CALIFORNIA ENERGY COMMISSION

ENERGY RESEARCH AND DEVELOPMENT DIVISION

FINAL PROJECT REPORT

Radiative Sky Cooling-Enabled Efficiency Improvements on Commercial Cooling Systems

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission, and distribution and transportation.

In 2012, the Electric Program Investment Charge (EPIC) was established by the California Public Utilities Commission to fund public investments in research to create and advance new energy solutions, foster regional innovation, and bring ideas from the lab to the marketplace. The EPIC Program is funded by California utility customers under the auspices of the California Public Utilities Commission. The CEC and the state's three largest investor-owned utilities—Pacific Gas and Electric Company, San Diego Gas and Electric Company, and Southern California Edison Company—were selected to administer the EPIC funds and advance novel technologies, tools, and strategies that provide benefits to their electric ratepayers.

The CEC is committed to ensuring public participation in its research and development programs that promote greater reliability, lower costs, and increase safety for the California electric ratepayer and include:

- Providing societal benefits.
- Reducing greenhouse gas emission in the electricity sector at the lowest possible cost.
- Supporting California's loading order to meet energy needs first with energy efficiency and demand response, next with renewable energy (distributed generation and utility scale), and finally with clean, conventional electricity supply.
- Supporting low-emission vehicles and transportation.
- Providing economic development.
- Using ratepayer funds efficiently.

Radiative Sky Cooling-Enabled Efficiency Improvements on Commercial Cooling Systems is the final report for EPC-18-006, conducted by SkyCool Systems, Inc.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the Energy Research and Development Division at ERDD@energy.ca.gov.

ABSTRACT

Global warming has already resulted in greater cooling system energy loads and more days per year with a demand for cooling. Peak summer temperatures are often 3 to 5 degrees Fahrenheit warmer than they were 10 years ago. As ambient temperatures continue to rise, refrigeration and air conditioning systems will become less efficient, and the demand for cooling will increase as more people install and run air conditioning to stay cool. SkyCool Systems has pioneered a passive cooling panel that uses multilayer reflective optical film to cool fluids with zero input electricity and without evaporating water. The panels can be connected to any air conditioning or refrigeration system to improve efficiency and cooling capacity. SkyCool Systems installed its energy-saving, capacity-improving panel arrays at two California supermarkets.

At the first site, located in Red Bluff, California, SkyCool Systems installed an 80-panel array to precool the supermarket's refrigeration system. The array added 30 to 45 kilowatts of additional heat rejection to the site's air-cooled condenser and resulted in 50 pounds per square inch lower compressor discharge pressures. This yielded a maximum energy savings of 15 percent and lowered the peak demand for the refrigeration system by 5 to 7 kilowatts. Additionally, the site's rooftop condenser needed to be cooled with water from a sprinkler to increase its capacity in the summer. With the addition of the array, the site was able to remove the sprinkler from the roof, saving tens of thousands of gallons of water each year.

At the second site, located in Milpitas, California, SkyCool Systems installed a 60-panel array that subcooled the refrigeration system when the ambient air temperature was lower than 75 degrees Fahrenheit and precooled the condenser the rest of the year. When the subcooler was operating, SkyCool Systems was able to add 10 to 25 degrees Fahrenheit of additional subcooling, resulting in a 15- to 20-percent reduction in energy usage. When the precooler was running, the array was able to add 25 to 30 kilowatts of additional capacity to the condenser, lowering the power demand in the summer by 3 kilowatts. The array resulted in nearly 20,000 kilowatt-hours of energy saved.

Keywords: Radiative cooling, efficiency, passive, refrigeration capacity, air conditioning

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Executive Summary

As ambient temperatures increase because of global warming, more energy and power will be needed to run cooling systems. This increase in power places a large strain on the utility grid and, if unchecked, could result in brownouts or blackouts for much of California. In addition, many existing commercial air conditioning and refrigeration systems were not sized for the high ambient temperatures of today. As a result, air conditioning and refrigeration systems will have more frequent compressor failures and may not cool when they are needed the most, resulting in thermal stress on people and wasted food during heatwaves.

SkyCool Systems (SkyCool) has pioneered a passive cooling technology that uses multilayer reflective optical film to keep surfaces cool, with zero input electricity and without evaporating water. With support from the California Energy Commission, SkyCool was able to demonstrate its first product, a cooling panel, as a means to add capacity and improve the efficiency of air conditioning or refrigeration systems. Under this project, arrays of panels were installed at two supermarkets: one serving a disadvantaged community in Red Bluff, California, and a second in Milpitas, California.

The Red Bluff site was selected because the supermarket was having condenser issues in the summer and was representative of many small to medium grocery store operators across the state and country. The site's condenser, installed in 2018, was not able to sufficiently cool when the ambient temperature was hotter than 100 degrees Fahrenheit, resulting in the store's refrigeration system shutting down. To address this, SkyCool installed a panel array as a precooler to the condenser. The objective of the installation was to add heat rejection capacity to the condenser and save energy and power during the hottest times of the summer.

As ambient temperatures continue to rise, refrigeration and air conditioning systems will become less efficient, and the demand for cooling will increase as more people install and run air conditioning to stay cool. Researchers estimate that higher temperatures will require up to 31 percent more peak generation capacity to power and meet the added demand on the grid (Sathaye, 2013). California has more than 4,500 grocery stores. Collectively, grocery stores consume more than 330 megawatts of power, and refrigeration systems need to run continuously. Targeted measures to reduce power usage of cooling equipment are needed to minimize the amount of added generation capacity and battery backup systems the state needs to procure under Senate Bill 100 (De León, Chapter 312, Statutes of 2018).

Project Purpose and Approach

This project had the following goals:

- Minimize the risk for SkyCool's passive panel technology by installing it at two sites
- Show that SkyCool's array could reduce energy usage in refrigeration systems by at least 10 percent
- Demonstrate that SkyCool's panels can be scaled throughout California

Initially, the project considered applications in both commercial refrigeration and heating, ventilation, and air conditioning (HVAC) applications. However, through customer conversations, SkyCool pivoted away from HVAC because many commercial buildings only run HVAC systems in the summer, and a key feature of SkyCool's cooling panels is that they can cool continuously. There are many cooling applications that run year-round, and grocery store refrigeration systems are a great fit because of their large and persistent refrigeration loads, open roof space, and large number of sites in California.

Key Results

SkyCool installed its energy-saving, capacity-improving panel array at two supermarkets in California. The first site was in Red Bluff, California, where an array was used to add modular heat rejection capacity to an underperforming condenser. SkyCool's array increased the heat rejection of the refrigeration cycle by 35 kilowatts (34 percent) and lowered the discharge pressure of the condenser by up to 50 pounds per square inch, gauge. As a result of the added capacity, the power demand for the refrigeration system was reduced by 5 to 7 kilowatts, and a maximum energy savings of 15 percent was achieved. Additionally, the array allowed the site to stop spraying the condenser with water from a sprinkler, saving tens of thousands of gallons of water annually.

At the second site in Milpitas, California, SkyCool demonstrated an array that could both subcool, adding efficiency during cooler times of the year, and precool, adding condensing capacity during the hotter times of the year. The array increased the heat rejection of the refrigeration system by 25 kilowatts (27 percent) and lowered the electrical demand of the medium-temperature compressors by 3 kilowatts. When the ambient temperature was lower than 75 degrees Fahrenheit (24 degrees Celsius), SkyCool's array was able to add between 10 to 25 degrees Fahrenheit (6 to 14 degrees Celsius) of additional subcooling, which improved the efficiency of the refrigeration system by 14 percent. The net benefit of SkyCool's panels saved nearly 20,000 kilowatt-hours per year.

There are more than 4,500 grocery stores in California, and assuming half of them have cooling systems similar to those at the Red Bluff and Milpitas sites (air-cooled condensers) and have nominal peak power demand of 100 kilowatts, then deploying SkyCool panels at 10 percent of these stores would result in a peak demand savings of 6.75 megawatts electric. If scaled across 10 percent of stores in California, the panels would save nearly 38,438 megawatt-hours[1] of electricity per year and reduce the risk of refrigeration systems failing during heat events. Maintaining sufficient refrigeration for food during a heatwave could result in potential savings as high as $50,000 per grocery store.

Knowledge Transfer and Next Steps

From these two successful demonstrations, SkyCool developed case studies and will publicize the results at tradeshows and other industry conferences. Data from these pilots will be developed into a whitepaper that can be shared with California investor-owned utilities, with the goal of developing prescriptive incentives. Additionally, these two demonstrations allowed

[1] SkyCool Systems estimate.

SkyCool to build out more detailed cost models for labor and materials, which are helpful for selling pilot demonstration systems to new customers.

SkyCool will continue to complete pilot deployments of panel systems in grocery stores. The team is working toward commercial contracts where it can complete larger rollouts of array systems with grocery stores in California and across the United States. Now that SkyCool has proven the ability of their panels to reject heat and has standardized the panel product, the team can explore applying panels to larger applications like cold storage and data centers.

