Reduced Energy Demand for Cooling with the Sky

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• A subcooler deployed at a Dining Facilities Administration Center (DFAC), where the array reduced net power and energy usage over the year by 22%.
• A remote condenser for a water source heat pump, cooling a data closet. The result was a 51% reduction in net power consumption and a 42% reduction in energy usage over the year.
While the results showed good technical performance in reducing energy consumption, we also learned that in order for these array systems to be economical at scale, they would need to be installed on cooling systems with greater than 50 tons (or have more than 50 panels per deployment) and that run at least 80% of the time. This is due to the significant economies of scale that come with installing larger array systems.

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Abstract

This project demonstrated the use of SkyCool's Passive Daytime Radiative Cooling panels to improve the energy efficiency of cooling systems at Ft Moore, GA. These panels work by passively emitting heat to the sky during the day even under direct sunlight. The following two integration modes using this technology were implemented at Ft Moore:

- A subcooler deployed at a Dining Facilities Administration Center (DFAC), where the array reduced net power and energy usage over the year by 22%.
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Acronym List

AC—Air conditioning
ARPAE—Advanced Research Projects Agency–Energy
ASHRAE-- American Society of Heating, Refrigerating and Air-Conditioning Engineers
COP—Coefficient of Performance
DFAC—dining facility
FMEA—Failure Modes and effects analysis
FPS—Feet per second
GHG-Greenhouse Gas
HVAC/R—Heating ventilation and air conditioning & refrigeration
LT Evaporator—Low Temperature Evaporator
MT Evaporator—Medium Temperature Evaporator
PDRC—Passive daytime radiative cooling
SDT—Saturation discharge temperature
WSHP—Water source heath pump

1.0 Executive Summary

- **Introduction**

Between June and August 2022, the United States experienced its third hottest summer on record[1], causing significant strain on air conditioners and increasing energy usage on utility grids to the point of failure. Additionally, during this time, many unairconditioned buildings became unsafe to work in. SkyCool Systems' passive radiative cooling panels reject heat to the sky, with no input electricity, 365 days per year. When used with cooling systems that run year round, the panels have the potential to save more than 2X the energy that could be generated with a solar panel for the same area.

- **Objectives**

The primary objectives of this project were to:

- demonstrate the energy efficiency and cooling capacity improvements for existing cooling systems located at DoD facilities.
- Demonstrate the seamless integration of SkyCool panels with existing HVAC equipment,
- Evaluate the value of SkyCool's passive radiative cooling panels in different integration modes, while in a humid climate

- **Technology Description**

Radiative sky cooling occurs naturally because Earth's atmosphere is partially transparent to infrared thermal radiation (the light wavelengths associated with heat). As a result, at night sky-facing surfaces emit more energy as thermal radiation to the sky than they receive from it. Radiative sky cooling is not a new concept. Its first recorded use was by ancient Persian civilizations, and they used it to make ice at night in the desert. Prior to our work, this effect was not observed during the day because the sun heats up all outdoor, sky-facing surfaces. However, this effect actually happens all the time and is most prominent on clear sky days and even occurs when clouds are present.

SkyCool Systems has developed a rooftop cooling panel, which uses radiative cooling to improve the efficiency of air conditioning and refrigeration. Our panels cool without evaporating water and only require the electricity to run a small circulating water pump. The radiative cooling effect from our panels occurs all day and is very well aligned with the 24/7 operation of refrigeration systems in supermarkets and cold storage facilities, and air conditioning systems in data centers. In typical operation, water-glycol is circulated through the panels in a closed loop, and the water-glycol is used to indirectly cool refrigerant after the condenser.

- Performance and Cost Assessment

In the proposed work, SkyCool's panels were deployed at two sites at Fort Moore (previously named Fort Benning). At the first site, 10 panels were integrated with a DFAC refrigeration system and at the second site, 20 panels were connected with an air conditioning system in a data closet. For the DFAC system, the panels reduced the power demand by the refrigeration system by 15% at 90ºF ambient and 22% over the entire year; and for the data closet, the panels reduced the net power demand by 20% reduction at 90ºF and 51% reduction over the entire year, relative to the baseline cooling systems. We estimate the energy saved over the year by these systems to be 22% and 42% respectively. While the percent savings are relatively high, the amount of energy saved per day for each system is small since both systems that were modified served small cooling loads (the DFAC cooling system is rated at 3.5 ton and the data closet cooling system 1.25 tons). For the DFAC system, the panels save about 14 kWh per day and the data closet system saves 8 kWh per day.

The installed cost of SkyCool's panel system can be split into fixed project costs and variable costs associated with the number of panels deployed at a site. The fixed costs include: project design, travel, installation labor for the heat exchanger, the pump skid, sensors, and commissioning. The variable costs include: panels, panel installation labor, pipe fittings, and racking. For these particular sites, the installed costs were high because: 1) the installation was timed during the peak of the pandemic when labor was difficult to find / expensive, 2) the installation occurred over several phases due to inaccurate information about the site roof structure, and 3) there was a relatively large distance between the array and cooling unit in the data closet.

Due to the fact that the cooling systems were relatively small, and the install costs were high due to several issues (see below), the payback in both sites is > 20 years. In general, these pilot projects show that in order for the deployment to have a sub 5 year payback, the systems need to have cooling loads of greater than 50 tons and need to run at least 80% of the time. The high runtimes will be true for datacenters, centralized cooling systems with high runtime, and commissary refrigeration systems and less likely to be applicable to distributed AC systems in offices or dormitories.

- **Implementation Issues**

While the energy savings measured at both sites met or exceeded our expectations, there were several challenges which we faced during the implementation of the cooling panels at these two sites. These include:

- COVID related supply chain issues procuring relatively common materials like plumbing components and increasing the cost of shipping containers
- COVID related labor issues resulted in the need to work with contractors that were remote from this site
- Installation started during Thanksgiving and continued through the winter holidays leading to lots of travel to and from the site.
- Two smaller sites that required one central location to store materials and it took time to transport materials from the storage site to the buildings
- Wrong rooftop drawings led to a pause in the installation

2.0 INTRODUCTION

On a global scale, air conditioning and refrigeration systems consume nearly 2,000 TWh of electricity per year, and are associated with the emissions of 8% of all greenhouse gases. In the US, cooling and refrigeration systems consume nearly 19% of all electricity in commercial buildings and electricity associated with cooling systems can be as high as 50% of the energy on the grid in the summer. As a result of increasing ambient air temperatures associated with global warming, the International Energy Agency expects energy demand for cooling to triple by 2050.

The vast majority of air conditioning and refrigeration systems are vapor-compression cycles, which consume electricity to remove heat from a conditioned space. Vapor-compression cooling systems become less efficient as air temperatures rise. The decrease in efficiency of refrigeration and air conditioning systems is challenging for grid stability during the hottest days of the year, results in high utility bills and reduces energy security for the United States. If left unchecked, the rise in electricity needed to run cooling systems will overburden electrical grids and require 30% to 50% more electricity generation capacity globally (See Figure 1).

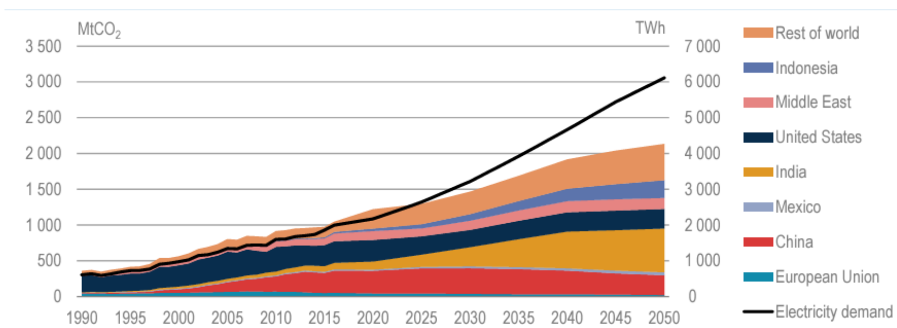


Figure 1: IEA estimated energy use associated with cooling under baseline conditions vs if efficiency measures were implemented to reduce the cost of cooling [1]

We have estimated that the DoD spends $28M-$35M a year on electricity to run cooling systems at its facilities. Using more efficient cooling methods will lower demand for electricity from cooling systems and help the DoD reduce facility operating costs. Reducing energy usage of cooling systems will also improve energy security and reduce the risk of blackouts at DoD facilities.

2.1 BACKGROUND

As air temperatures rise due to global warming, vapor compression air conditioning and refrigeration systems will become less efficient. Additionally, cooling will be more critical to ensure the thermal comfort of troops in domestic military bases, forward operating locations as well as in the military's cold chain and data centers which require cooling for everyday operation.

Passive Daytime Radiative Cooling (PDRC) is one of a handful of new technologies to emerge in the cooling segment that can improve the efficiency of existing cooling systems (AC and refrigeration) and reduce the energy requirements for buildings. PDRC is enabled by a coating that is highly reflective of energy from the sun and simultaneously emissive of energy in the infrared. Due to properties of Earth's atmosphere, the emitted energy from PDRC films is able to go through much of our atmosphere and exchange energy with the cold sky. SkyCool's product is a rooftop fluid cooling panel that employs PDRC films to cool water that enters the panels. Cold water from the panels is then used to subcool refrigerant or replace the condenser of traditional vapor compression systems.

For this work, SkyCool's panels were deployed in two buildings at Ft. Moore to validate the energy savings when SkyCool's panels are connected to refrigeration and air conditioning systems. With the installation of SkyCool's panels connected to refrigeration systems as an add-on subcooler, we expected to see energy savings of 10%-20% and when connected to AC systems as a part of a condenser replacement, 30%-40% savings. In addition to demonstrating the energy savings potential of SkyCool's panels, we collected data on panel heat rejection capabilities in a hot, humid climate. By evaluating the performance of our panels this new climate zone, we will be able to improve the accuracy of our models under different weather conditions.

2.2 Current Technology State of the Art

SkyCool Systems has developed a breakthrough platform cooling technology that enables air conditioning and refrigeration systems to run more efficiently. Additionally, in limited circumstances, SkyCool's technology could even be used to replace air conditioning systems in office buildings when combined with thermal storage, or replace cooling towers, significantly increasing the reliability of cooling systems, and reducing the energy needed to operate the facilities.

SkyCool's panels reject heat to the sky by radiation and convection. The cooling effect of the panels is enabled by the company's patented multilayer cooling film technology. The film reflects sunlight to prevent the panels from heating up during the day and also emits infrared heat to the cold sky, which keeps the panels and any fluid flowing in them cool 24/7/365.

In 2012, with ARPA-e support, SkyCool Systems' founding team began researching ways to enable radiative sky cooling during the day. The output of this research was the world's first daytime radiative cooling film. The two enabling properties of this film are: 1) reflective of energy from the sun, and 2) emissive of infrared light in the 8 to 13 micron wavelength range. The film is applied on a panel that is approximately 3 ft x 6 ft and deployed on the rooftops of buildings using racking from the solar industry, shown in Figure 2a. A fluid is pumped through the panels, which cool passively, 24/7, even when the panel is under direct sunlight. In typical deployments the panels are connected in a closed loop, reverse return layout, shown in Figure 2b, ensuring a uniform flow distribution through the panels.

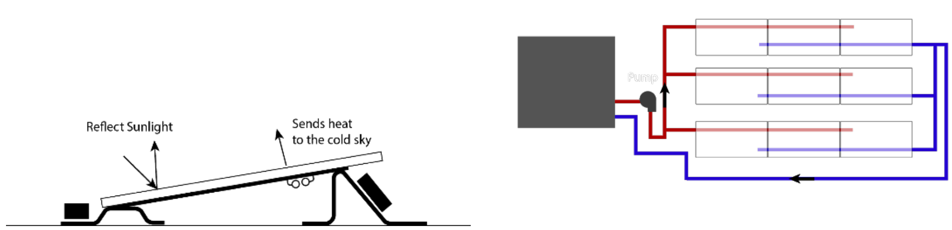


Figure 2: a) panels reflect energy from the sun and radiate infrared light to the sky. Panels are ballasted or mechanically attached to rooftops using common solar racking

components; b) panels are connected in parallel and only require a small circulating water pump to deliver cooling to a load. A reverse return layout ensures uniform flow through each panel.

The ability of panels to reject heat has been well documented in third party tests, with refrigeration and air conditioning systems and with more controlled lab experiments. Shown in Figure 2, is data, collected at SkyCool's office, that demonstrates the heat rejection capabilities as a function of approach temperature (inlet fluid temperature minus the ambient air temperature).

