2.34 | 1.88 | 1.56 |
| $338,800 | 1.95 | 1.56 | 1.30 |

**DPBP**

| Initial Cost | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| $225,866 | 6.65 | 8.53 | 10.53 |
| $282,333 | 8.53 | 11.05 | 13.77 |
| $338,800 | 10.53 | 13.77 | 17.35 |

tCO2
(Not Applicable)

%Solar
(Not Applicable)

**Table 33: Two-Way Analysis of Initial Cost vs Collector Area**

**IRR**

| Initial Cost | Collector Area | | |
|---|---|---|---|
| | 8,534 | 10,667 | 12,800 |
| $225,866 | 10.9% | 12.8% | 14.4% |
| $282,333 | 8.1% | 9.7% | 11.1% |
| $338,800 | 6.1% | 7.5% | 8.7% |

**NPV**

| Initial Cost | Collector Area | | |
|---|---|---|---|
| | 8,534 | 10,667 | 12,800 |
| $225,866 | $239,313 | $303,547 | $361,028 |
| $282,333 | $182,846 | $247,080 | $304,561 |
| $338,800 | $126,379 | $190,613 | $248,094 |

**SPBP**

| Initial Cost | Collector Area | | |
|---|---|---|---|
| | 8,534 | 10,667 | 12,800 |
| $225,866 | 8.45 | 7.43 | 6.70 |
| $282,333 | 10.57 | 9.29 | 8.38 |
| $338,800 | 12.68 | 11.14 | 10.05 |

**SIR**

| Initial Cost | Collector Area | | |
|---|---|---|---|
| | 8,534 | 10,667 | 12,800 |
| $225,866 | 2.06 | 2.34 | 2.60 |
| $282,333 | 1.65 | 1.88 | 2.08 |
| $338,800 | 1.37 | 1.56 | 1.73 |

**DPBP**

| Initial Cost | Collector Area | | |
|---|---|---|---|
| | 8,534 | 10,667 | 12,800 |
| $225,866 | 9.90 | 8.53 | 7.60 |
| $282,333 | 12.90 | 11.05 | 9.79 |
| $338,800 | 16.20 | 13.77 | 12.14 |

tCO2
(Not Applicable)

%Solar
(Not Applicable)

**Table 34: Two-Way Analysis of Initial Cost vs Absorptivity**

**IRR**

| Initial Cost | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| $225,866 | 11.74% | 12.27% | 12.80% |
| $282,333 | 8.80% | 9.26% | 9.71% |
| $338,800 | 6.70% | 7.10% | 7.50% |

**NPV**

| Initial Cost | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| $225,866 | $266,698 | $285,122 | $303,547 |
| $282,333 | $210,231 | $228,655 | $247,080 |
| $338,800 | $153,764 | $172,188 | $190,613 |

**SPBP**

| Initial Cost | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| $225,866 | 7.98 | 7.70 | 7.43 |
| $282,333 | 9.98 | 9.62 | 9.29 |
| $338,800 | 11.98 | 11.55 | 11.14 |

**SIR**

| Initial Cost | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| $225,866 | 2.18 | 2.26 | 2.34 |
| $282,333 | 1.74 | 1.81 | 1.88 |
| $338,800 | 1.45 | 1.51 | 1.56 |

**DPBP**

| Initial Cost | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| $225,866 | 9.27 | 8.88 | 8.53 |
| $282,333 | 12.04 | 11.53 | 11.05 |
| $338,800 | 15.06 | 14.39 | 13.77 |

tCO2
(Not Applicable)

%Solar
(Not Applicable)

**Table 35: Two-Way Analysis of Fuel Cost vs Seasonal Efficiency**

**IRR**

| | Efficiency | | |
|---|---|---|---|
| Fuel Cost | 60% | 75% | 90% |
| $6.40 | 9.71% | 7.04% | 5.12% |
| $8.00 | 12.80% | 9.71% | 7.50% |
| $9.60 | 15.73% | 12.19% | 9.71% |