CHAPTER 1: Introduction

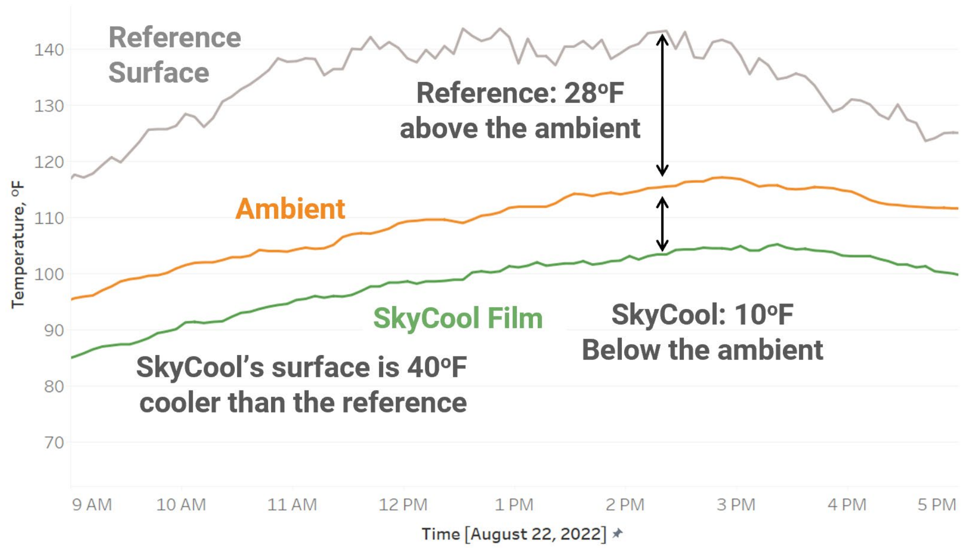
As air temperatures rise because of global warming, vapor compression air conditioning and refrigeration systems will become less efficient. Additionally, cooling will be more critical to maintaining thermal comfort of building occupants, maintaining food at safe temperatures within cold chains (refrigerated trucks and rail cars, cold storage warehouses, and grocery story refrigeration), and cooling computers in data centers.

In 2012, with United States Department of Energy (U.S. DOE) Advanced Research Projects Agency - Energy (ARPA-E) support, the SkyCool Systems (SkyCool) founding team began researching ways to enable radiative sky cooling during the day (Raman, 2014). 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 feet by 6 feet and deployed on the rooftops of buildings using racking from the solar industry. A fluid is pumped through the panels, which cools passively and continuously, even when the panel is under direct sunlight. In typical deployments the panels are connected in a closed loop, reverse return layout, ensuring a uniform flow distribution through the panels.

Passive daytime radiative cooling (PDRC) is one of a handful of new technologies to emerge that can improve the efficiency of existing cooling systems (air conditioning and refrigeration) and reduce the energy requirements for buildings. PDRC is enabled by a film that is highly reflective of energy from the sun and simultaneously emissive of energy in the infrared spectrum. Based on the properties of Earth's atmosphere, the energy emitted from SkyCool's film can go through much of the atmosphere and exchange energy with the cold sky. As a result, when left outside, SkyCool's film will be cooler than the ambient air temperature (abbreviated hereafter as "ambient"), even under direct sunlight.

Data collected from Palm Desert, in Southern California, are shown in Figure 1. The plot shows the measured temperature of the film, a white reference surface, and the ambient over the day. Based on the unique optical properties of SkyCool's film, the surface temperature is 10 degrees Fahrenheit (°F) (6 degrees Celsius [°C]) below the ambient, and 40°F (22°C) cooler than a reference white surface.

Figure 1: Temperature Measurement of SkyCool's Film in Palm Desert, California

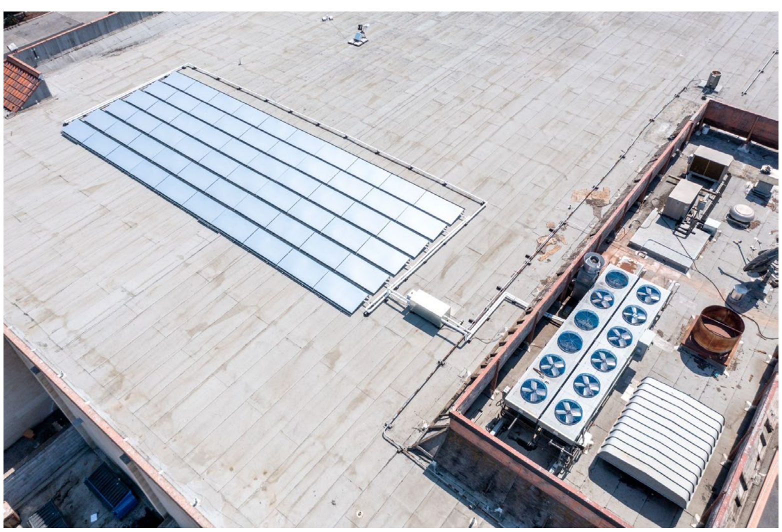


Source: SkyCool Systems

Having a material that can stay cooler than the ambient, even under direct sunlight, can have significant implications on the utility grid and the planet. At a global level, using the film as a roof or façade material can result in the passive cooling of cities and the end of heat islands. Heat islands raise temperatures by between 1°F and 7°F (0.6°C and 4°C) and result in increased energy use for heating, ventilation, and air conditioning (HVAC) as well as increased heat stress or heat-related deaths. When used with heating, ventilation, air conditioning, and refrigeration (HVAC/R) systems, the material can reduce energy use for cooling by 10 to 30 percent.

SkyCool's first product is a rooftop fluid-cooling panel (Figure 2) that employs a PDRC film to cool water that enters the panels. Cold water from the panels is then used to precool or subcool refrigerant entering or leaving condensers of refrigeration equipment.

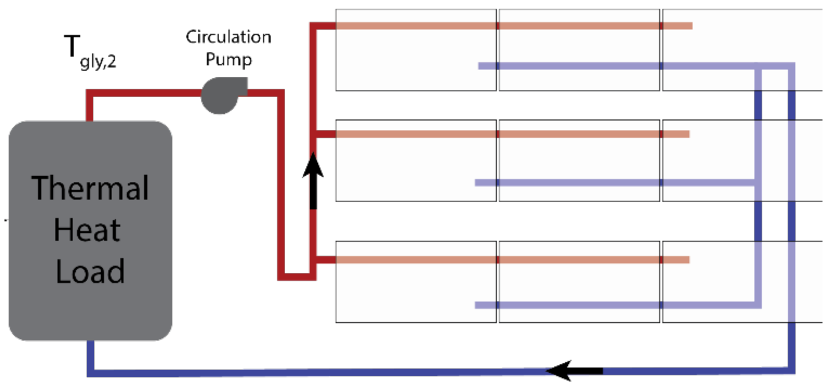
Figure 2: SkyCool Array Installed at the Milpitas, California Site



Source: SkyCool Systems

SkyCool's panels reject heat to the sky by thermal radiation. 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 continuously. Figure 3 shows a schematic of a SkyCool panel array.

Figure 3: Schematic of Panel Array

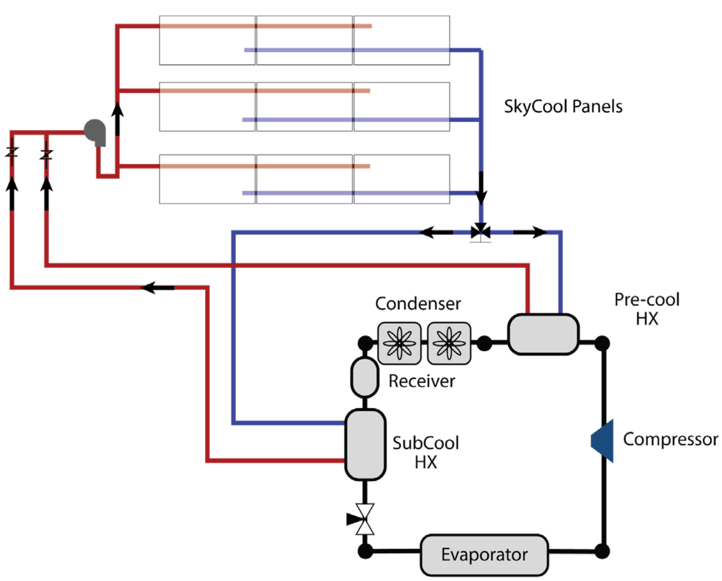


Panels are connected in parallel and only require a small circulating water pump to deliver cooling to a load. A reverse return layout ensures uniform flow through each panel. Blue lines are cold water leaving panels and red lines are hot water entering the panels.

Source: SkyCool Systems

The integration of the array with both subcooling and precooling heat exchangers is shown in Figure 4. Heat exchangers are relatively common in refrigeration systems and can be installed in two to four hours.