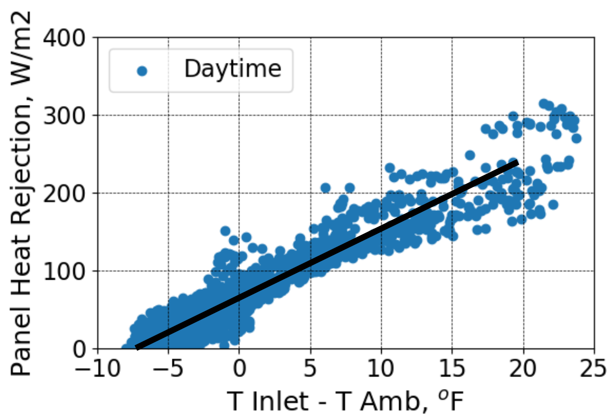


Figure 3: Panel heat rejection capabilities as a function of the inlet fluid temperature relative to the ambient air

2.3 Current State of Technology in DoD:

The vast majority of cooling systems are based on vapor compression cycles. Regardless of the end application in air conditioning, data centers/data closets, or the cold chain, vapor compression cycles have four main components: compressors, condensers, evaporators, and expansion valves. An example vapor compression system is shown in Figure 4.

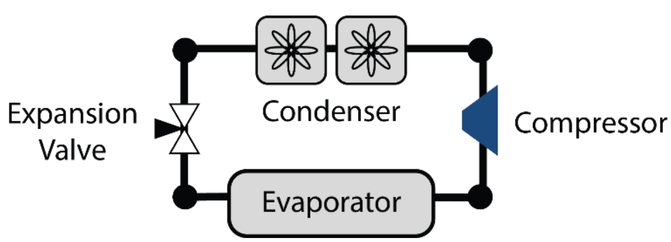


Figure 4: Vapor Compression Cycle showing four main components: compressor, condenser, evaporator and expansion valve

In most cooling systems relevant to DoD bases (where thermal loads are less than 100 tons), fans blowing dry air are utilized to cool refrigerant in the condensers. One big drawback of air cooled condensers is that the refrigerant in the condenser must always be hotter than the ambient air. This is because a temperature gradient is needed to drive the heat transfer between the hot refrigerant and cooler air. Often the saturation discharge temperature (SDT) of the refrigerant in the condenser is typically 10 and 25ºF above the ambient. It is not possible or practical to have a lower approach temperature to the ambient using air cooled systems because as the refrigerant approaches the ambient air temperature, there is less driving force for heat transfer. However, there are a number of benefits to having a lower SDT. As the SDT of the condenser is lowered, the compressors require less energy to operate, and the refrigerant has a greater cooling capacity when it is expanded in the evaporator. If the SDT remains unchanged, there is still a benefit to cooling liquid refrigerant out of a condenser. This is known as subcooling and also gives the refrigerant more cooling capacity when it is expanded in the evaporator.

Lowering the SDT or adding more subcooling have the greatest potential to improve the efficiency of vapor compression cycles. SkyCool's unique technology provides access to a heat sink that is cooler than ambient air and, this can be used to improve the overall cycle efficiency of the cooling system.

2.4 Technology Opportunity:

Air conditioning and refrigeration loads account for 19% of building electricity usage. Lower demand for electricity from cooling systems will help the DoD reduce facility operating costs. The use of SkyCool Panels will also significantly improve the reliability of the electrical grids serving DoD facilities. The highest demand for electricity is typically during summer afternoons/early evenings when cooling demand is greatest. This is in part because refrigeration and air conditioning systems are also least efficient during these hottest times. Reducing the demand for cooling reduces the need for demand response from utility operators, which often uses less efficient methods of generation, more expensive fuels, and emit more GHGs (greenhouse gases). The overall safety of DoD personnel is enhanced by improving energy security, and reducing the risk of blackouts.

It has been reported that the DoD runs upwards of 3,300 data centers across the United States and spends upwards of $500M / year on electricity to cool them. Additionally, the DoD manages over 4,700 sites and 279,000 buildings. Estimating 1% of the buildings are mess halls with 15 ton refrigeration systems, the DoD is spending approximately $14M to $18M on electricity to run refrigeration systems annually. Additionally, there are over 1 billion ft^2 of floor space associated with administration buildings, family housing, community facilities, and hospitals. While all this area is not all conditioned space, much of it may need to be as air temperatures increase.

2.5 Project Economic Analysis

The goal of this research was to demonstrate the performance of SkyCool's technology and generate data demonstrating the energy savings at a typical DoD facility. Given the average cost of electricity in the US and projected scale costs for a panel system, we believed that systems with greater than 50 panels will have a sub 8 year payback and save end users between 10% to 20% on their refrigeration energy usage or 30% to 40% on HVAC use in computer room air conditioning systems.

SkyCool Panels are a simple add-on to existing refrigeration systems and require minimal maintenance. The expected maintenance is to clean the surface of the panels once a month in dry periods of the year.

2.6 OBJECTIVE OF THE DEMONSTRATION

The main objectives of this project were to demonstrate the energy efficiency and cooling capacity improvements for existing cooling systems located at Fort Moore. With the installation of SkyCool panels connected to refrigeration systems as an add-on subcooler, we expected to see energy savings of 10-20% and when connected to AC system as part of a condenser replacement, 30-40% savings.

In addition to demonstrating the energy savings potential of SkyCool Panels, we also collected data on SkyCool panel heat rejection capabilities in a hot, humid climate. This was one of the first demonstrations outside of California and in a humid climate zone. By evaluating the performance of our panels in a humid location, we hope to be able to improve the accuracy of our models under different weather conditions.

- Validate:

Energy consumption, power use and cooling capacity data was collected when SkyCool's pump was on (test condition) vs off (the baseline condition). We compared the energy use of the system as a function of the ambient temperature and other relevant parameters to determine the power and energy savings. Additionally, we documented the installation process and will use learnings from the early demonstrations to improve upon the installation for later deployments. A detailed cost accounting of labor and materials was used to determine the projects ROI and longer-term benefit to the base.

- Technology Transfer:

As this is a new technology, these demonstrations will introduce the radiative cooling concept to the energy managers and facilities teams at military bases. This will serve as the basis for training local teams to install and maintain and operate this new technology. Additionally, learnings collected from these demonstrations will be published in the form of case studies on our website and at relevant conferences. Data collected from these sites will also be used to improve our models. These models will ultimately be shared publicly as a tool to help channel partners successfully deploy radiative cooling technology at additional private and military facilities.

- Acceptance:

The adoption of new and innovative technologies is often slow because there is limited data available of proving out the efficacy in relevant buildings and climates. These demonstrations have yielded data showing the value of SkyCool's panel technology as a simple efficiency add-on to cooling equipment at military bases in hot, humid climates.

2.7 REGULATORY DRIVERS

As part of its climate resilience strategy, the DoD has set requirements to use renewable energy and improve energy management and efficiency as directed through several legislative and executive actions. Through federal policies and mandates such as the Energy Policy Act and

Executive Order 13834, the federal government has set aggressive goals for federal agencies to cultivate sustainability and reduce greenhouse gas emissions. Energy efficiency, environmental sustainability, energy security, and long-term savings are all drivers for SkyCool's technology. By reducing the electricity consumption of refrigeration and air conditioning systems located within DoD facilities, SkyCool's passive radiative cooling technology will address the following drivers:

- **Energy Policy Act:** The Energy Policy Act (EPA) addresses energy efficiency in the United States and encourages all Federal agencies to "take actions to maximize the efficiency of air conditioning and refrigeration equipment, including appropriate cleaning and maintenance, including the use of any system treatment or additive that will reduce the electricity consumed by air conditioning and refrigeration equipment." The primary value proposition of SkyCool's technology is the reduction of electricity consumed by air conditioning and refrigeration systems. Radiative cooling is one of a very small number of truly game changing technologies to emerge in the area of cooling and will have major impacts on future electricity loads.
- **Executive Order (EO) 13834**: EO 13834 affirms that "agencies shall meet such statutory requirements in a manner that increases efficiency, optimizes performance, eliminates unnecessary use of resources, and protects the environment." By reducing energy usage and increasing the efficiency of operations of cooling systems in DoD facilities, SkyCool's technology will help the DoD maximize efficient use of energy, cut waste and reduce impacts on the environment.
- **DoD Sustainability Implementation Plan :** According to the DoD's 2020 Sustainability Report and Implementation plan, energy efficiency is an important part of strengthening the DoD's energy resilience and energy security. For this project, SkyCool will demonstrate the energy savings of its technology when connected to cooling systems with high run times. Implementation of SkyCool's technology will help the DoD reduce energy consumption and energy use intensity of its facilities.
- **Whole Building Design Guide:** UFC 4-826-10 provides general criteria for the design of refrigeration systems for cold storage. The guide states that systems should be designed to "provide the lowest life-cycle cost with maximum energy efficiency and give special consideration to safety and low maintenance." SkyCool's radiative cooling system can be connected to new and existing refrigeration systems to provide additional cooling capacity and energy savings to these systems. In addition, SkyCool's panel system is considered safe and reliable - the panels have no electrical connections and only require cleaning during dry seasons.

3.0 TECHNOLOGY DESCRIPTION

Radiative sky cooling occurs naturally because Earth's atmosphere is partially transparent to infrared thermal radiation (the light wavelengths associated with heat). As a result, at night sky-facing surfaces emit more energy as thermal radiation to the sky than they receive from it. Radiative sky cooling is not a new concept. Its first recorded use was by ancient Persian civilizations, and they used it to make ice at night in the desert. Prior to our work, this effect was not observed during the day because the sun heats up all outdoor, sky-facing surfaces. However, this effect actually happens all the time and is most prominent on clear sky days and even occurs when clouds are present.

3.1 TECHNOLOGY OVERVIEW

Beginning in 2012 at Stanford University, with DOE-ARPA-e support, SkyCool Systems' founding team began researching ways to enable radiative sky cooling during the day and use the effect to improve the efficiency of cooling systems. In 2014, the first results demonstrating this effect were published in *Nature*, showing that specialized optical surfaces could passively cool up to 20°F below air temperature, even under direct sunlight. Testing of our surfaces demonstrated the ability of this approach to passively cool fluids below the ambient air temperature (presented at the 2016 Annual ASHRAE conference, and published in *Nature Energy*).

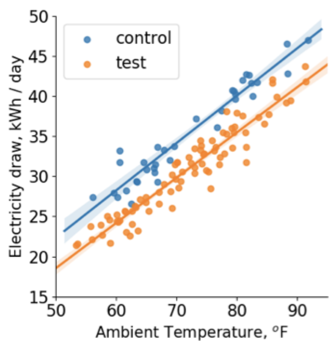
SkyCool Systems was formed at the beginning of 2016, it has since then completed numerous demonstrations to advance its Technology Readiness Level (TRL) to 8. The SkyCool team has performed detailed modeling and executed technology demonstrations of radiative sky cooling. In Q1 2019, SkyCool Systems deployed panels as a passive sub-cooler of a walk-in freezer and cooler, and replaced the condenser of an ice machine in a commercial convenience store (Sacramento, CA), and installed panels as a passive subcooler of an air conditioning system in a commercial office building (Sunnyvale, CA).

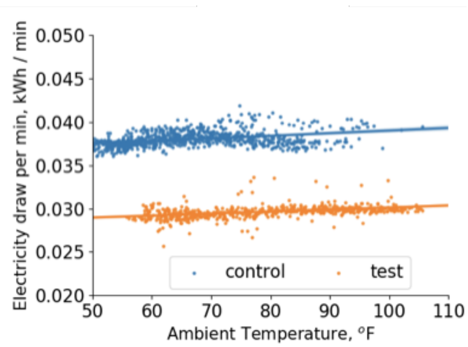
For the walk-freezer demonstration, SkyCool's panels were used as a passive subcooler, and generated a 10%-15% reduction in kWh consumption per day (depending on the ambient temperature). For the ice machine, SkyCool's panels were used to replace the remote air cooled condenser and the installation of SkyCool's panels resulted in 25% reduction in kWh and kW draw. The energy draw for the freezer and ice machine are shown in Figure 5.

From the proposed demonstrations, we wanted to:

- develop a process to implement our system on military bases,
- collect data validating the energy savings of our cooling panels with HVAC equipment typically installed on military bases, and
- study the performance impact of using radiative cooling in a hot, humid climate.

High humidity will reduce the atmospheric transparency to infrared radiation, and thus reduce the effectiveness of this technology. At the same time, high humidity also will increase the cooling requirements and reduce the efficiency of HVAC equipment. Part of the goal of completing a deployment in a humid location was to collect data that can improve our models of radiative cooling.