**NPV**

| | Efficiency | | |
|---|---|---|---|
| Fuel Cost | 60% | 75% | 90% |
| $6.40 | $247,080 | $141,198 | $70,609 |
| $8.00 | $379,434 | $247,080 | $158,845 |
| $9.60 | $511,787 | $352,963 | $247,080 |

**SPBP**

| | Efficiency | | |
|---|---|---|---|
| Fuel Cost | 60% | 75% | 90% |
| $6.40 | 9.29 | 11.61 | 13.93 |
| $8.00 | 7.43 | 9.29 | 11.14 |
| $9.60 | 6.19 | 7.74 | 9.29 |

**SIR**

| | Efficiency | | |
|---|---|---|---|
| Fuel Cost | 60% | 75% | 90% |
| $6.40 | 1.88 | 1.50 | 1.25 |
| $8.00 | 2.34 | 1.88 | 1.56 |
| $9.60 | 2.81 | 2.25 | 1.88 |

**DPBP**

| | Efficiency | | |
|---|---|---|---|
| Fuel Cost | 60% | 75% | 90% |
| $6.40 | 11.05 | 14.49 | 18.31 |
| $8.00 | 8.53 | 11.05 | 13.77 |
| $9.60 | 6.95 | 8.94 | 11.05 |

tCO2
(Not Applicable)

%Solar
(Not Applicable)

**Table 36: Two-Way Analysis of Fuel Cost vs Absorptivity**

**IRR**

| Fuel Cost | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| $6.40 | 6.26% | 6.65% | 7.04% |
| $8.00 | 8.80% | 9.26% | 9.71% |
| $9.60 | 11.17% | 11.69% | 12.19% |

**NPV**

| Fuel Cost | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| $6.40 | $111,718 | $126,458 | $141,198 |
| $8.00 | $210,231 | $228,655 | $247,080 |
| $9.60 | $308,743 | $330,853 | $352,963 |

**SPBP**

| Fuel Cost | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| $6.40 | 12.48 | 12.03 | 11.61 |
| $8.00 | 9.98 | 9.62 | 9.29 |
| $9.60 | 8.32 | 8.02 | 7.74 |

**SIR**

| Fuel Cost | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| $6.40 | 1.40 | 1.45 | 1.50 |
| $8.00 | 1.74 | 1.81 | 1.88 |
| $9.60 | 2.09 | 2.17 | 2.25 |

**DPBP**

| Fuel Cost | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| $6.40 | 15.86 | 15.14 | 14.49 |
| $8.00 | 12.04 | 11.53 | 11.05 |
| $9.60 | 9.71 | 9.31 | 8.94 |

tCO2
(Not Applicable)

%Solar
(Not Applicable)

**Table 37: Two-Way Analysis of Fuel Cost vs Collector Area**

**IRR**

| Fuel Cost | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| $6.40 | 5.66% | 7.04% | 8.23% |
| $8.00 | 8.12% | 9.71% | 11.07% |
| $9.60 | 10.40% | 12.19% | 13.75% |

**NPV**

| Fuel Cost | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| $6.40 | $89,810 | $141,198 | $187,182 |
| $8.00 | $182,846 | $247,080 | $304,561 |
| $9.60 | $275,882 | $352,963 | $421,940 |

**SPBP**

| Fuel Cost | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| $6.40 | 13.21 | 11.61 | 10.47 |
| $8.00 | 10.57 | 9.29 | 8.38 |
| $9.60 | 8.81 | 7.74 | 6.98 |

**SIR**

| Fuel Cost | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| $6.40 | 1.32 | 1.50 | 1.66 |
| $8.00 | 1.65 | 1.88 | 2.08 |
| $9.60 | 1.98 | 2.25 | 2.49 |

**DPBP**

| Fuel Cost | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| $6.40 | 17.08 | 14.49 | 12.76 |
| $8.00 | 12.90 | 11.05 | 9.79 |
| $9.60 | 10.38 | 8.94 | 7.95 |

tCO2
(Not Applicable)