Figure 4: Typical Integration Schematic



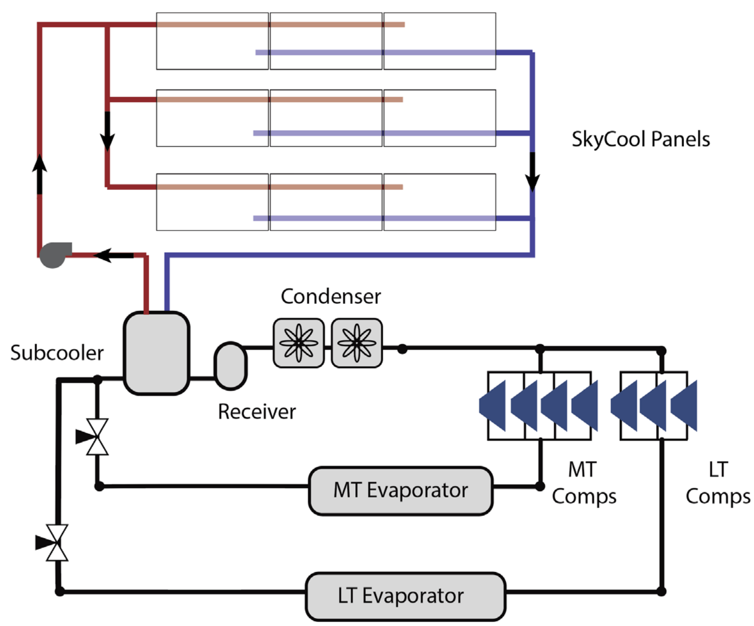
Typical integration of power, discharge pressure, and drop leg versus ambient.

Source: SkyCool Systems

Passive Subcooling with SkyCool Panels: How it Works

Subcooling occurs when refrigerant is cooled below the saturated liquid temperature of the condenser. By subcooling the refrigerant below the saturation temperature, the cooling capacity of the refrigerant in the evaporator is increased when it is expanded in the evaporator. As a result, more cooling can be achieved for the same electricity input to the system, or less electricity is needed to provide the same amount of cooling. Nominally, for every 1°F (0.6°C) of subcooling, the cooling capacity of the refrigerant increases by 0.5 percent (ASHRAE, 2024). Additional subcooling is desirable and could dramatically improve efficiency. However, additional subcooling to subambient temperatures is often not practical because it requires a secondary chiller (mechanical subcooling). Mechanical subcooling requires running a separate compressor or flowing more refrigerant through the existing compressors. This increases the electricity consumed by the system and, on average, only provides marginal improvement. Subcooling is a Title 24 requirement for low-temperature freezers but is not implemented on medium-temperature (35°F to 40°F [2°C to 4°C]) and high-temperature (50°F to 60°F [10°C to 16°C]) cooling systems. SkyCool achieves subcooling by installing a brazed plate heat exchanger after the receiver and before the expansion valves in the refrigeration system (Figure 5).

Figure 5: Vapor Compression System with SkyCool Subcooler

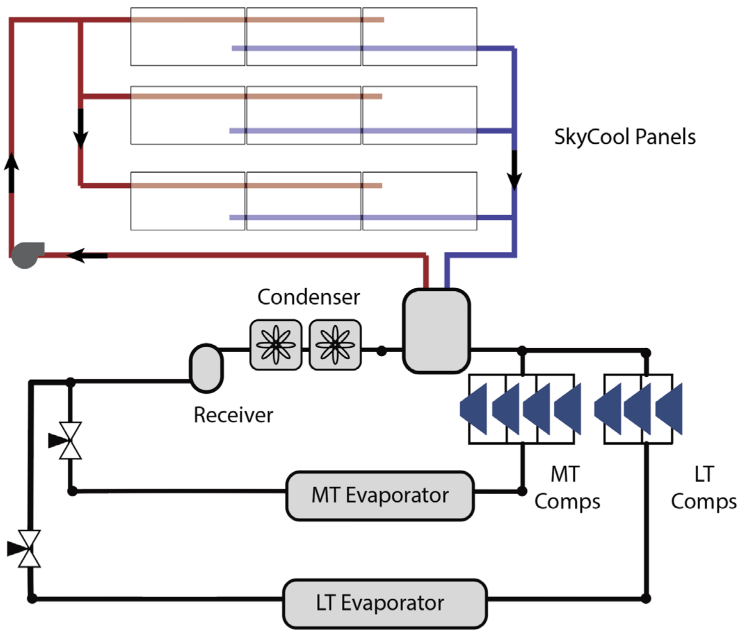


Source: SkyCool Systems

Passive Precooling with SkyCool Panels: How it Works

Precooling provides additional heat rejection capabilities on the condenser side of the refrigeration system. Precooling is implemented by installing a heat exchanger after compressors or before the condenser in the refrigeration system (Figure 6). Precooling will have the biggest impact on condensers that are aged or undersized. For these underperforming condensers, precooling will lower saturation discharge pressure, and this will reduce power usage and improve the cooling capacity of the refrigeration system. For refrigeration systems with evaporative condensers, this can reduce water usage by up to 40 percent, and for transcritical[2] carbon dioxide systems, precooling can reduce the number of transcritical operating hours by up to 100 percent.

Figure 6: Precooling Integration

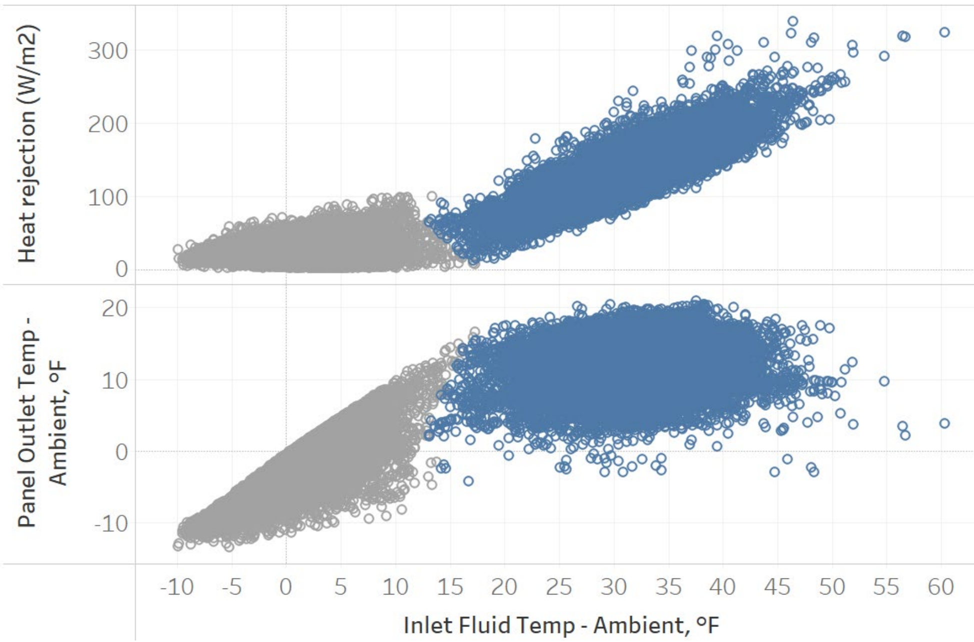


Source: SkyCool Systems

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. Data from the Milpitas site demonstrate the heat rejection capabilities as a function of approach temperature (inlet fluid temperature minus the ambient) (Figure 7). As the fluid gets hotter relative to the ambient, greater heat rejection occurs. A notable feature of this technology is that even with the fluid entering the panel at the ambient (that is, 0-degree approach with the ambient), cooling can still occur.

[2] A refrigeration system where the discharge pressure and temperature are above the critical point. The critical point is the state where one can't distinguish between vapor and liquid.

Figure 7: Panel Heat Rejection

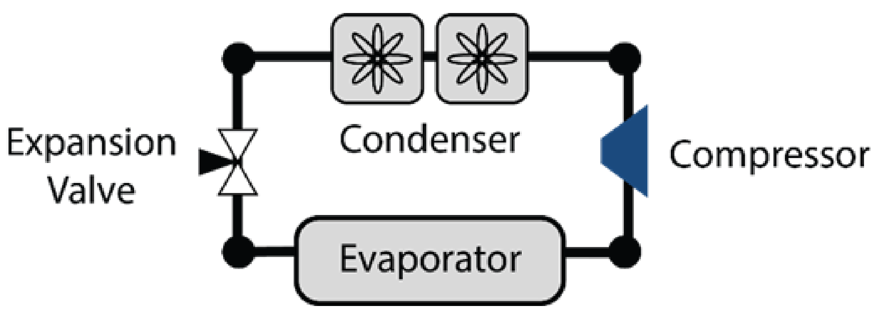


Panel heat rejection and panel outlet temperature - ambient as a function of the inlet fluid temperature relative to the ambient; subcooling mode in gray and precooling mode in blue; Milpitas site panel array.

W/m2=watts per square meter
Source: SkyCool Systems

The vast majority of cooling systems are based on vapor compression cycles. Regardless of whether the end application is in air conditioning or refrigeration systems, vapor compression cycles have four main components: compressors, condensers, evaporators, and expansion valves. An example vapor compression system is shown in Figure 8.

Figure 8: Vapor Compression Cycle



Vapor compression cycle showing four main components: compressor, condenser, evaporator, and expansion valve.

Source: SkyCool Systems

In most cooling systems (where thermal loads are less than 100 tons), fans blowing dry air are used to cool refrigerant in the condensers. While air-cooled condensers are very simple, one big drawback 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.