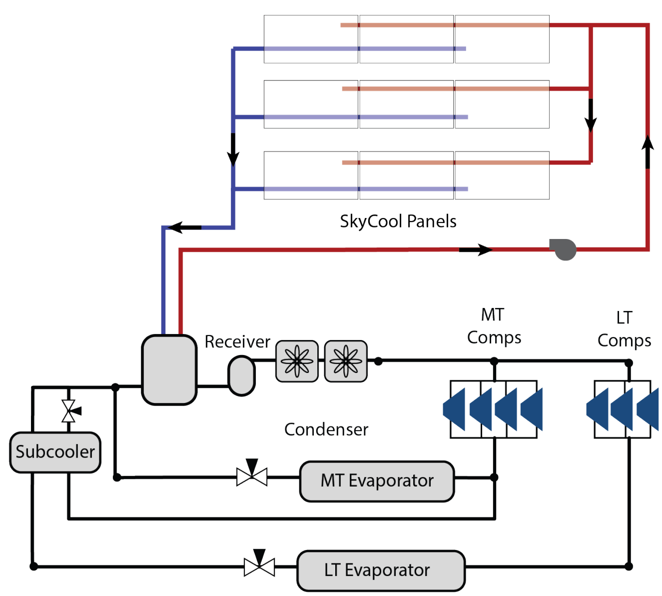


Panel A **Panel B**

Figure 5: a) net savings, including pump and fan electricity, for SkyCool panel system as an add-on for a walk-in freezer. b) net savings, including pump and fan electricity, for the replacement of an air-cooled condenser of an ice machine.

3.2 TECHNOLOGY DEVELOPMENT

Prior to this project, our technology was deployed at 3 commercial sites including a convenience store, a supermarket and an office building. At these project sites, the panels were demonstrated as a subcooler and as a condenser replacement. The integration for these systems is shown in Figure 6.



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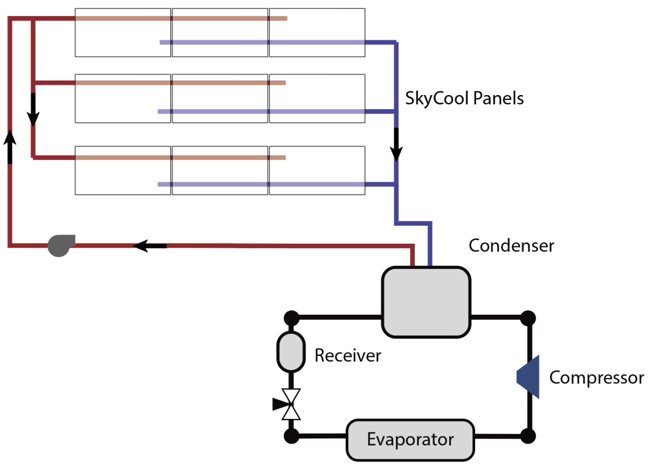

b)

Figure 6: Previous deployments of SkyCool's panel technology; a) integration of panels with a parallel compressor refrigeration system; b) integration of panels as a condenser replacement

Below in **Figure 7**, is a techno-economic analysis that we performed for different types of cooling systems and it shows the relative payback that the panels can support for a given cost of electricity.

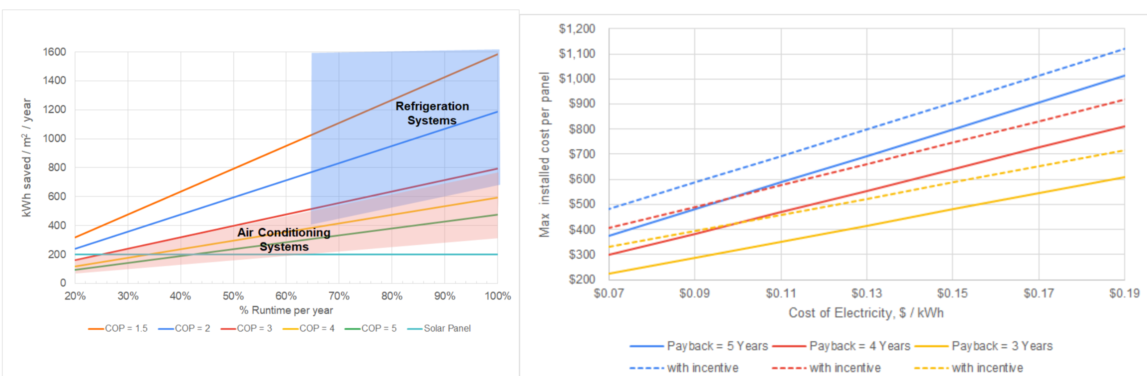

Figure 7: (left) Estimate of energy savings per m2 of panel for vapor compression COPs between 2 and 5 (typical for refrigeration applications [COP: 1.5 to 3] and air conditioning [COP: 3 to 5]; (right) maximum cost per panel as a function of the electricity cost, assuming each panel saves 550 kWh / m2 / year. Incentive amount is $0.1 / kWh. Note each panel is 2 m^2.

3.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Passive daytime radiative cooling panels are a relatively new approach used to cool outdoor surfaces and improve the efficiency of HVAC/R equipment. Even though it is new, there are applications where cooling panels have a clear advantage over incumbent approaches as well as situations where radiative cooling is at a disadvantage.

SkyCool's panels have the potential to save energy and improve the efficiency of cooling systems. As it is being used as a cooling efficiency technology, it's value is proportional to the runtime of the cooling system.

<u>Performance Advantages</u>:

- As the panels have a similar form factor to solar, and occupy roof space, they are often compared to solar panels. SkyCool's radiative cooling save more electricity when connected to persistent cooling loads than solar PV will generate over a 24 hr period. Solar panels in a hot climate like Las Vegas, NV will typically generate 200 to 250 kWh / m^2 / year. In a similar climate and when connected to a persistent cooling load, cooling panels can save more than 500 kWh / m^2 / year.
- Panels can be used to provide additional subcooling or lower the condenser operating conditions; traditional air cooled condensers cool fluids that are 5 to 25F above the ambient air temperature.
- The panels only require the electricity to run a circulating water pump, and therefore provide savings with very little operating cost
- An alternative approach to provide subcooling or lower condensing conditions is to evaporate water into air. Evaporative or adiabatic cooling systems require open water systems and this can make them impractical to implement at small scales
- The panels reflect 94% to 97% of incident sunlight, keeping roofs cooler than they would otherwise have been, reducing local heat islands.
- The panels are relatively easy to maintain and operate; panels can be cleaned with the same labor used to wash solar panels, using water hoses or pressure washers
- The technology works best in hot dry climates, often aligned where cooling loads are the largest

<u>Cost Advantages</u>:

- Can save kWh and reduce demand charges when connected to cooling systems
- The panels can also be used provide extra condenser heat rejection capacity, allowing operators to sweat assets or add capacity to systems that are under performing

<u>Performance Limitations</u>:

- The panels only save electricity when a cooling system is running; for applications where cooling is not the dominant load, savings will drop off and can be less than solar
- It is difficult to verify energy savings as cooling loads are highly dependent on the local weather, building occupation states and installed cooling equipment
- A key aspect to daytime performance of PDRC panels having a high reflectivity. As the panels become dirty, the solar reflectivity of the panels is reduced and the panels cooling capacity can be reduced
- High humidity could reduce the heat rejection capacity of PDRC materials since the sky is emitting more infrared light. There is very limited data on radiative cooling systems operating in non-ideal climatic zones; as a part of this project, one of the key outputs was to collect data in a hot-humid area.

Cost Limitations:

- The system currently has a high installation and material costs because it is a new system being manufactured in small volumes

Potential Barriers to Acceptance:

- The panels need open roof space with sky access to operate
- The panels are most cost effective on low rise buildings and are not a good for dense cities with many floors. When on a multistory building, the floor to roof area ratio becomes too large and the fraction of heat that can be rejected by the array becomes small relative to the total cooling load
- There is limited long term performance data validating savings over the entire expected lifetime of the product

4.0 PERFORMANCE OBJECTIVES

Table 1: Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria
Quantitative Performance Objectives			
Subsystem Energy Usage	Energy (kWh) and power (kW) draw	Meter readings of energy	10% to 20% reduction in compressor energy usage as a subcooler and 30% to 40% reduction as a condenser for a WSHP
Runtime Reduction	Runtime of the compressor	On-off time from compressors	10% to 20% reduction in compressor runtime as a subcooler and 30% to 40% reduction as a condenser for a WSHP
Direct Greenhouse Gas Emissions	Energy (kWh) draw reduction	Meter readings of energy	10% to 20% reduction in GHG emissions as a subcooler and 30% to 40% as a condenser for WSHP
System Economics	%, $, Years	Dollar costs, discount rate, usable life	% Reduction in energy usage and total dollars saved per year

4.1 SUBSYSTEM ENERGY USAGE

- Name and Definition: Facility energy use

- Purpose: Compare facility energy use when SkyCool panels provide cooling vs when the baseline system was providing cooling. Reducing facility energy use contributes to DoD energy security, cost avoidance, and greenhouse gas reduction.
- Metric: The key performance metric was % energy reduction relative to baseline operation. Baseline operation was defined as when the pump (which must be on for the SkyCool panels to provide cooling) is off.
- Data: Both test (pump on) and baseline (pump off) measurements were made throughout the data collection period. For subcooling systems, the pump was turned on and off periodically in order to collect both active and baseline data throughout the seasonal weather variations of the data collection period. For WSHP systems, the set point for the WSHP or existing unit was raised or lowered to have it be the primary system meeting the cooling load. Energy data was monitored by current clamps and collected through the our remote data collection platform.
- Analytical Methodology: Data was analyzed relative to ambient temperature
- Success Criteria: 10% to 20% energy reduction will be considered a success for the systems with panels performing as a subcooler and 30% to 40% will be considered a success for those with a WSHP and panels performing as a condenser.

4.2 RUNTIME REDUCTION

- Name and Definition: Runtime of compressor.
- Purpose: Compare compressor runtime when SkyCool panels are providing cooling to when they are not providing cooling. Reducing runtime contributes to DoD energy security, cost avoidance, and greenhouse gas reduction.
- Metric: The key performance metric is % compressor runtime reduction relative to baseline operation. Baseline operation was defined as when the pump is off.
- Data: Both active (pump on) and baseline (pump off) data were acquired throughout the data collection period. The pump was turned on and off in order to collect both active and baseline data throughout the seasonal weather variations of the data collection period. Compressor runtime data wase determined by energy data, which was monitored by current clamps and collected through the data collection platform.
- Analytical Methodology: Data was analyzed relative to ambient temperature
- Success Criteria: 10% to 15% compressor runtime reduction will be considered a success.

4.3 SUBSYSTEM DIRECT GREENHOUSE GAS EMISSIONS

- Name and Definition: Facility GHG emissions.
- Purpose: Compare facility GHG emissions when SkyCool panels are providing cooling to when they are not providing cooling. Reducing GHG emissions contributions is a goal of the DoD and this can be achieved through SkyCool's system by reducing energy usage of existing cooling systems.
- Metric: The key performance metric is % GHG emissions reduction relative to baseline operation. Baseline operation will be defined as when the pump is off.
- Data: Both active (pump on) and baseline (pump off) data were acquired throughout the data collection period. The pump was turned on and off in order to collect both active and baseline data throughout the seasonal weather variations of the data collection period. Energy data will be monitored by current clamps and collected through the data collection platform.

- Analytical Methodology: energy savings was used as the primary metric for determining green house gas reduction.
- Success Criteria: 10% to 15% energy reduction will be considered a success.

4.4 SYSTEM ECONOMICS

- Name and Definition: Unit economics and lifetime of panel array systems
- Purpose: Measuring system economics will help us understand if the solution is scalable by providing the DoD with an attractive return on investment.
- Metric: % energy savings and $ savings, # of years of system lifecycle and payback period.
- Data: Both test (pump on) and baseline (pump off) data were measured throughout the data collection period. For subcooling systems, the pump was turned on and off in order to collect both active and baseline data throughout the seasonal weather variations of the data collection period. Energy data was monitored by current clamps and collected through the data collection platform. Cost of installation (on a $ amount per panel basis) was documented and opportunities for cost reduction have been considered as we think about scaling the solution. Estimated system lifecycle will be determined by how the various systems hold up in different climate conditions.
- Analytical Methodology: System costs were measured on a per panel installed basis. Installation costs, BOS (balance of system) and panel costs make up the cost per panel installed. For energy costs, we assumed $0.1 per kWh.

5.0 FACILITY/SITE DESCRIPTION

For the proposed work, SkyCool deployed 2 systems at Fort Moore. Table 2 summarizes the site locations, climate zone, and application. The site-specific information in this report was collected through site assessments conducted by SkyCool or its contractor.