%Solar
(Not Applicable)

**Table 38: Two-Way Analysis of Collector Area vs Seasonal Efficiency**

**IRR**

| Collector Area | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 8,534 | 10.95% | 8.12% | 6.08% |
| 10,667 | 12.80% | 9.71% | 7.50% |
| 12,800 | 14.41% | 11.07% | 8.72% |

**NPV**

| Collector Area | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 8,534 | $299,141 | $182,846 | $105,316 |
| 10,667 | $379,434 | $247,080 | $158,845 |
| 12,800 | $451,284 | $304,561 | $206,745 |

**SPBP**

| Collector Area | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 8,534 | 8.45 | 10.57 | 12.68 |
| 10,667 | 7.43 | 9.29 | 11.14 |
| 12,800 | 6.70 | 8.38 | 10.05 |

**SIR**

| Collector Area | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 8,534 | 2.06 | 1.65 | 1.37 |
| 10,667 | 2.34 | 1.88 | 1.56 |
| 12,800 | 2.60 | 2.08 | 1.73 |

**DPBP**

| Collector Area | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 8,534 | 9.90 | 12.90 | 16.20 |
| 10,667 | 8.53 | 11.05 | 13.77 |
| 12,800 | 7.60 | 9.79 | 12.14 |

**tCO2**

| Collector Area | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 8,534 | 219 | 175 | 146 |
| 10,667 | 249 | 199 | 166 |
| 12,800 | 276 | 221 | 184 |

**%Solar**

| Collector Area | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 8,534 | 51.1% | 56.7% | 61.1% |
| 10,667 | 65.3% | 70.2% | 73.8% |
| 12,800 | 79.8% | 83.2% | 85.6% |

**Table 39: Two-Way Analysis of Airflow Rate vs Fuel Cost**

**IRR**

| Airflow Rate | Fuel Cost $6.40 | Fuel Cost $8.00 | Fuel Cost $9.60 |
|---|---|---|---|
| 42,666 | 6.03% | 8.54% | 10.87% |
| 53,333 | 7.04% | 9.71% | 12.19% |
| 64,000 | 7.88% | 10.67% | 13.30% |

**NPV**

| Airflow Rate | Fuel Cost $6.40 | Fuel Cost $8.00 | Fuel Cost $9.60 |
|---|---|---|---|
| 42,666 | $103,269 | $199,670 | $296,070 |
| 53,333 | $141,198 | $247,080 | $352,963 |
| 64,000 | $173,559 | $287,532 | $401,506 |

**SPBP**

| Airflow Rate | Fuel Cost $6.40 | Fuel Cost $8.00 | Fuel Cost $9.60 |
|---|---|---|---|
| 42,666 | 12.75 | 10.20 | 8.50 |
| 53,333 | 11.61 | 9.29 | 7.74 |
| 64,000 | 10.78 | 8.63 | 7.19 |

**SIR**

| Airflow Rate | Fuel Cost $6.40 | Fuel Cost $8.00 | Fuel Cost $9.60 |
|---|---|---|---|
| 42,666 | 1.37 | 1.71 | 2.05 |
| 53,333 | 1.50 | 1.88 | 2.25 |
| 64,000 | 1.61 | 2.02 | 2.42 |

**DPBP**

| Airflow Rate | Fuel Cost $6.40 | Fuel Cost $8.00 | Fuel Cost $9.60 |
|---|---|---|---|
| 42,666 | 16.31 | 12.36 | 9.96 |
| 53,333 | 14.49 | 11.05 | 8.94 |
| 64,000 | 13.23 | 10.13 | 8.22 |

tCO2
(Not Applicable)

%Solar
(Not Applicable)

**Table 40: Two-Way Analysis of Airflow Rate vs Initial Cost**

**IRR**

| Airflow Rate | Initial Cost $225,866 | $282,333 | $338,800 |
|---|---|---|---|
| 42,666 | 11.44% | 8.54% | 6.46% |
| 53,333 | 12.80% | 9.71% | 7.50% |
| 64,000 | 13.93% | 10.67% | 8.36% |