An ever-growing challenge for the installed air-cooled vapor compression systems is that summer ambient temperatures are rising beyond the designed capacity of many condensers. Rising temperatures will lead to less efficient cooling systems but also greater demand for cooling. As a result, energy usage for cooling is expected to grow two to four times in the coming years, placing a large strain on the utility grid in the summers, making it more costly to deploy renewables to meet summer loads, and resulting in higher costs for California ratepayers.

CHAPTER 2: Project Approach

A key barrier to developing a new cooling technology is that there are a lot of perceived risks and limited performance data. Additionally, there are a lot of unknowns that make it difficult to estimate savings, costs, and value. The goals of this project were to minimize the risk from SkyCool's passive panel technology by installing it at two sites, show that SkyCool's array could reduce energy usage in refrigeration systems by at least 10 percent, and demonstrate that SkyCool's panels can be scaled throughout California. Initially, the project considered applications in both commercial HVAC and HVAC/R applications. However, after customer conversations, the team pivoted away from HVAC because many commercial buildings only run HVAC systems in the summer, and a key feature of SkyCool's cooling panels is that they can cool continuously. Many cooling applications run year-round, and grocery store refrigeration systems are a great fit because of their large and persistent refrigeration loads, open roof space, and large number of sites in California.

For this project, SkyCool partnered with two organizations: Interface Engineering to support project design, and Electric Power Research Institute (EPRI) to support measurement and verification for the projects. Because of changes in project scope, Interface Engineering had limited involvement in the final installations. EPRI played a critical role in developing the measurement and verification plan for the project; however, it had limited involvement in the final analysis because of a lack of available project funds.

To validate the performance benefit of add-on products in the cooling systems, data were collected over a long time to characterize variability in the system. This is generally because there are many different independent variables that can alter the performance of a cooling system. These include factors such as varying weather conditions but also different cooling loads on the equipment (for example, days with high sales versus low sales), degradation of equipment (for example, a failing fan or leaking refrigerant), and different controls settings.

To evaluate the addition of panels, SkyCool toggled the array pump on and off periodically and measured the refrigeration system's power consumption and cooling capacity over time. Then the team normalized the data for the local weather conditions (and other variables that can be held constant) and developed an appropriate comparison of performance before and after the technology was installed. Unlike most products that are used with cooling systems, one can easily turn the circulating water pump on versus off and measure the changes that occur in cooling capacity and power consumption of the refrigeration system.

Key milestones for the project were:

- Creating system layouts for panels integrated with commercial refrigeration systems
- Installing the system at two sites
- Collecting data demonstrating the benefits of the panels
- Creating case studies and developing a plan to scale projects across California and the world

As these deployments were the first of their kind, a lot of effort was spent figuring out how to simplify the installation process. Arrays were designed to look like solar arrays, such that the methods used to install panels are the same as those used by solar installers. To reduce time spent on roofs, many of the components in the system were preassembled offsite.

CHAPTER 3: Results

SkyCool installed its energy-saving, capacity-improving panel array at two supermarkets under this project. The first site was in Red Bluff, California, and the second site was in Milpitas, California.

The Red Bluff site was selected because it was having condenser issues in the summer. To address the issues, SkyCool installed a panel array as a precooler to the condenser. The objective of the installation was to add heat rejection capacity and prevent the need to replace the condenser. For the Milpitas site, in addition to installing a precooler heat exchanger, which is run when the ambient is warmer than 75°F (24°C), the team also installed a subcooler heat exchanger to improve the efficiency of the rack when the ambient temperature is lower than 75°F (24°C).

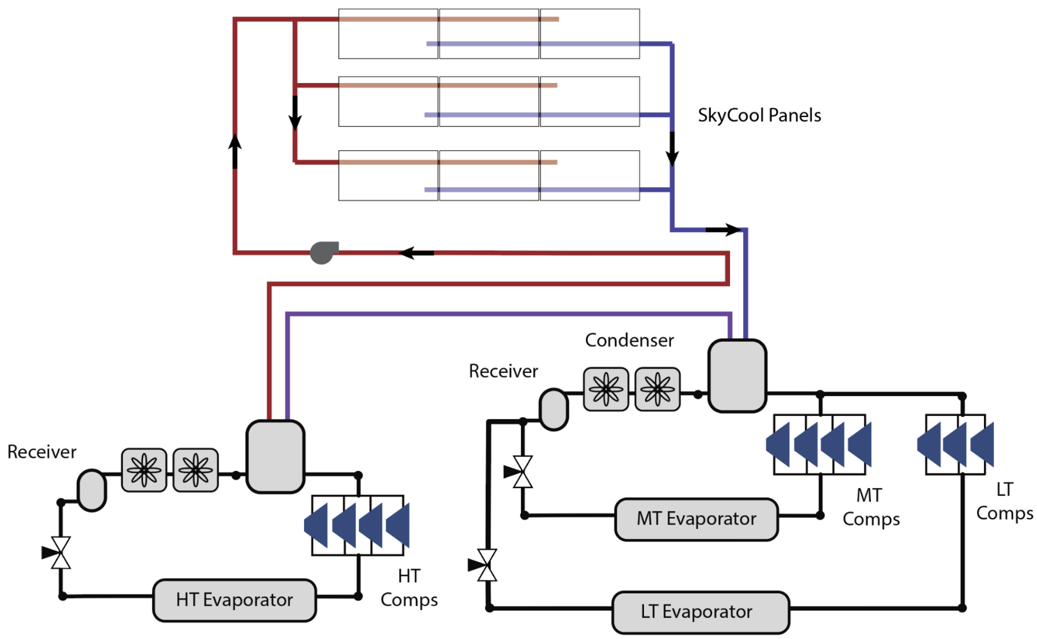
At the Red Bluff site, SkyCool's array increased the heat rejection of the refrigeration cycle by 30 to 45 kilowatts (kW) (34 percent) and lowered the discharge pressure of the condenser by up to 50 pounds per square inch, gauge (psig) relative to the sprayed condenser—or 50 to 75 psig relative to the existing condenser without being sprayed with water using a sprinkler. As a result of the added capacity, the demand for the refrigeration system was reduced by 5 to 7 kW, and a maximum energy savings of 15 percent was achieved. Additionally, the array allowed the site to stop spraying the condenser with water from a sprinkler, thereby saving water. Over the test period, the array saved 27,000 kilowatt-hours (kWh) of electricity.

For the Milpitas site, in addition to installing a precooler heat exchanger, which is run when the ambient temperature is warmer than 75°F (24°C), the team also installed a subcooler heat exchanger to improve the efficiency of the rack when the ambient temperature is lower than 75°F (24°C). As a result, the array increased the heat rejection of the refrigeration system by 25 kW (27 percent) and lowered the electrical demand of the medium-temperature compressors by 3 kW. When the ambient temperature was lower than 75°F (24°C), SkyCool's array was able to add between 10°F to 25°F (6°C to 14°C) of additional subcooling, which improved the efficiency of the refrigeration system by 14 percent. The net benefit of SkyCool's panels was saving nearly 20,000 kWh per year.

Red Bluff Site

At the Red Bluff site, SkyCool installed 80 panels with a precooler configuration for both the low-temperature, medium-temperature, and high-temperature (specifically, air conditioning) circuits of the condenser (Figure 9). Figure 10 shows the heat exchangers and condenser circuit piping, and Figure 11 shows the installed array at Red Bluff.

Figure 9: Red Bluff, California Site System Diagram



HT = high-temperature compressors, MT = medium-temperature compressors, LT = low-temperature compressors
Source: SkyCool Systems

Figure 10: Photo of SkyCool Heat Exchangers Being Installed

Source: SkyCool Systems

Figure 11: Photo of the SkyCool Array at Red Bluff Site

Source: SkyCool Systems

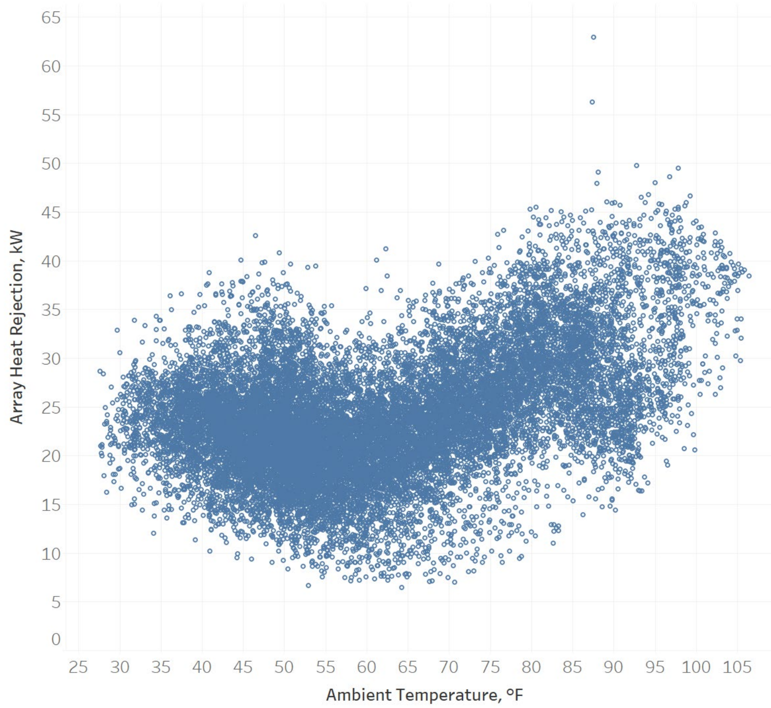
Panel and Refrigeration System Data, Red Bluff

At the Red Bluff site, SkyCool precooled the supermarket's air-cooled condenser to increase its capacity. Figure 12 shows the heat rejected by the array as a function of the ambient. Figure 13 shows the discharge pressure, dropleg-ambient[3], and power consumption for two similar days at the Red Bluff site. From the panel showing the dropleg-ambient, the impact of spraying the condenser can be seen, resulting in a significant amount of additional subcooling and lowering the discharge pressure by 20 to 35 psig. When the array is operating relative to the sprayed condenser, SkyCool can further reduce the discharge pressure by 40 to 50 psig.