Table 2: Test system matrix of the sites and system demonstrations

Site Location	**Fort Moore, GA**	**Fort Moore, GA**
Base Location	Building 6, Room 117	5252 Moye Rd DFAC at Ft Moore, GA
System description	Data Closet	Walk in cooler
Application	Remote Condensing Circuit	Subcooling
Panel Array size*	20 panels	10 panels
System tons of cooling	1.25 tons	3.5 tons
Climate	Hot, Humid ASHRAE 3A	Hot, Humid ASHRAE 3A

**Standard panel size is 39" x 79"*

The number of panels on each building was determined based on the cooling load at the site. Once the number of panels was determined, SkyCool worked with PanelClaw, a solar racking manufacturer, to determine the panel layout, ballast requirements and points of attachment to the building. With the final array design from PanelClaw, SkyCool had a third party structural engineer review the building drawings and panel layout to ensure the building could support the additional weight of the array.

5.1 FACILITY/SITE LOCATION AND OPERATIONS

There were three criteria that were used to identify and select sites for the proposed work. These criteria are related to: cooling applications, facility representativeness, and climatic conditions. Cooling applications are highly segmented in military bases (and in buildings in general) and include space cooling in office buildings, barracks, residences, refrigeration applications, and data centers. SkyCool is focused on cooling applications that have persistent runtime like those in refrigeration systems and data centers. Within DoD facilities, we identified dining facilities, commissaries and cold storage sites as the primary refrigeration applications and data closets for data centers due to the relevant scale of our current product offering. In addition to the cooling applications, we wanted to identify cooling systems that are repeatedly used in many building applications.

Refrigeration and data center cooling systems are typically segmented by the type of condensers that they use: air cooled vs water cooled. In cooling systems that are less than 100 tons, condensers are most often air cooled due to the lower operational costs. Water cooled systems use less energy relative to air cooled systems, however they have higher operational costs because they consume water and require a dedicated person or team to manage water quality. For our demonstration sites, we focused on cooling systems with air cooled condensers. While we don't know exact numbers on how many cooling systems on military bases have air cooled condensers, it is likely the majority given the fact that most cooling systems have loads that are less than 100 tons.

The last criteria that we used for site selection was the climate zone of the demonstration site. For site selection, we wanted to have a demonstration in a hot humid location. The initial proposal was to implement our technology at 3 other bases but due to funding constraints, the project was scaled back to one DoD base in a hot humid climate.

5.2 FACILITY/SITE CONDITIONS

Fort Moore-DFAC Cooler:

- Demonstration Site Description:

The first demonstration site at Fort Moore is a medium temperature refrigeration system in a dining facility, nominally providing 3.5 tons of cooling. In this system, we installed 10 panels (2 rows of 5 panels each) to provide additional subcooling to the existing system. The dining facility address is 5252 Moye Rd, Ft Moore, GA. The building has a flat roof, and the refrigeration equipment modified in this system is located on the roof.

- Key Operations:

The panel system was engaged when the fluid circulation pump is running and was turned off when the pump is not operating.

- Location/Site Map:

Figure 8: 5252 Moye Rd DFAC at Ft Moore, GA

Fort Moore- Data Closet:

- Demonstration Site Description:

The second proposed demonstration site at Fort Moore is a communication closet in Room-117 of Building 6. The communication closet is currently being cooled by a split air conditioning system. We installed 20 panels (4 rows of 5 panels each) and a 1.25 ton water source heat pump (WSHP) with a waterside economizer. In this system, the panels served two roles depending on the ambient temperature: during low ambient, the heat pump will run in economizer mode allowing the panels to directly provide free cooling to the IT equipment (no compressor will run). During high ambient conditions, the panels will be the heat sink for the condenser in water source heat pump's vapor-compression system in lieu of air. This site is unique because it is the first high humidity climate where radiative cooling panels and WSHP will be replacing a split air conditioning system.

- Key Operations:

The WSHP panel system was controlled by a thermostat in the data closet room.

- Location/Site Map:

Figure 9: Building 6, Ft Moore, GA

5.3 SITE-RELATED PERMITS AND REGULATIONS

In order to deploy our product on a commercial building, we sought similar permits to solar projects. The primary consideration was to make sure that the building structure can hold the added weight from the array, and to verify that the panels will remain on the roof under all weather conditions expected at the site. Both checks were completed by a third party engineering firm.

- Regulations:

SkyCool's rooftop panels have been intentionally designed to look like solar panels and use components from the solar industry to attach to building roofs. As a result, the panels meet the same requirements for connecting to building roofs as solar panels. Additionally, since the panels are mostly aluminum and there are no active components in the panels, there is no risk of electrical fires within them.

- Environmental Permits: Environmental reviews at Fort Moore were approved.
- Agreements: All electrical work at Fort Moore was completed by a mechanical contractor that was familiar with the base.
- Military Requirements: SkyCool received approval from Fort Moore regarding the data collection plan. Additionally, a project manager from the base supported testing by turning the pump on and off on the subcooling system, and lowering and raising the set point on the WSHP system.

6.0 TEST DESIGN

As a part of the proposed demonstrations, SkyCool installed a number of sensors to validate the efficacy of radiative cooling panels in reducing energy use cooling applications. The two applications being tested were:

1) using the panels as a subcooler in a refrigeration system and
2) using the panels as a remote heat sink for the condenser of a water source heat pump (WSHP).

The data was collected with a wireless data platform and used to improve modeling of radiative cooling in different climates and with different cooling systems (heat pumps and subcooling refrigeration systems). Note that for the WSHP system, the baseline system was the existing equipment being used to cool the space. The baseline system remained in place during our testing.

- Fundamental Problem:

SkyCool's technology is attempting to address the challenge of high energy usage in cooling systems. SkyCool's panels are being used in two different ways to accomplish this goal. Additionally, the demonstrations are being conducted in a hot, humid area; the performance of SkyCool's radiative cooling system needed to be assessed in regions outside of California.

- Demonstration Question:

These demonstrations answered questions around the energy savings potential, climate zone impact and O&M costs of SkyCool's radiative cooling panels in refrigeration and data center cooling applications.

6.1 CONCEPTUAL TEST DESIGN

Below is an overview of the test design used to evaluate the performance objectives for the subcooling and WSHP integration modes.

Subcooling:

- Hypothesis: SkyCool's panels will reduce energy consumption of the refrigeration system by 10% to 20%
- Independent variable: The independent variable used in this testing was the state of the circulating water pump. When the circulation water pump was turned on, the panels provided additional cooling capacity to the system. When the circulation water pump was off, the system operated in its baseline condition.
- Dependent variable(s): There are a number of variables that were measured to determine the effectiveness of SkyCool's radiative cooling panels:
    - Power and Energy: pump, compressor and condenser fans
    - Temperature: refrigerant temperature into and out of the heat exchanger and water temperature into and out of the heat exchanger
- Controlled variable(s): The primary control variable will be the cooling load in the refrigeration system. It was assumed that the usage of the DFAC system did not change over the course of the testing program. From the data, it was clear that this wasn't strictly true. There were two suction pressures that were measured over the course of the deployment: 60 psig and 110 psig, indicating that the setpoint of the cooler was likely changed.

- Test Design:

During the testing period, the SkyCool circulation water pump was turned on (test period) and off (control period). Over the test and control time periods, we measured the thermal states of the cooling system, as well as the power and energy consumption of the pump, compressors and condensers in the refrigeration system/heat pump and the ambient weather.

- Test Phases: There were several phases to the proposed testing
  - Setup and calibration: The sensors were calibrated prior to being installed at the site
  - Commissioning: Once the system components were installed, we worked with RSC Mechanical to commission the system and ensure its smooth operation over the test and control periods
  - Test period: the time when the pump is operational, and the panels are providing additional cooling
  - Control: time period when the pump is off, and the system is in its baseline configuration

WHSP / Condenser Replacement:

- Hypothesis: SkyCool's panels will reduce energy consumption for space cooling by 30% to 40% relative to the installed cooling system.
- Independent variable: The independent variable used in this testing was the room thermostat. The desired air temperature for the room was specified by the base. When we wanted to disengage either the WSHP or the baseline unit, we raised the setpoint for that particular system. When we wanted to engage a particular unit, we lowered its setpoint to the desired room temperature. A contact at the base made these changes to the system.
- Dependent variable(s): There are a number of variables that were assessed to determine the effectiveness of SkyCool's radiative cooling panels:
  - Power and Energy: pump, compressor and condenser fans of the baseline and WSHP unit
  - Temperature: refrigerant temperature into and out of the heat exchanger and water temperature into and out of the heat exchanger
  - Ambient Weather: dew point, solar irradiance, wind speed, ambient temperature
  - Room thermal conditions
- Controlled variable(s): The primary control variable was the thermal load in networking rooms or data closets. We assumed that the thermal load in the data closet did not vary over the course of the evaluation period. This assumption was also likely not true. Through conversations with the base, we were told that the door to the data closet was periodically left open, allowing heat to enter or leave the room.

- Test Design:

During the testing period, the thermostat temperature for the baseline and WSHP system were raised or lowered to engage or disengage a given unit. During the test period, the WSHP setpoint was lowered and the baseline system raised by 5ºF. During the control period, the WSHP setpoint was raised 5ºF and the baseline system setpoint lowered. Over the test and control time periods, we measured the thermal states of the cooling system, as well as the power and energy consumption of the compressors, & condenser fans in the WSHP and baseline AC unit, the circulation water pump and the ambient weather.

- Test Phases: There were several phases to the testing
  - Setup and calibration: The sensors were calibrated prior to being installed at the site
  - Commissioning: Once the system components were installed, we worked with RSC Mechanical to commission the system and ensure its smooth operation over the test and control periods
  - Test period: the time when the WHSP has a lower setpoint
  - Control: time when the baseline system has a lower setpoint

6.2 BASELINE CHARACTERIZATION

Baseline data was measured periodically over the test year. For the subcooling application, the baseline system was assessed by turning the pump off in the SkyCool panel array. For the WSHP system, the baseline system was assessed by raising the setpoint of the WSHP and lowering the setpoint for the baseline system, making it the unit that provided the primary cooling to the space.

- Reference Conditions: The baseline setpoint for the data closet was 72F
- Baseline Collection Period: During the baseline period, the SkyCool circulation pump was turned off or the WSHP setpoint raised, for approximately one week.
- Baseline Estimation: All energy performance data was correlated with ambient temperature. Energy savings was based on load conditions for the space and thermal load from the ambient.
- Data Collection Equipment: Data was collected remotely through cell modems.

6.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

Describe the components and provide a depiction of the demonstrated system.

- System Design:
  - Subcooling of refrigeration systems: For the subcooling system integration, a brazed plate heat exchanger was installed on the liquid line of the condenser.

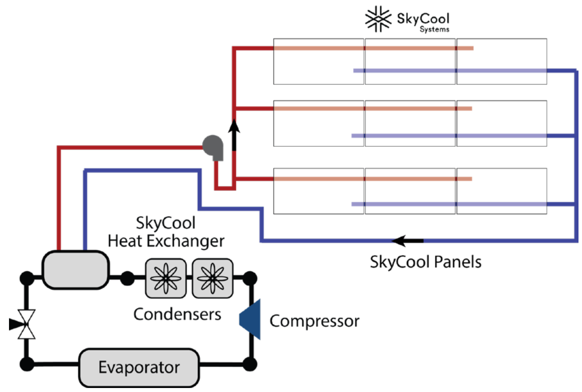

Figure 10: System diagram of SkyCool's panels attached to a refrigeration system. Note the vapor compression cycle is the existing equipment and we are adding

- WSHP: For the WSHP systems, the WSHP unit was installed in parallel to the existing cooling unit at the site. We coordinated with each base that the setpoint for the WSHP unit be raised or lowered during the test / control conditions. The WSHP itself was mounted inside (where) and connected to panels on the roof with water piping.