**NPV**

| Airflow Rate | Initial Cost $225,866 | $282,333 | $338,800 |
|---|---|---|---|
| 42,666 | $256,137 | $199,670 | $143,203 |
| 53,333 | $303,547 | $247,080 | $190,613 |
| 64,000 | $343,999 | $287,532 | $231,065 |

**SPBP**

| Airflow Rate | Initial Cost $225,866 | $282,333 | $338,800 |
|---|---|---|---|
| 42,666 | 8.16 | 10.20 | 12.24 |
| 53,333 | 7.43 | 9.29 | 11.14 |
| 64,000 | 6.90 | 8.63 | 10.35 |

**SIR**

| Airflow Rate | Initial Cost $225,866 | $282,333 | $338,800 |
|---|---|---|---|
| 42,666 | 2.13 | 1.71 | 1.42 |
| 53,333 | 2.34 | 1.88 | 1.56 |
| 64,000 | 2.52 | 2.02 | 1.68 |

**DPBP**

| Airflow Rate | Initial Cost $225,866 | $282,333 | $338,800 |
|---|---|---|---|
| 42,666 | 9.50 | 12.36 | 15.48 |
| 53,333 | 8.53 | 11.05 | 13.77 |
| 64,000 | 7.85 | 10.13 | 12.59 |

tCO2
(Not Applicable)

%Solar
(Not Applicable)

**Table 41: Two-Way Analysis of Airflow Rate vs Seasonal Efficiency**

**IRR**

| Airflow Rate | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 42,666 | 11.44% | 8.54% | 6.46% |
| 53,333 | 12.80% | 9.71% | 7.50% |
| 64,000 | 13.93% | 10.67% | 8.36% |

**NPV**

| Airflow Rate | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 42,666 | $320,170 | $199,670 | $119,336 |
| 53,333 | $379,434 | $247,080 | $158,845 |
| 64,000 | $429,999 | $287,532 | $192,555 |

**SPBP**

| Airflow Rate | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 42,666 | 8.16 | 10.20 | 12.24 |
| 53,333 | 7.43 | 9.29 | 11.14 |
| 64,000 | 6.90 | 8.63 | 10.35 |

**SIR**

| Airflow Rate | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 42,666 | 2.13 | 1.71 | 1.42 |
| 53,333 | 2.34 | 1.88 | 1.56 |
| 64,000 | 2.52 | 2.02 | 1.68 |

**DPBP**

| Airflow Rate | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 42,666 | 9.50 | 12.36 | 15.48 |
| 53,333 | 8.53 | 11.05 | 13.77 |
| 64,000 | 7.85 | 10.13 | 12.59 |

**tCO2**

| Airflow Rate | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 42,666 | 227 | 181 | 151 |
| 53,333 | 249 | 199 | 166 |
| 64,000 | 268 | 215 | 179 |

**%Solar**

| Airflow Rate | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 42,666 | 84.0% | 86.8% | 88.7% |
| 53,333 | 65.3% | 70.2% | 73.8% |
| 64,000 | 53.3% | 58.7% | 63.1% |

**Table 42: Two-Way Analysis of Airflow Rate vs Collector Area**

**IRR**

| Airflow Rate | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 42,666 | 7.09% | 8.54% | 9.75% |
| 53,333 | 8.12% | 9.71% | 11.07% |
| 64,000 | 8.97% | 10.67% | 12.15% |

**NPV**

| Airflow Rate | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 42,666 | $142,984 | $199,670 | $248,757 |
| 53,333 | $182,846 | $247,080 | $304,561 |
| 64,000 | $217,119 | $287,532 | $351,177 |

**SPBP**

| Airflow Rate | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 42,666 | 11.56 | 10.20 | 9.26 |
| 53,333 | 10.57 | 9.29 | 8.38 |
| 64,000 | 9.84 | 8.63 | 7.76 |