Prior to the project, the site's air-cooled condenser had a sprinkler under it to increase its capacity in the summer. A sprinkler was only used in the summer when the array was not operating (baseline conditions). Figure 14 shows the measured drop leg temperature relative to the ambient and the discharge pressure as a function of time, when the sprinkler was being used. The addition of the sprinkler not only adds considerable subcooling to the system, but it also lowers the discharge pressure by 25 to 35 psig, resulting in measured demand reduction.

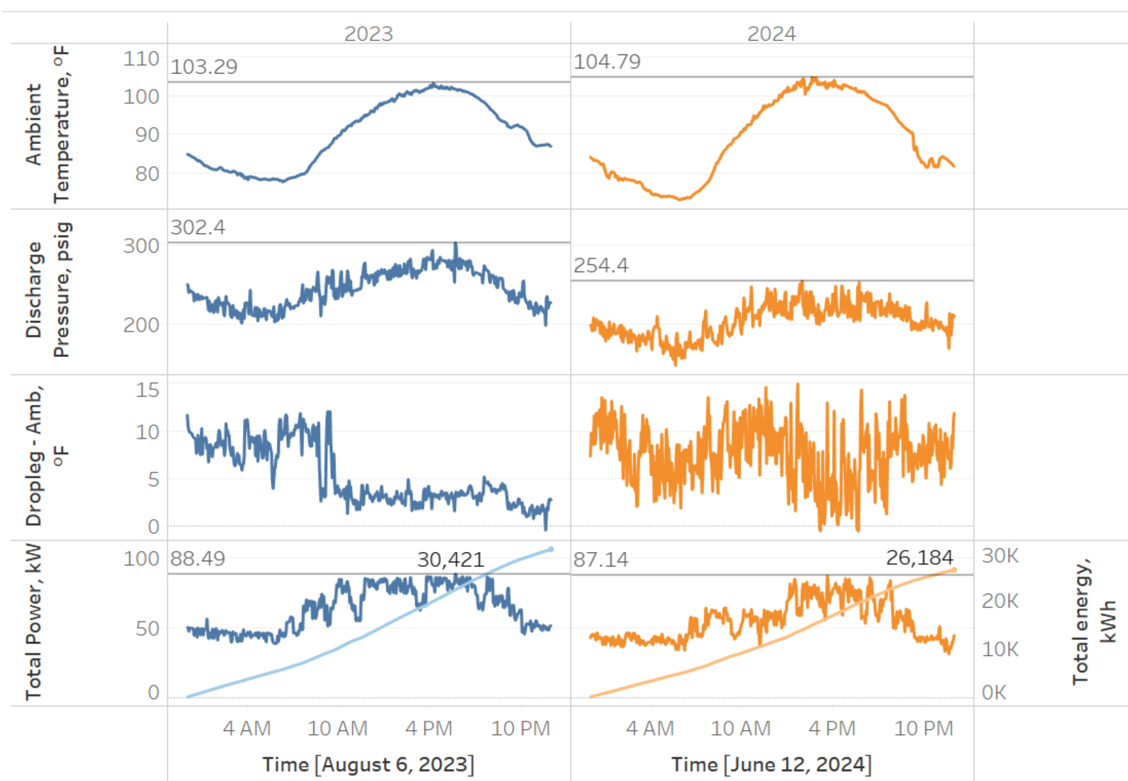
[3] Refrigerant temperature leaving the condenser.

Figure 12: Panel Heat Rejection as a Function of the Ambient Temperature



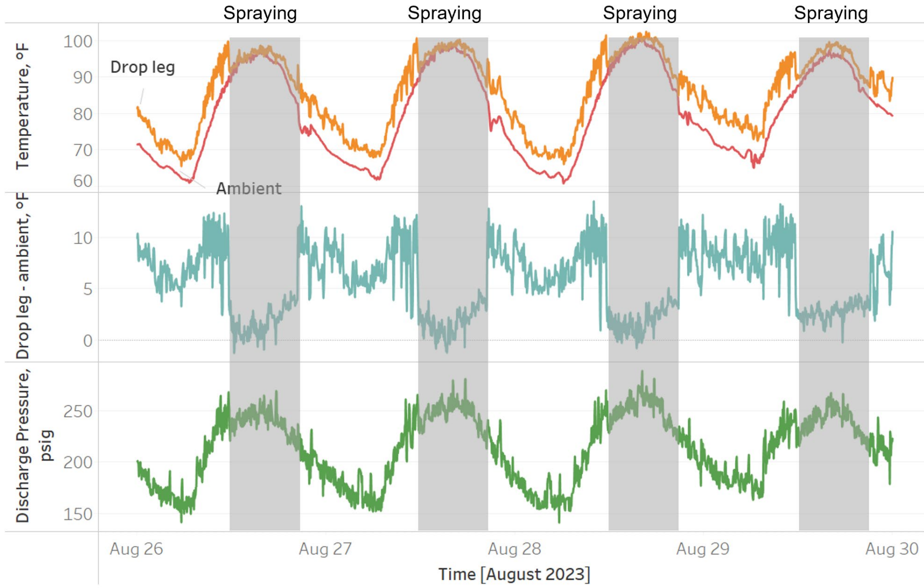
Source: SkyCool Systems

Figure 13: Power Usage for Two Similar Days, Red Bluff Site



Source: SkyCool Systems

Figure 14: Red Bluff Site Drop Leg Temperature Versus Time

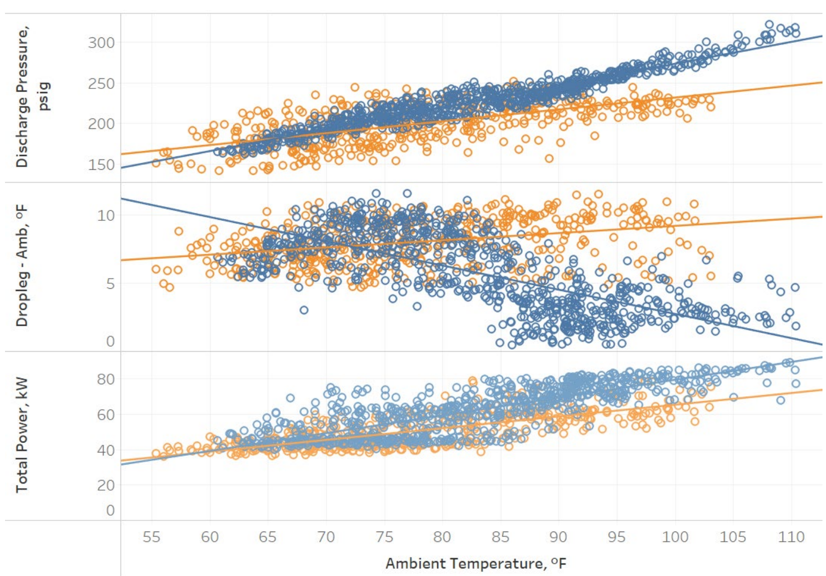


Drop leg temperature versus time at the Red Bluff, California site. This plot illustrates the usage of sprinklers during the middle of the day. Red is the ambient and orange is the drop leg temperature.

Source: SkyCool Systems

Figure 15 shows correlations of power, pressure, and drop leg as a function of the ambient temperature. In this plot, data are averaged per hour. The figure shows that as a precooler, the array is having a bigger impact as the ambient temperature increases. At 100˚F (38°C), there is a 10-kW reduction in power because of the 50-psig reduction in discharge head pressure.