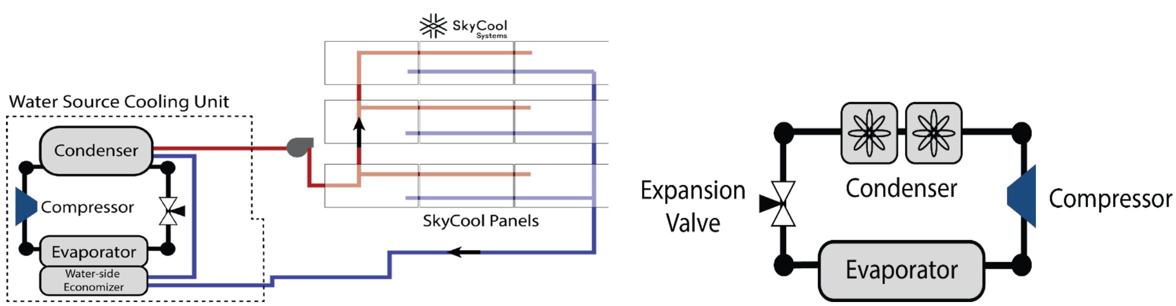

Figure 11: System diagram of a WSHP connected to SkyCool's panels. Note for the WSHP systems, the existing cooling systems will remain in place (shown as the right image)

- Components of the System:
  - Panels-- each panel is approximately 21 ft^2, 39" wide and 79" long. The panels have pipe's on the back of them and PDRC film on the top flat side
  - Pump Skid-- each system has a pump skid which has a circulation pump, expansion bladder, fill and drain valve, pressure sensors and a flow sensor. The pump skid is protected from the elements by a sheet metal enclosure.
  - Heat Exchanger (for subcooling demonstrations)-- a brazed plate heat exchanger, specifically designed for each system based on the refrigerant and water flowrate through the system

- WSHP-- cooling platform to interface with the panels; the WSHP unit has a compressor, blower fan, expansion valve and heat exchanger serving as the condenser

- System Depiction:

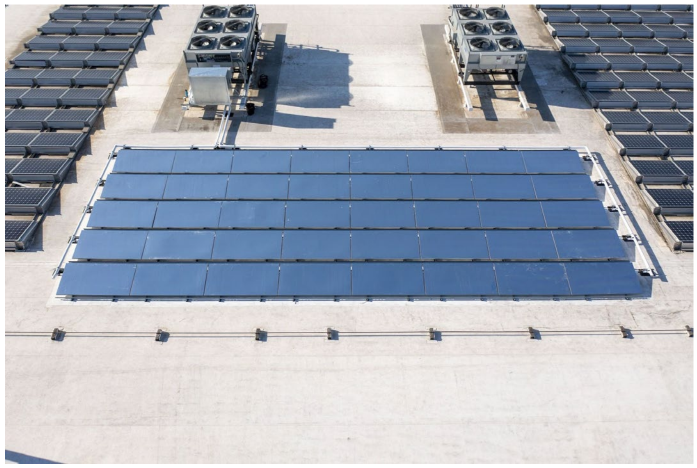

Figure 12: Example photo of panel array

Figure 13: Example photo of Trane WSHP Units

Figure 14: Example photo of brazed plate heat exchanger

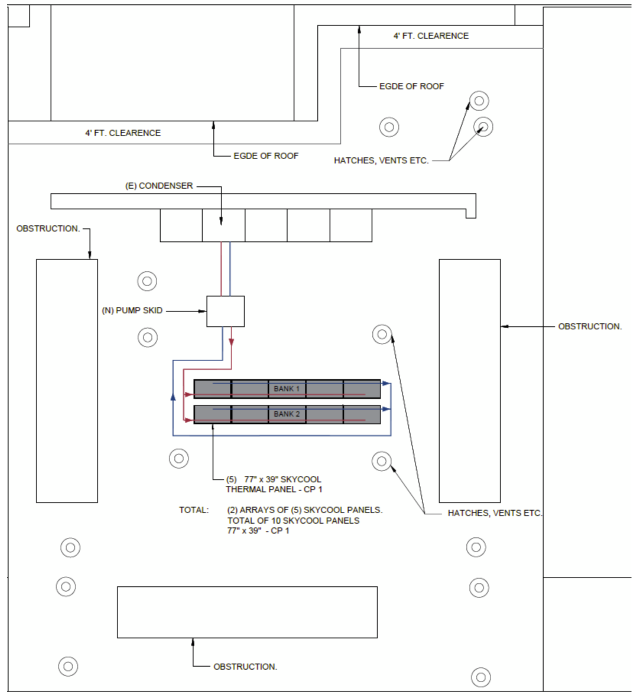

Figure 15: System Schematic for Fort Moore Subcooler

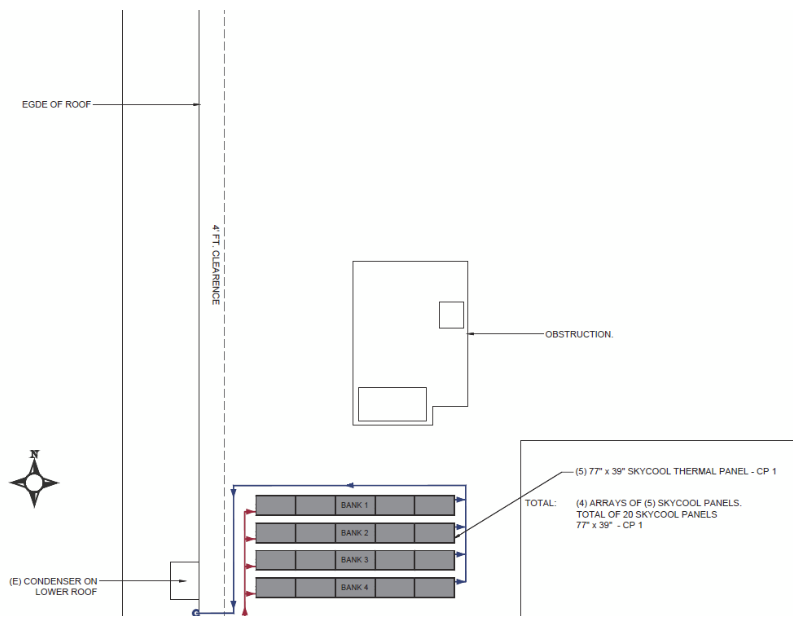

Figure 16: System Schematic for Fort Moore WSHP

- <u>System Integration</u>:

SkyCool Panels as a Passive Subcooler:

When SkyCool's panels are used as a passive subcooler, they should reduce the electricity consumption of a refrigeration system by 10% to 20%. The panels cool refrigerant leaving the condenser, and this increases the refrigerant's cooling capacity when it's expanded in the evaporator. As a result the refrigeration system has more refrigeration capacity for the same amount of electricity input.

Shown in Figure 17a is the cycle diagram for a typical vapor compression system with SkyCool panels. As a passive subcooler, a heat exchanger is added to the outlet of the condenser and cold fluid from the panels is used to cool the refrigerant beyond what the fans in the air cooled condenser can achieve. Shown in Figure 16b is a pressure enthalpy diagram when SkyCool panels are used as a passive subcooler. This shows that as subcooling is increased, the cooling capacity of the unit increases while the energy input to the system remains the same.

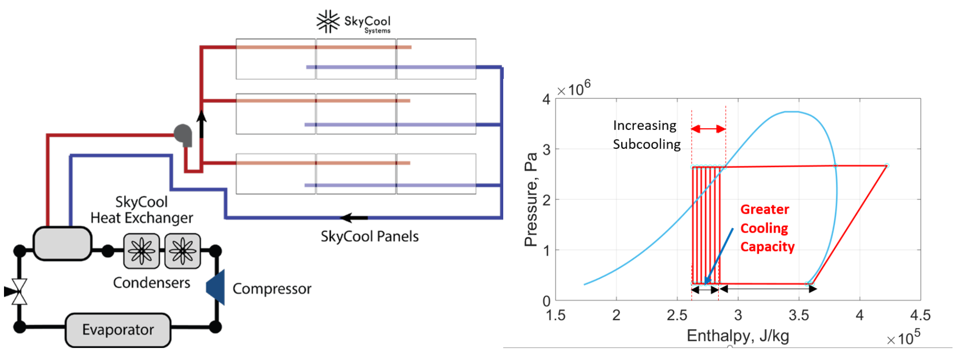

Figure 17: a) Vapor-compression diagram with a panel closed loop subcooling refrigerant out of the condenser; b) pressure-enthalpy diagram when additional subcooling is provided to the vapor compression cycle. This results in an increase in cooling capacity for the same energy input.

Failure Mode Effects Analysis-Subcooling

Our subcooling approach is designed to have minimal impact on the operation of the baseline cooling system if failure mode does occur. Adding the heat exchanger into the system is the only significant risk to the operation of the refrigeration system. While leaking refrigerant is a risk, it can be mitigated by testing the unit during the installation process. Additionally, adding in a brazed plate heat exchanger is a very common task for refrigeration technicians. While the severity of failure is high, it is easily detected and has a low probability of occurring.

SkyCool Panels as a remote condenser:

When SkyCool's panels are used as a remote condenser, the system should reduce the electricity consumption of the cooling system by 30% to 40%. The panels cool the refrigerant leaving the compressor to a much lower temperature and pressure than an air cooled condenser could achieve, reducing the energy input required by the compressor. Additionally, the energy to run a liquid pump in the SkyCool array is much less than the energy to run a fan in a traditional air cooled condenser. As a result the refrigeration system has more refrigeration capacity for the same amount of electricity input.

Shown in Figure 18a is the cycle diagram for a typical vapor compression system with SkyCool panels and in Figure 18b is a pressure enthalpy diagram when SkyCool panels are used as a remote condenser. This shows that as condensing temperature decreases, the cooling capacity increases and the energy input to the system decreases.

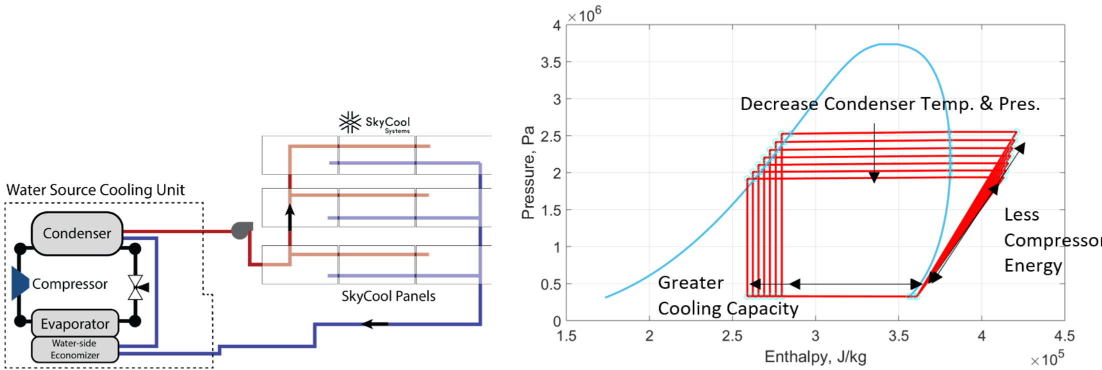

Figure 18: a) Vapor-compression diagram with panels used as a remote condenser; b) pressure-enthalpy diagram when the head pressure of the condenser is reduced.

FMEA-Condenser Replacement

Using the panels as a remote condenser has the promise of greater energy savings however at the same time, it means that the panels always need to be operational. Unlike the subcooling system, if there is a leak in the panel array, it will need to be remedied to ensure the cooling system can continue to function. In the future, we can have a make-up water port in the system to ensure that if there is a leak, the system will not stop functioning.

- System Controls:

For the proposed deployments, the subcooling and WSHP systems were managed locally by our points of contact at each base and they will each have different control systems. As the WSHP system is an off the shelf system manufactured by Trane Technologies, its control system is a basic thermostat which is located in the data closet room. The circulation pump in the system is be wired into the WSHP circuitry and will run whenever the WSHP unit is operating. For the subcooling system, the control strategy will be to turn the pump on and off to test the operation of the panels. The pump will have a switch on it, such that our local base contact can turn the pump on and off every two weeks. In the event of an emergency situation, the WSHP, and pump skids for the WSHP and subcooler will have electrical disconnects. Additionally, when the pump for the subcooling system is turned off, the refrigeration system will revert to its baseline level of energy usage.

6.4 OPERATIONAL TESTING

Below is a description of each significant operational phase in the work.

- Operational Testing of Cost and Performance:

Fill and drain procedure

SkyCool recommends charging the array with water-glycol using a force fluid purging method. This approach forces water through the system and drives out air that is in the panels and system piping. The panel array was charged with water-glycol using the fill/drain valve shown in the left panel of Figure 18. Note the valve has a fill valve, drain valve and a shutoff valve to block flow between the fill and drain. SkyCool provided a charge cart, shown in the right half of Figure 18, to fill the system. The charging cart has a reservoir, inlet and outlet ports, and pump to fill water into the array. Initially, as the system fills with water-glycol, air will exit the upstream port of the purge valve. Eventually, a stream of air and water will come out from the exit port and is carried back to the fluid reservoir in the charge cart. It is important to keep the end of the return hose in the charge cart reservoir under the liquid level in order to avoid creating bubbles that get pulled back into the charge cart pump.