**SIR**

| Airflow Rate | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 42,666 | 1.51 | 1.71 | 1.88 |
| 53,333 | 1.65 | 1.88 | 2.08 |
| 64,000 | 1.77 | 2.02 | 2.24 |

**DPBP**

| Airflow Rate | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 42,666 | 14.41 | 12.36 | 11.01 |
| 53,333 | 12.90 | 11.05 | 9.79 |
| 64,000 | 11.84 | 10.13 | 8.97 |

**tCO2**

| Airflow Rate | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 42,666 | 160 | 181 | 198 |
| 53,333 | 175 | 199 | 221 |
| 64,000 | 188 | 215 | 239 |

**%Solar**

| Airflow Rate | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 42,666 | 70.5% | 86.8% | 100.0% |
| 53,333 | 56.7% | 70.2% | 83.2% |
| 64,000 | 47.1% | 58.7% | 69.9% |

**Table 43: Two-Way Analysis of Airflow Rate vs Absorptivity**

**IRR**

| Airflow Rate | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| 42,666 | 7.66% | 8.10% | 8.54% |
| 53,333 | 8.80% | 9.26% | 9.71% |
| 64,000 | 9.75% | 10.22% | 10.67% |

**NPV**

| Airflow Rate | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| 42,666 | $164,989 | $182,329 | $199,670 |
| 53,333 | $210,231 | $228,655 | $247,080 |
| 64,000 | $248,938 | $268,337 | $287,532 |

**SPBP**

| Airflow Rate | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| 42,666 | 10.99 | 10.58 | 10.20 |
| 53,333 | 9.98 | 9.62 | 9.29 |
| 64,000 | 9.25 | 8.93 | 8.63 |

**SIR**

| Airflow Rate | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| 42,666 | 1.58 | 1.65 | 1.71 |
| 53,333 | 1.74 | 1.81 | 1.88 |
| 64,000 | 1.88 | 1.95 | 2.02 |

**DPBP**

| Airflow Rate | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| 42,666 | 13.54 | 12.92 | 12.36 |
| 53,333 | 12.04 | 11.53 | 11.05 |
| 64,000 | 11.00 | 10.55 | 10.13 |

**tCO2**

| Airflow Rate | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| 42,666 | 168 | 175 | 181 |
| 53,333 | 185 | 192 | 199 |
| 64,000 | 200 | 207 | 215 |

**%Solar**

| Airflow Rate | Absorptivity 0.850 | 0.895 | 0.940 |
|---|---|---|---|
| 42,666 | 76.7% | 81.7% | 86.8% |
| 53,333 | 62.3% | 66.2% | 70.2% |
| 64,000 | 52.3% | 55.5% | 58.7% |

**Table 44: Two-Way Analysis of Absorptivity vs Seasonal Efficiency**

**IRR**

| Absorp-tivity | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 0.850 | 11.74% | 8.80% | 6.70% |
| 0.895 | 12.27% | 9.26% | 7.10% |
| 0.940 | 12.80% | 9.71% | 7.50% |

**NPV**

| Absorp-tivity | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 0.850 | $333,371 | $210,231 | $128,137 |
| 0.895 | $356,403 | $228,655 | $143,491 |
| 0.940 | $379,434 | $247,080 | $158,845 |

**SPBP**

| Absorp-tivity | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 0.850 | 7.98 | 9.98 | 11.98 |
| 0.895 | 7.70 | 9.62 | 11.55 |
| 0.940 | 7.43 | 9.29 | 11.14 |

**SIR**

| Absorp-tivity | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 0.850 | 2.18 | 1.74 | 1.45 |
| 0.895 | 2.26 | 1.81 | 1.51 |
| 0.940 | 2.34 | 1.88 | 1.56 |

**DPBP**

| Absorp-tivity | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 0.850 | 9.27 | 12.04 | 15.06 |
| 0.895 | 8.88 | 11.53 | 14.39 |
| 0.940 | 8.53 | 11.05 | 13.77 |