Figure 15: Project Correlations

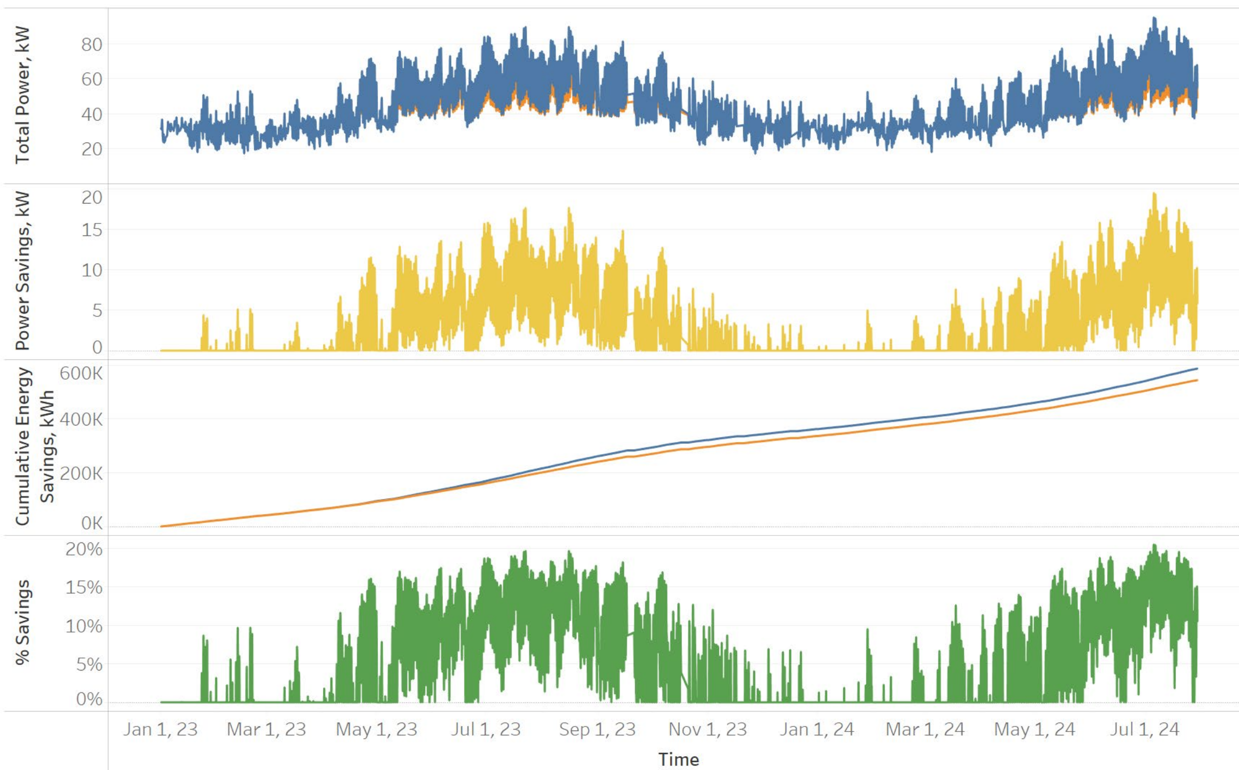


Correlations of power, discharge pressure, and drop leg versus ambient.

Source: SkyCool Systems

Using the correlations from Figure 15, energy use of the refrigeration system can be estimated based on the ambient temperature measurements that were made over the entire year. Figure 16 shows the estimated power usage over the year, cumulative energy usage, and the energy saved per hour. As this system is a precooler, it is only saving energy when the ambient is warm (approximately 80°F [27°C] or warmer) and the condenser is under capacity. This model estimates 27,000 kWh of energy saved over the test period.

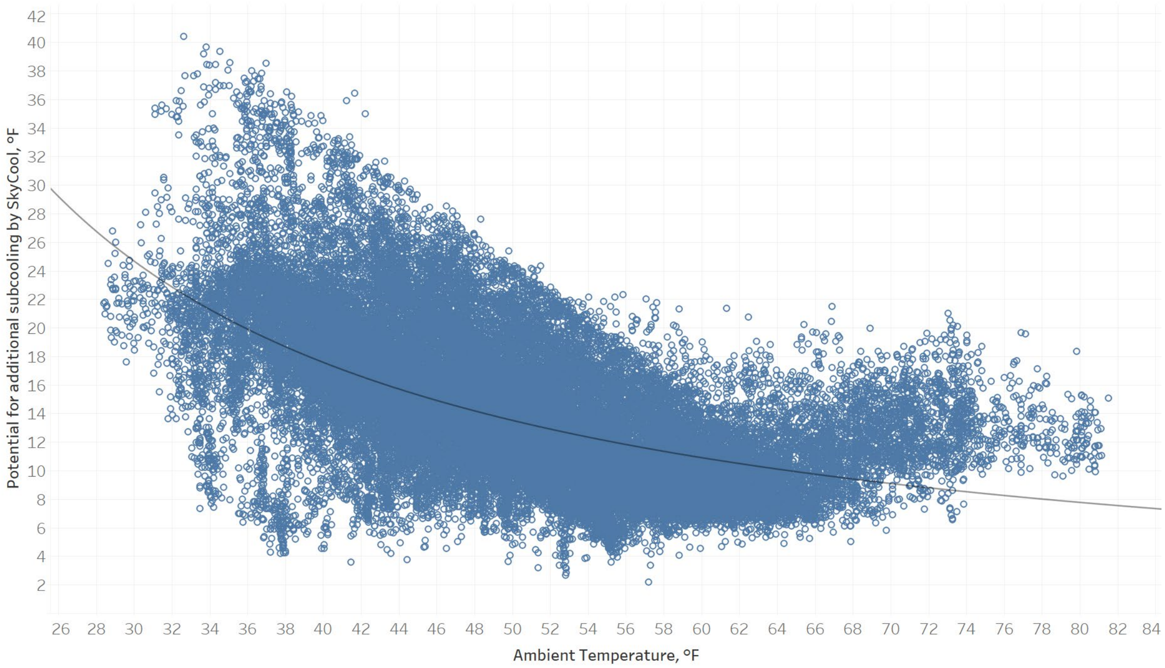
Figure 16: Energy Savings at Red Bluff Site



Source: SkyCool Systems

At the Red Bluff site, SkyCool only installed a precooling heat exchanger circuit. A key limitation of only precooling is that the array will only provide significant savings in the summer. One simple addition that could be made to use the array further would be to add a subcooling heat exchanger onto the refrigeration rack. Figure 17 shows the potential additional subcooling that can be provided by SkyCool panels with the additional heat exchanger. In general, for every 1°F (0.6°C) of additional subcooling, SkyCool will improve the energy efficiency of the compressors by 0.05 to 0.1 percent. At this particular site, SkyCool could provide an additional 10 to 15 percent in energy savings with subcooling.

Figure 17: Potential for Additional Subcooling

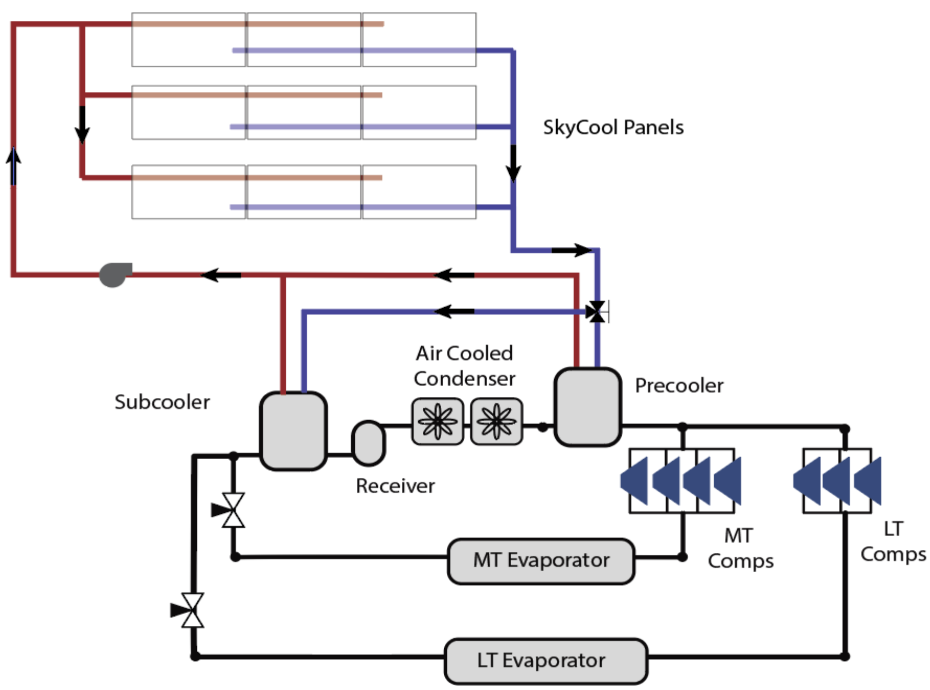


Source: SkyCool Systems

Milpitas Site

At the Milpitas site, SkyCool installed 60 panels with both subcooling and precooling heat exchangers with the integration shown in Figure 18.