Figure 19: left) Fill and drain assembly; right) charge cart

A flow velocity of at least 2 ft per second (FPS) is recommended to remove air from the system. Table 3 shows the water-glycol flowrate required to achieve 2 FPS for different pipe diameters.

Table 3: Flow rate requirements to achieve 2 FPS in a given pipe size

Tube size	Flow Rate to achieve 2 FPS
¾”	3.2 gpm
1”	5.5 gpm
1 ½”	11.4 gpm
2”	19.8 gpm

Data Collection:

Sensors collected data at a 1 minute sample rate automatically through the data collection platform. Data was reviewed over the test year to ensure all the sensors were working correctly. SkyCool personnel also communicated with local base contacts to ensure the systems are toggled on and off in order to collect baseline and test data.

- Modeling and Simulation:

SkyCool has developed a full suite of modeling tools that were used to predict the heat rejection capabilities of radiative cooling panels, as well as the energy use of WSHPs and refrigeration systems. Key inputs to the model are the ambient weather conditions at the site. To date, the models have been used to size arrays at over 15 sites.

6.5 SAMPLING PROTOCOL

- Data Collector(s): Data collection occurred via an automated platform. Data was collected every minute and stored on a secured server
- Data Recording: Data was collected every minute
- Data Description: We collected energy use, weather and thermal states of the refrigeration system.
- Data Storage and Backup: Each data collection box has the ability to store three to four days of data if the data link is broken. If power was lost at the site, data collection as well as the cooling systems, would stop operating.
- Survey Questionnaires:
- In order to ensure the cooling load in the testing space does not change, we are going to ask the site the following questions each quarter post installation:
  - Have any changes occurred to the operation of the room where the deployment is being conducted?
  - Have any new cooling systems been installed in the space where the test is being conducted?
  - What is the delivery schedule of product into the conditioned space?

- Have there been any changes to the food dining schedule?
- Have there been any changes to setpoints of the conditioned space?

6.6 SAMPLING RESULTS

Fort Moore WSHP:
For the IT closet at Fort Moore, SkyCool collected data from the summer of 2022 through the summer of 2023. Show in Figure 20 is the power of the baseline and WHSP unit over the performance period. The blue data is the power usage of the baseline unit and the orange data is of the WSHP unit. In addition to this data, SkyCool also measured the ambient temperature, suction and discharge pressure of both the baseline and WSHP units, and the indoor air temperature at the thermostat of the room.

In conversations with the site, there was indication of operational issues and variations with the heat generated by the IT equipment. While no formal survey data could be collected, the site staff indicated that often the datacloset doors were left open and heat was allowed into the room or cold air allowed to leave the room. Additionally, the site staff reported that the baseline unit struggeled to maintain the air temperature within the IT closet.

In Figure 22 and Figure 23, baseline power and energy use for the testing period is shown. For Figure 21, the power is plotted as a function of the ambient temperature, binned every 5°F. At temperatures below 55°F, the array was able to directly cool the air inside the data closet without the need of running a compressor. This led to a signficant reduction in power usage relative to the baseline system: 0.6 kW for the baseline unit vs 0.2 kW for the WSHP. The net power reduction at 90F was 20% and on average over all of the data, it was 51%. With this data, a correlation was created and used to estimate the energy usage over the entire testing period, including energy consumed by the circulating water pump(0.15 kW). Typically the pump power is a small percentage of the total power draw. In this case, since the number of panels and total cooling load were relativelys small, the pump power was a larger fraction of the site power usage. Typcially for commerical systems connected to ~100 tons of cooling capacity, the pump power is nominally 1 kW.

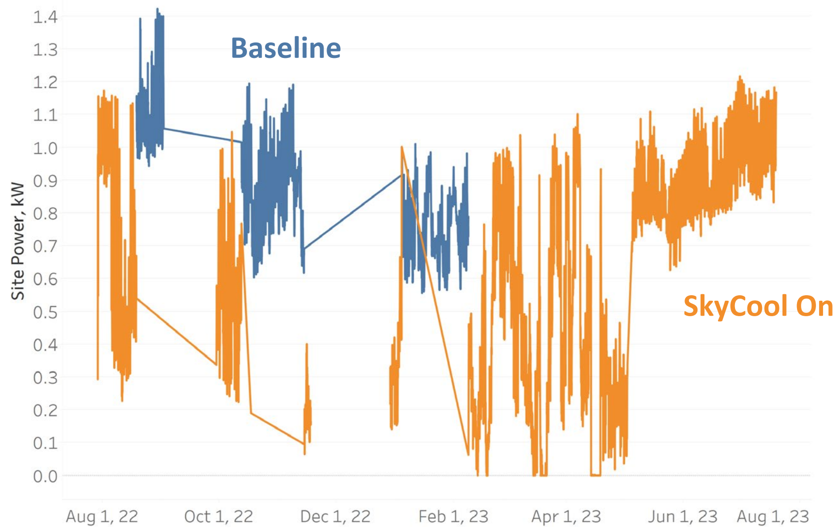

Figure 20: Site power vs time

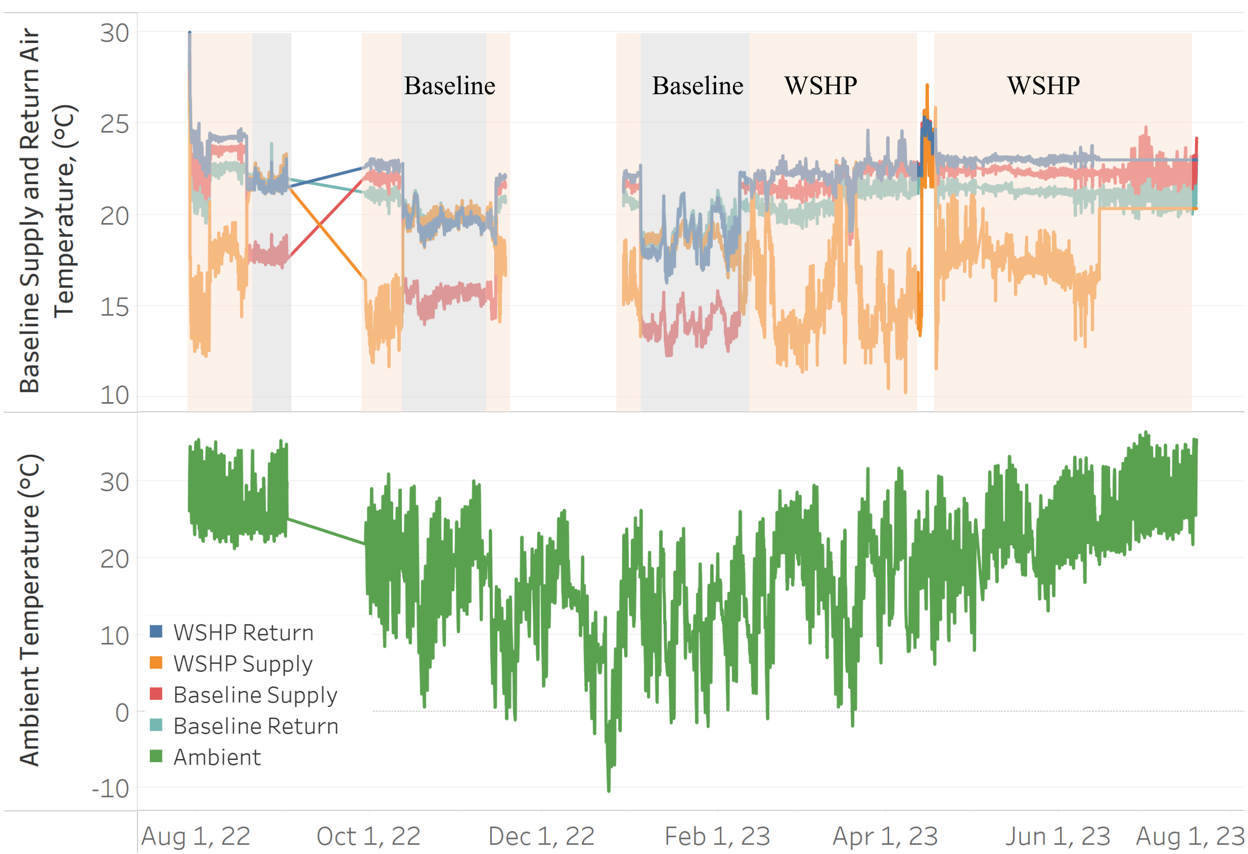

Figure 21: supply and return temperatures for baseline and WSHP unit within the data closet.

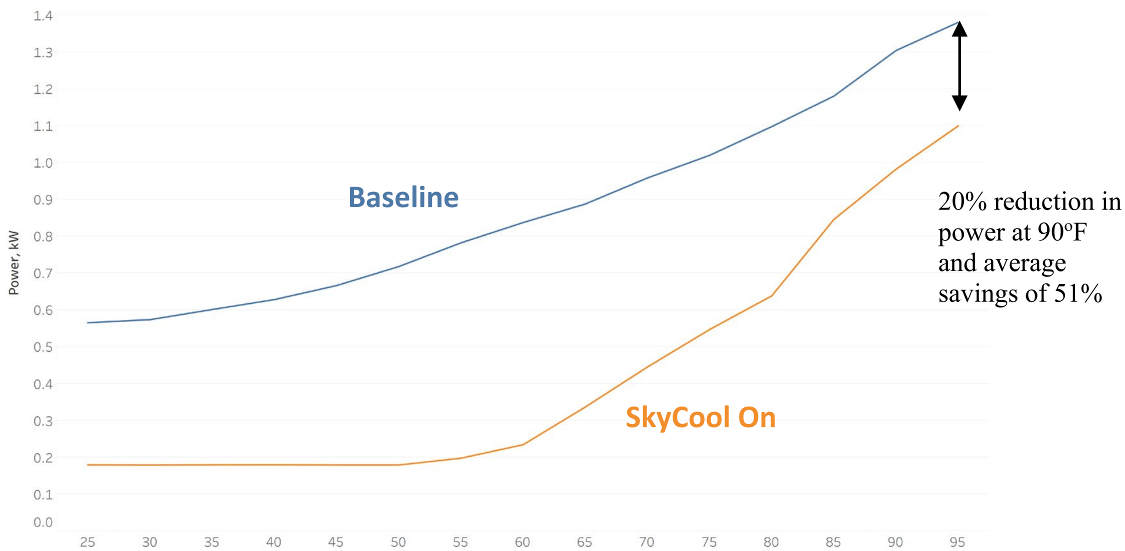

Figure 22: Binned power data of the baseline and WSHP unit's power vs ambient temperature (including circulating water pump power; 0.15 kW)

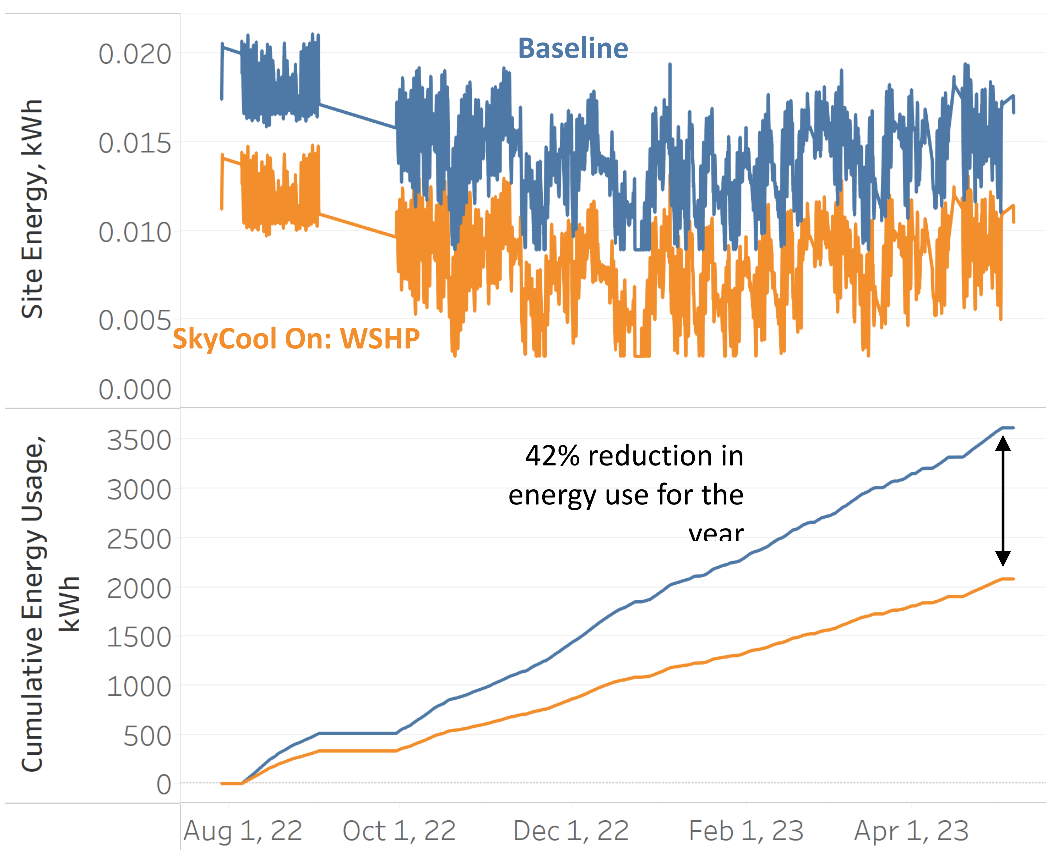

Figure 23: Energy usage vs time (including pump power; modeled)

Fort Moore DFAC

The follow section shows the power and energy measurements for the DFAC system at Fort Moore. Figure 23 shows the compressor and condenser fan power over the entire test period. Shown in Figure 24, is the power measurements for the compressor and condenser fan on the walk in cooler, along with the ambient temperature, and in Figure 27, the energy usage for the entire test period. The net power reduction at 90ºF was 15% and over the entire dataset 22%.