**tCO2**

| Absorp-tivity | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 0.850 | 232 | 185 | 155 |
| 0.895 | 241 | 192 | 160 |
| 0.940 | 249 | 199 | 166 |

**%Solar**

| Absorp-tivity | Efficiency 60% | 75% | 90% |
|---|---|---|---|
| 0.850 | 56.9% | 62.3% | 66.5% |
| 0.895 | 61.0% | 66.2% | 70.1% |
| 0.940 | 65.3% | 70.2% | 73.8% |

**Table 45: Two-Way Analysis of Absorptivity vs Collector Area**

**IRR**

| Absorp-tivity | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 0.850 | 7.31% | 8.80% | 10.08% |
| 0.895 | 7.72% | 9.26% | 10.58% |
| 0.940 | 8.12% | 9.71% | 11.07% |

**NPV**

| Absorp-tivity | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 0.850 | $151,553 | $210,231 | $262,435 |
| 0.895 | $167,251 | $228,655 | $283,498 |
| 0.940 | $182,846 | $247,080 | $304,561 |

**SPBP**

| Absorp-tivity | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 0.850 | 11.33 | 9.98 | 9.02 |
| 0.895 | 10.94 | 9.62 | 8.69 |
| 0.940 | 10.57 | 9.29 | 8.38 |

**SIR**

| Absorp-tivity | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 0.850 | 1.54 | 1.74 | 1.93 |
| 0.895 | 1.59 | 1.81 | 2.00 |
| 0.940 | 1.65 | 1.88 | 2.08 |

**DPBP**

| Absorp-tivity | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 0.850 | 14.05 | 12.04 | 10.68 |
| 0.895 | 13.45 | 11.53 | 10.22 |
| 0.940 | 12.90 | 11.05 | 9.79 |

**tCO2**

| Absorp-tivity | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 0.850 | 163 | 185 | 205 |
| 0.895 | 169 | 192 | 213 |
| 0.940 | 175 | 199 | 221 |

**%Solar**

| Absorp-tivity | Collector Area 8,534 | 10,667 | 12,800 |
|---|---|---|---|
| 0.850 | 50.4% | 62.3% | 73.6% |
| 0.895 | 53.5% | 66.2% | 78.3% |
| 0.940 | 56.7% | 70.2% | 83.2% |

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**14. ABSTRACT**

The purpose of this research was to evaluate the use of solar air heating at United States (U.S.) Air Force installations. Specifically, this thesis analyzed Unglazed Transpired Collector (UTC) technology, more commonly known as SolarWalls®. This thesis sought to determine if UTC systems are an economically and environmentally viable technology which Air Force energy managers should include in their portfolio of alternative energy options. This research question was answered through the use of case studies and life-cycle cost analysis. Case studies were performed at various U.S. military installations which have already utilized UTC systems to provide a consolidated source of lessons learned. A life-cycle cost analysis was performed to quantify the potential cost savings at various Air Force installations to help Air Force energy leaders determine if the technology should be further implemented, and if so, which installations should be considered for future UTC use. The quantitative results of this evaluation determined that the Air Force could realize significant economic and environmental benefits from the use of UTC technology. The information gathered from case studies can help ensure that future users of UTC systems utilize their systems in the most effective manner possible.

**15. SUBJECT TERMS**

Solar Air Heating, Transpired Collector, Unglazed Transpired Collector, UTC, SolarWall, Solar Wall, Alternative Energy, Energy Efficiency, Green Energy, Green Technology, Air Force Energy Initiatives

| **16. SECURITY CLASSIFICATION OF:** | | | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | **19a. NAME OF RESPONSIBLE PERSON** Lt Col Eric J. Unger (AFIT/ENV) |
|---|---|---|---|---|---|
| **a. REPORT** | **b. ABSTRACT** | **c. THIS PAGE** | | | **19b. TELEPHONE NUMBER** *(Include area code)* |
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