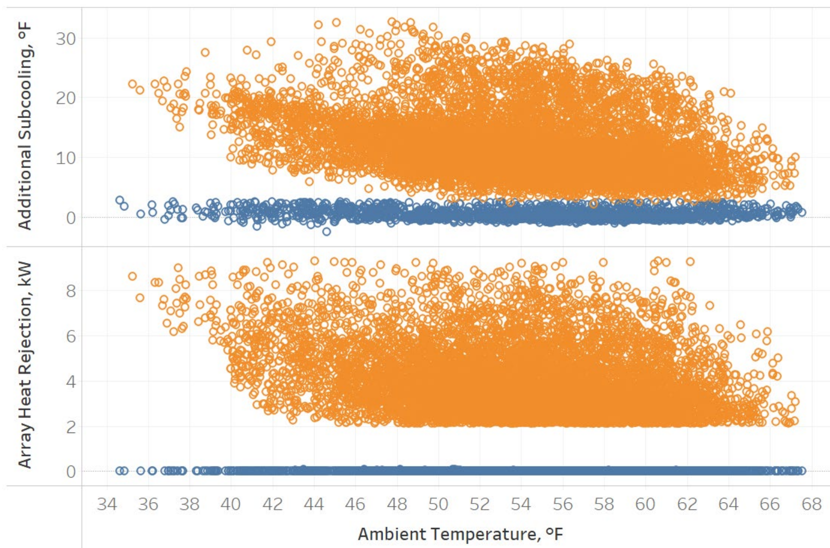
Figure 18: Milpitas System Diagram



Source: SkyCool Systems

Figure 19 shows the additional subcooling and array heat rejection provided by the SkyCool array at the Milpitas site. On average, the array is adding between 7°F to 30°F (4°C to 17°C) of additional subcooling, depending on the ambient. Figure 20 shows the amount of heat and the temperature difference across the precooling (desuperheating[4]) heat exchanger as a function of the ambient. On average, the array is providing between 20 kW and 30 kW of additional heat rejection on the condenser circuit.

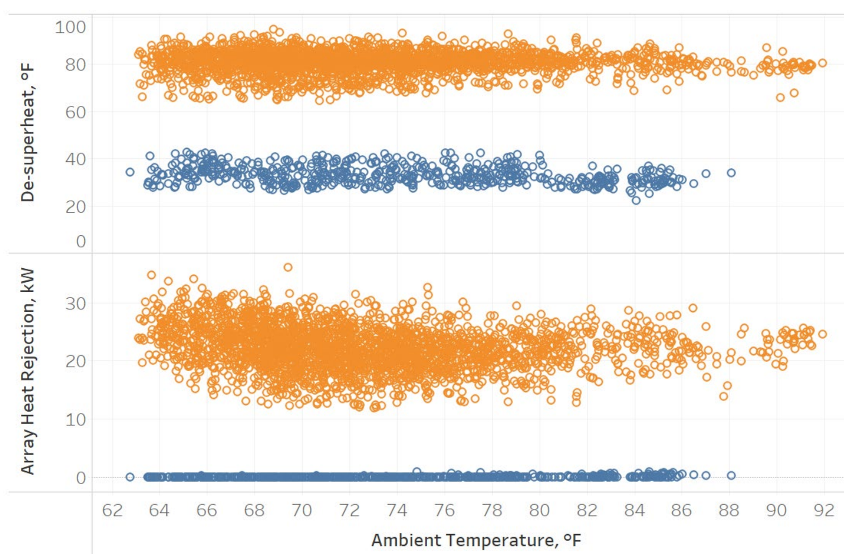
Figure 19: Added Subcooling for the Refrigeration System



The additional subcooling is defined as the drop leg temperature minus the refrigerant temperature out of the SkyCool heat exchanger.

Source: SkyCool Systems

Figure 20: Panel Heat Rejection as a Pre-cooler

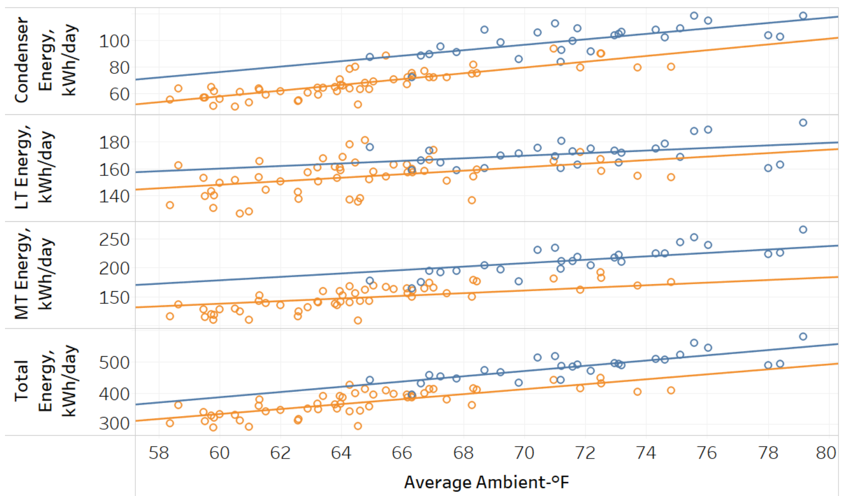


Source: SkyCool Systems

[4] Cooling the refrigerant to be a saturated vapor.

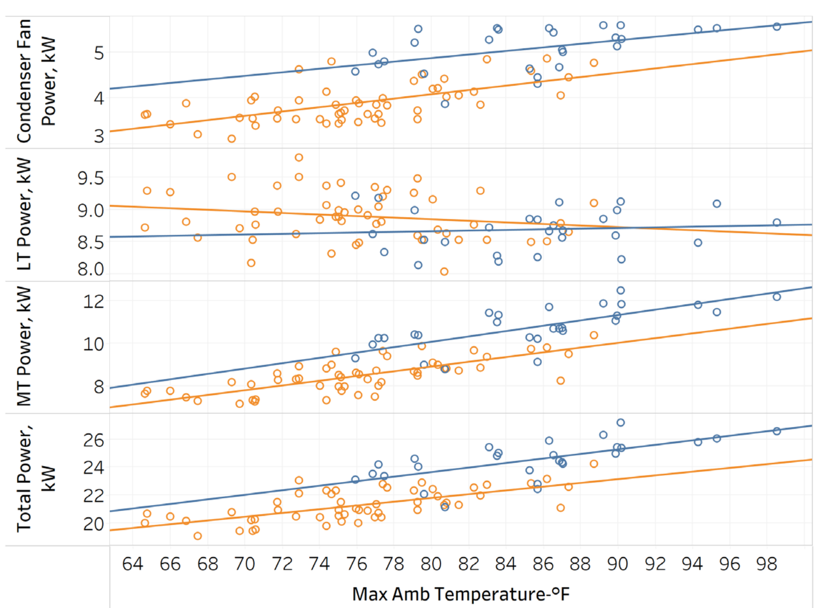
Figure 21 and Figure 22 show daily energy usage and average power usage from the condenser fans, and low-temperature and medium-temperature compressors normalized by the ambient temperature. Using the correlations and the annual energy usage for the City of Milpitas (Figure 23), SkyCool was able to estimate the energy saved over the year to be 20 megawatt-hours per year (the test data are for 340 days). SkyCool's technology has the biggest impact when the ambient is below 70°F (21°C), where subcooling is greatest. When the ambient is the hottest, SkyCool was able to add 21 to 30 kW of additional heat rejection to the condenser, lowering the discharge pressure by 5 to 10 psig and lowering the demand on the refrigeration system.

Figure 21: Energy Usage per Day



Source: SkyCool Systems

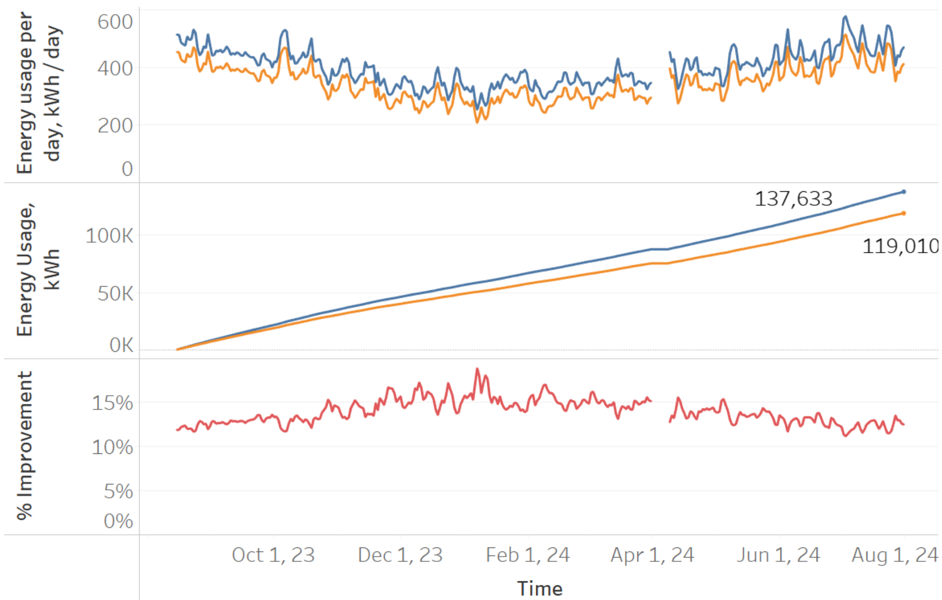
Figure 22: Average Power Usage



Average power usage for the condenser fans, LT compressors, and MT compressors.