Subcooling adds capacity to the refrigeration unit while it is running and as a result, reduces the amount of time that the compressor needs to be on to provide the same amount of cooling. When our system was on, we observed that the compressor ran 30% less frequently as seen in Figure 24 for a day and then Figure 25 for the latter half of 2022. The power savings below about 65ºF is limited because the offset in energy savings is balanced by the energy penalty of the pump.

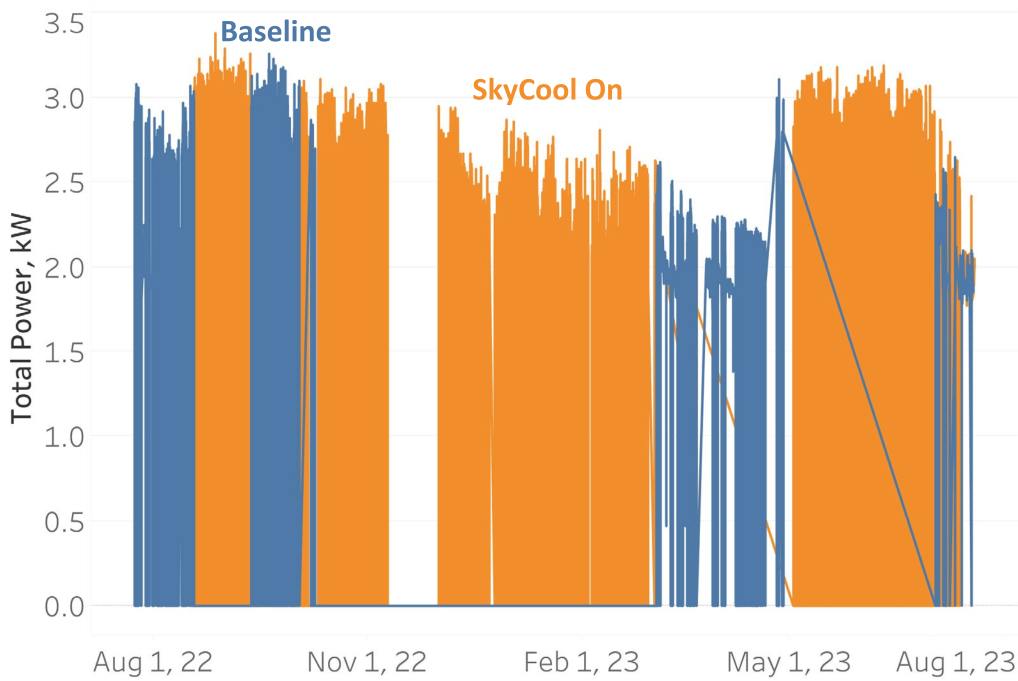

Figure 24: power vs time for the entire test period for the baseline and test conditions

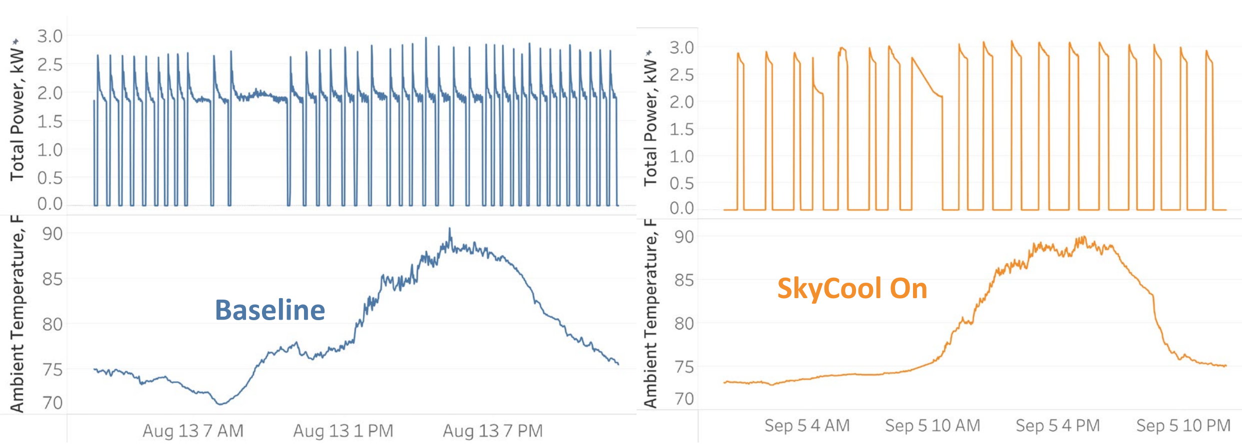

Figure 25: Total Power for the baseline system in Aug. 13th (left) and for the test period on Sept 5th (right) for two days with similar ambient temperature. Adding subcooling increases the cooling capacity of the unit and allows the compressor to run less frequently, as a result, the data shows that the compressors ran 33% less often.

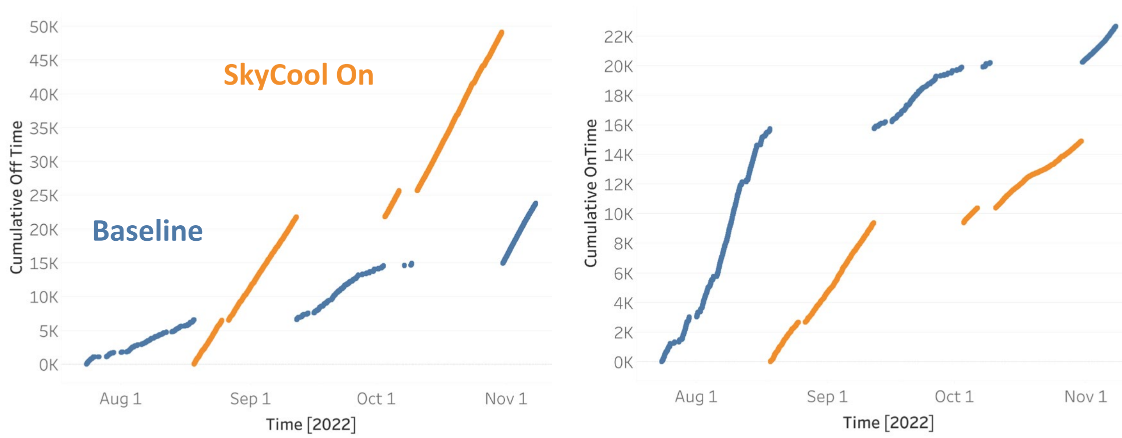

Figure 26: Compressor Off time minutes (left) and compressor on time (right). When the SkyCool array was running, the compressor needed to be on less often to maintain the walk-in-cooler at the desired set point conditions. The % off time for the baseline system was 51.2% and % off time for the SkyCool active test was 76.7%

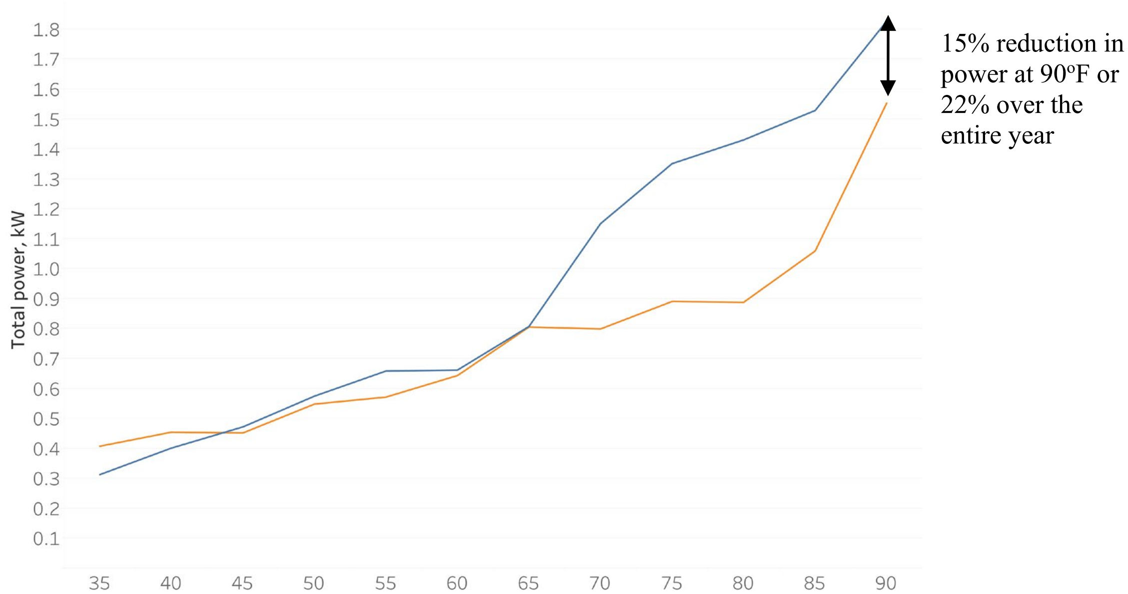

Figure 27: Averaged compressor and condenser fan power vs (binned, 5ºF) ambient temperature (including time when the unit was meeting its set point and excluding time when the system was not running); including pump power

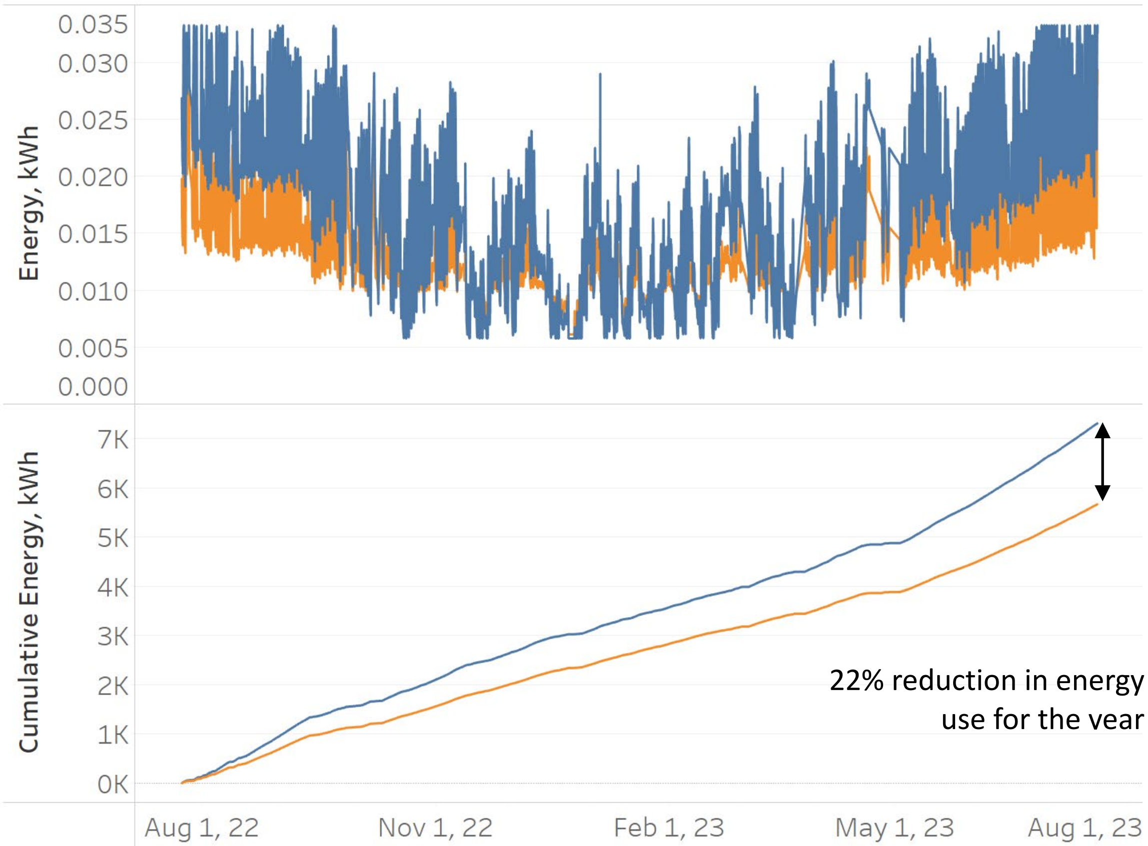

Figure 28: Energy Usage vs time (including pump power; integrated over the year); note greater energy savings occurs during hotter months and less during cooler months