Source: SkyCool Systems

Figure 23: Annual Energy Usage for Milpitas, California



Source: SkyCool Systems

Implementation Issues

A key challenge to piloting a technology at a commercial business is that operational changes at the site can occur at any time. For both sites, there were operational changes that the project team attempted to characterize and filter out of the analysis. At the Red Bluff site, the local refrigeration contractors installed a sprinkler under the condenser but never communicated when the sprinkler was turned on. Figure 24 is a photo of the Red Bluff condenser with a sprinkler underneath it. The sprinkler was installed because the condenser of the refrigeration system was unable to reject enough heat during the summer.

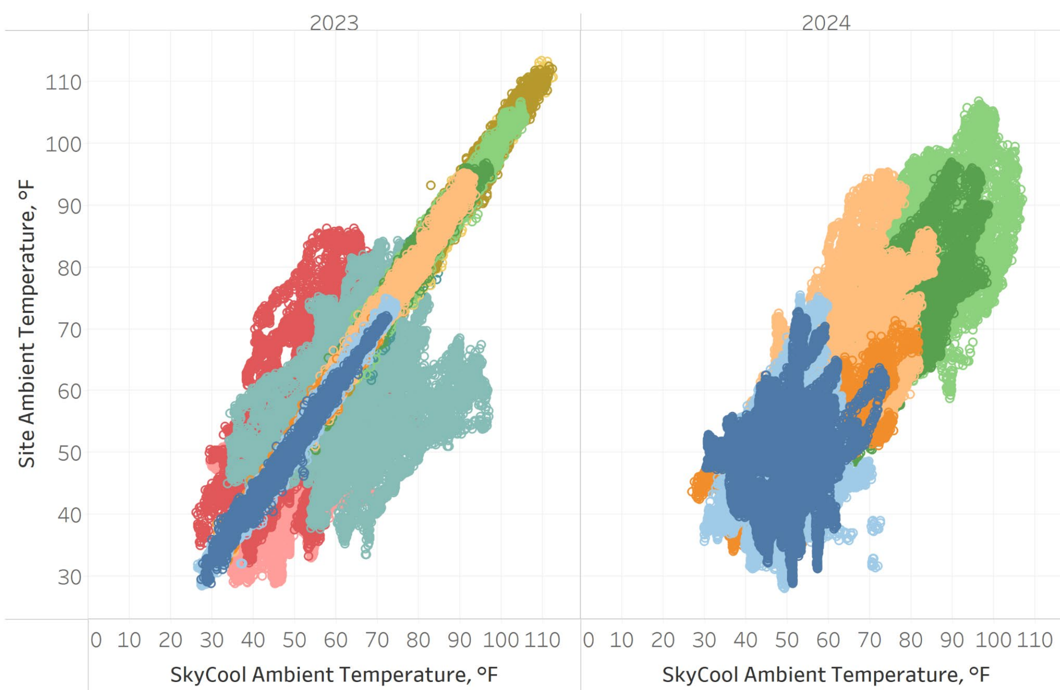
Figure 24: Red Bluff Site with Sprinkler Under the Air-cooled Condenser

Source: SkyCool Systems

At the Milpitas site, the refrigeration system used reverse cycle hot gas defrost. Prior to the installation, the team did not think this hot gas defrost control strategy was noteworthy; however, the way the site implemented hot gas defrost cycles increased the condenser temperature to 90°F (32°C), even when the ambient temperature was at or below the minimum condensing temperature. Normally, hot gas defrost cycles are only run a small fraction of the time; however, at this site the hot gas cycles ran about 30 percent of the time because each low-temperature (refrigerated) case is defrosted sequentially (as opposed to in groups, which would minimize the amount of hot gas defrost cycle time).

To characterize the impact of SkyCool's passive radiative cooling panels, the team installed new sensors and also used existing sensors that were connected to the site's refrigeration system. To access some of the data from each site, SkyCool used an application program interface set up by Copeland Refrigeration, a compressor and controls company. In October 2023, Copeland changed the way they store data for the Red Bluff site, and the data that was uploaded to their server was corrupted. SkyCool first realized this when it plotted values comparing duplicated sensors. Figure 25 shows the Red Bluff site's ambient temperature sensor on the y-axis and SkyCool's ambient temperature on the x-axis for different months in 2023 and 2024. For January 2023 through September 2023, there is agreement between the two sensors. However, starting in October 2023, the sensors no longer correlate with each other.

Figure 25: Correlation Plot of the Site Sensors Versus SkyCool's Sensors



From January 2023 through September 2023, there is a good correlation between the sensors; however, from October 2023 and July 2024, the correlation breaks down, indicating the data (or the sensors) are bad.

Source: SkyCool Systems

Market and Policy Barriers

By design, SkyCool's panels look very similar to solar photovoltaic (PV) panels. They use the same rooftop racking, the same installation labor, and the same design process. The key difference between SkyCool panels and solar panels is that SkyCool's panels are nonelectrical. For permitting, the key item that needs to be reviewed by local officials is whether the building can hold the weight of the array and whether the array is appropriately ballasted or attached to the roof of the building.

Since SkyCool's panels are nonelectrical, permitting should have been simpler. However, permit offices often assumed the panels were generating electricity (because of the similarity to solar PV) and asked about UL certification and other electrical requirements. This back and forth with the permit office added a significant amount of time for approval and cost to the permit fee, but this experience helped SkyCool understand what to present during the permit process. SkyCool now has a more standardized process for implementing systems.

In general, building owners and operators (especially for grocery stores), are very conservative when it comes to making modifications to cooling systems. This is understandable because, while cooling is core to operations and building function, it is something that is just expected to work. As a result, at the beginning of the project, it was difficult to convince stores to try SkyCool's technology as the team had to rely on models to estimate energy savings and value. Now that there are data from actual customers, the barrier to talking with new customers is significantly lower.

Public Outreach and Technology Transfer

Since the start of this project in 2019, SkyCool has completed more than 15 panel projects across the United States. This project has allowed SkyCool to standardize the design, permit, and installation process of its panels. To communicate the findings from this study and others, SkyCool developed case studies and presented a summary of findings from the pilots at a variety of both public and private events. These include The Food Industry Association, Institute of Electrical and Electronics Engineers Leadership Forum, Verge, ARPA-e Summit, the National Grocers Association, and the United States Green Building Conference.

CHAPTER 4: Conclusion

As the planet gets warmer, energy use for cooling is estimated to triple by 2050. While cooling uses about 10 percent of all electricity annually, during summers it can be as much as 50 percent of the demand (Howarth et al., 2023). During extreme heat events, existing air conditioning and refrigeration systems will become even less efficient and potentially fail to maintain people and food at the desired temperatures. The likely result is that even more cooling capacity will be added to buildings. In California, from 2013 to 2022, there were more than 100 multiday heat events. In the next decade, it is expected that these events will continue to increase in frequency and intensity. According to the California Department of Insurance, individual heat events can impact tens of millions of Californians and cost the state billions of dollars, depending on how widespread they are (IEc, 2024).

To meet the new demand from increased cooling usage and equipment, significantly more renewable generation and storage capacity will be needed, making it more expensive for California to meet the 2045 renewable generation goals of Senate Bill 100 (De León, Chapter 312, Statutes of 2018).

SkyCool has developed a unique technology that can keep any outdoor surface cooler than the ambient, even under direct sunlight. During this project, SkyCool tested one of its products, a cooling panel, to add capacity and improve efficiency or lower energy usage to existing refrigeration systems. The project showed that, with the addition of SkyCool's panels, refrigeration systems can use between 10 to 20 percent less electricity and have lower peak demand in the summer.

Grocery stores and cold storage facilities are all critical to California. Rising temperatures will put high stress on already aged infrastructure and lead to high utility bills, broken equipment, and even wasted food. The results of this study show that SkyCool's panels can be easily added to existing refrigeration systems to add much-needed capacity while using less electricity and not increasing the amount of refrigerants. There are approximately 4,500 grocery stores in California. If 10 percent of them had SkyCool's panels, then it is reasonable to expect a 6.75-megawatt reduction in power and a 38,000-megawatt-hour reduction in electricity usage.

GLOSSARY AND LIST OF ACRONYMS

Term	Definition
ambient	ambient air temperature
ARPA-E	Advanced Research Projects Agency - Energy (U.S. DOE)
°C	degrees Celsius
CEC	California Energy Commission
EPIC	Electric Program Investment Charge
EPRI	Electric Power Research Institute
°F	degrees Fahrenheit
HT	high-temperature
HVAC	heating, ventilation, and air conditioning
HVAC/R	heating, ventilation, air conditioning, and refrigeration
kW	kilowatt
kWh	kilowatt-hour
LT	low-temperature
MT	medium-temperature
PDRC	passive daytime radiative cooling
psig	pounds per square inch gauge (pressure relative to the atmospheric pressure)
PV	photovoltaic
SkyCool	SkyCool Systems, Inc.
U.S. DOE	United States Department of Energy
W/m^2	watts per square meter

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Project Deliverables

The following deliverables were prepared as part of this project. The project deliverables, including interim project reports, are available upon request by submitting an email to pubs@energy.ca.gov.

- Planning Document
- Critical Project Review Reports
- Site Deployment Plans Report
- M&V Plan and Results Reports