7.0 PERFORMANCE ASSESSMENT

Table 4: Performance assessment Results

Performance Objective	Success Criteria	Results
Subsystem Energy Usage	10% to 20% reduction in compressor energy usage as a subcooler and 30% to 40% reduction as a condenser for a WSHP	Verified energy and power reduction for both the DFAC subcooler (42% energy reduction over the year and 24% power reduction at 90F) and WSHP (40% energy reduction over the year and 36% power reduction at 90F) replacement for a traditional split AC system
Runtime Reduction	10% to 20% reduction in compressor runtime as a subcooler	For the DFAC subcooler, directly measured a 33% reduction in runtime.
Direct Greenhouse Gas Emissions	10% to 20% reduction in GHG emissions as a subcooler and 30% to 40% as a condenser for WSHP	The GHG emissions reduction will be directly proportional to the amount of energy the system uses (See figures above)
System Economics	% Reduction in energy usage and total dollars saved per year	Direct energy savings (DFAC + WSHP): 7.2 MWh per year. Due to the high installation costs, and the relatively small system size, the net payback is greater than 20 years

In addition to these performance objectives, SkyCool also used the data collected from this and other sites to validate thermal models of our cooling panels. Figure 29 shows the relative heat rejection performance of a panel under different conditions (low and high humidity as well as clear sky, high clouds and middle clouds), as a function of the fluid temperature entering a panel relative to the ambient. The model, which was calibrated with test data from humid locations, indicates less sensitivity to higher humidity and greater sensitivity to cloud cover.

In general, while cloud cover and humidity hurt the performance of this technology, the energy savings is more dependent on its utilization (runtime) over an entire year. Environments with very low clouds a large fraction of the year, like Seattle, will be the most difficult to operate in but even in a humid location like the South East, as long as the cooling equipment runs year round, we believe our panels will financially make sense.

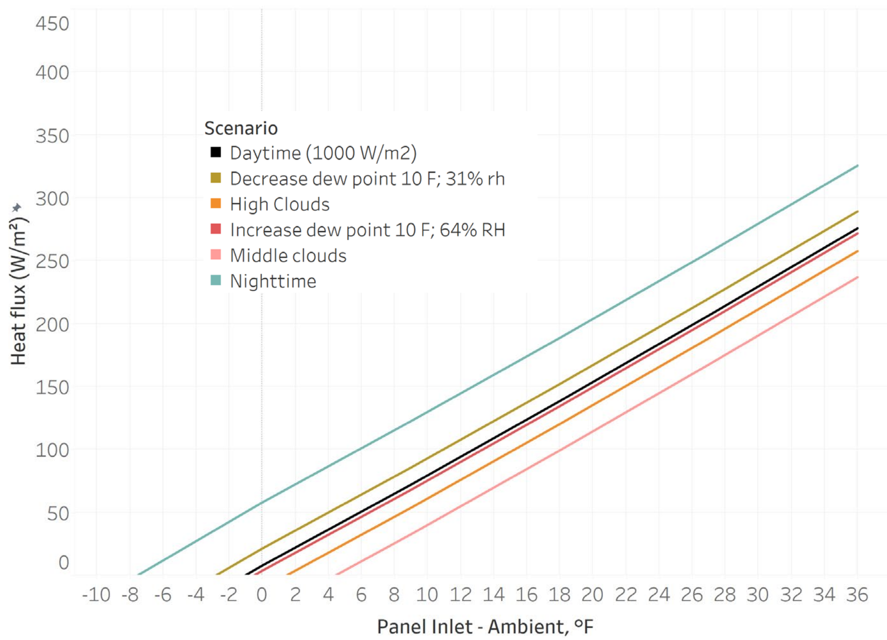

Figure 29: Panel heat rejection model as a function of low and high humidity environments

8.0 COST ASSESSMENT

The installed cost of SkyCool's panel systems can be split into fixed and variable costs associated with the number of panels deployed at a site. The larger the array, the greater the energy saved and the more the fixed costs can be spread out over the individual components, resulting in a faster ROI. Fixed costs include: project design, travel, installation labor for the heat exchanger, the pump skid, sensors, and commissioning. The variable costs include: panels, panel installation labor, pipe fittings, and racking.

For these two sites at Fort Moore, both the fixed and variable costs were high because: 1) the installation was timed during the peak of the pandemic when labor and basic materials were difficult to find, 2) the installation occurred over several phases due to inaccurate information about the site roof structure, and 3) there was a relatively large distance between the array and cooling unit in the data closet.

Additionally, the arrays at both sites were relatively small, consisting of 10 and 20 panels each. This means that there are fewer panels to spread the fixed costs per project over. Finally, the amount of energy offset by the array is small (even though it is a large percent reduction) because the baseline cooling systems had relatively low cooling loads (each less than 5 tons). We estimate the baseline energy use of these systems (combined) is nominally 6500 kWh per year. At $0.1 / kWh, the utility costs for these units are $650 and even if we saved all of the energy from these systems, the simple payback would be unacceptably high.

In order for the deployment to have a sub 5 year payback, the systems need to have cooling loads of greater than 50 tons or have a minimum of 50 panels, and need to run at least 80% of the time. The high runtimes will be true for datacenters and refrigeration systems and less likely to be applicable to AC systems in offices or dormitories.

8.1 COST MODEL

Below is a list of the key costs and breakdown of materials used in the system.

Table 5: Cost Element table

Cost Element	Data Tracked During the Demonstration	Estimated Costs
Hardware capital costs	Estimates made based on component costs for demonstration	$56,172
Installation costs	Labor and material required to install	$73,548
Consumables	Energy usage of the baseline systems, kWh	6500 kWh or $650 per year, assuming $0.1 / kWh
Facility operational costs	Reduction in energy required vs. baseline data	Reduced energy usage by 30%; 1960 kWh or $196 per year
Maintenance	• Frequency of required maintenance • Labor and material per maintenance action	Cleaning panels to maintain reflectivity ($500 / cleaning); Checking the pH of the glycol to maintain it at neutral levels ($300 every other year)
Hardware lifetime	Estimate based on components degradation during demonstration	15 years
Operator training	Estimate of training costs	N/A

8.1.1 Labor

A summary of the installation costs is listed in Table 6. The contractor labor for the project was billed at $140 per hour and the project took approximately 400 person hours to complete. In addition to the time at the site, additional costs in this category came in from travel to the site (per diem for workers & travel time), procurement of tools and for the crane / fork lift, to bring materials to the roof of the site.

Both the labor rate and # of hours to complete the project are very high relative to other projects we have completed. The drivers for the high number of hours is: 1) there was significant idle time where contractors were at the site but not able to get onto the roof, 2) there was significant travel time due to the project spanning several weeks (travel to the site on Monday and returning home on Friday; 8 hrs of drive time), 3) components were assembled at the site, instead of at a factory, 4) there were missing materials and the site labor needed to construct parts at the site to complete the job. Typical projects, which are much larger than these, take 3 to 5 days to complete with a 4 person crew. This is equivalent to $140 / hr x 8 hrs x 4 days x 4 people = $17,920.

Table 6: Summary of Installation Costs

Installation Costs	
Crane	$8,512
Site Install Labor	$55,685
Subcontractor Expense	$9,351
Description	**Cost**
Tools	$3,728
Travel	$9,861

8.1.2 Materials

The materials used in this system can be broken down into the following cost categories listed in Table 7. The dominant costs are for the panels, heat exchanger, pump racking and sensors. On a panel basis, the material component of the costs is $1800 per panel. In typical systems, the per panel installed cost is usually between $700 and $1500 per panel.

Table 7: breakdown of material costs

<u>Material Cost</u>	<u>% Breakdown</u>
Panels Cost	*27.77%*
Fittings	*7.28%*
Heat Exchanger	*12.21%*
Heat Exchanger Materials	*1.26%*
Insulation	*0.74%*
Insulation Covering	*3.78%*
Other	*0.44%*
Pipe Support	*2.40%*
Piping	*1.66%*
Pump Skid	*16.51%*
Racking	*10.85%*
Sensors	*15.10%*

8.2 Cost Drivers

A summary of the major costs is listed in Table 8. The key cost drivers for an array are:

- The size of the array
- The labor rate for installers
- If the array is ballasted or attached to a rooftop
- Distance between the array and cooling equipment

During the design and installation phase of this project, we had the added complication that the pandemic was just starting. As a result, it was very difficult to procure some basic plumbing components, as well as to secure a shipping container to store materials at the site. Since the beginning of the pandemic, we have standardized the parts in our system, started to pre-build components and no longer have the issues we did.

The labor rate we were billed during this project was $140 per hour and it took the tech's nearly 400 person-hours to complete the project, in addition to per diam costs. Any materials not sent to the site, and purchased by the installers were also subject to a 35% markup.

Table 8: Summary of the project costs

Materials Cost	$56,172
Installation Cost	$73,548
Shipping Costs	$4,545
Total	**$134,265**

8.3 COST ANALYSIS AND COMPARISON

The costs associated with this project were not representative of typical deployments. SkyCool has successfully installed lager arrays (50 to 100 panels) in 3 to 5 days. Figure 28 shows two such arrays that were deployed in 2023.

Figure 30: SkyCool arrays deployed in 2023; the left image shows an array of 100 panels and the right image an array of 70 panels

For HVAC/R systems that are at least 50 tons in size, on an open roof, the installation cost is typically between $700 and $1500 per panel installed, depending on the labor, the number of panels used in the system and the distance between the array and the heat exchanger.

9.0 IMPLEMENTATION ISSUES

The primary challenges that we faced during this project were related to: 1) the development stage of our product, 2) implementing a project during a global pandemic, and 3) communication between our contractors and the base. Specific implementation issues include:

- COVID related supply chain issues procuring relatively common materials like plumbing components and increasing the cost of shipping containers
- COVID related labor issues resulted in the need to work with contractors that were remote from this site
    - This added cost for travel time as well as per diem
- Two smaller sites that required one central location to store materials and it took time to transport materials from the storage site to the buildings
- Wrong rooftop drawings led to a pause in the installation
- Installation started during Thanksgiving and continued through the winter holidays leading to lots of travel to and from the site.

As a result of implementing our technology under this project, we have now standardized how we communicate scopes of work with contractors and now have several contractors that we regularly work with to implement our panel systems. A key failure early on in this project was around poorly defined scopes of work and misunderstandings of site conditions. As a result, there were several false starts, and a lot of idle time for the contractors., With our new approach, we have a higher degree of confidence around what can be completed at a site in a given period of time.

Additionally, as a result of this project, we no longer will implement systems that are smaller than 50 panels, and require that panels be installed in rows of 10 panels each. By standardizing around 10 panel rows, we can pre-build and kit all the materials at our warehouse, thus increasing the likelihood of all the required parts being delivered to the site. During this project, we missed shipping several items to the site and only found out about the missing parts, when they were needed by the installing contractor. As a result, the contractors had to make several trips to a local plumbing shop. While a majority of the components in our system can be procured locally, it is very expensive and takes a lot of time for a contractor to leave the site, find the part and return to the site. If the part is critical, it can also stop work for the other contractors working on the same portion of the project. Along with the materials in our system, we also now have a standardized toolbox that also ships to a site, and reduces the risk of a key tool not being available.

10.0 KEY ADDITIONAL PROJECT RESULTS

Case studies summarizing the results of this work will be published at www.SkyCoolSystems.com

11.0 Appendix A: Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Eli A Goldstein	SkyCool Systems, Inc	eli@skycoolsystems.com	Principal
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Teresa Peters	SkyCool Systems, Inc	teresa@skycoolsystems.com	Engineer
Todd Krawjewski	SkyCool Systems, Inc	todd@skycoolsystems.com	Engineer
Justin Andrea	SkyCool Systems, Inc	justin@skycoolsystems.com	Project Manager