Field study of phase change material (PCM) use for passive thermal regulation

Phase I: Modeling Report

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Conservation Applied Research and Development (CARD) Report

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Definition of Terms and Acronyms

BAS – Building automation system

BLCC – Building life cycle cost

CBECS – Commercial Building Energy Consumption Survey

CIP – Conservation Improvement Program

DX - Direct expansion

LCC – Life cycle cost

PCES – Phase Change Energy Solutions

PCM – Phase change material

VAV - Variable air volume

TMY - Typical Meteorological Year

kWh/m^2 – Kilowatt hours per meter squared

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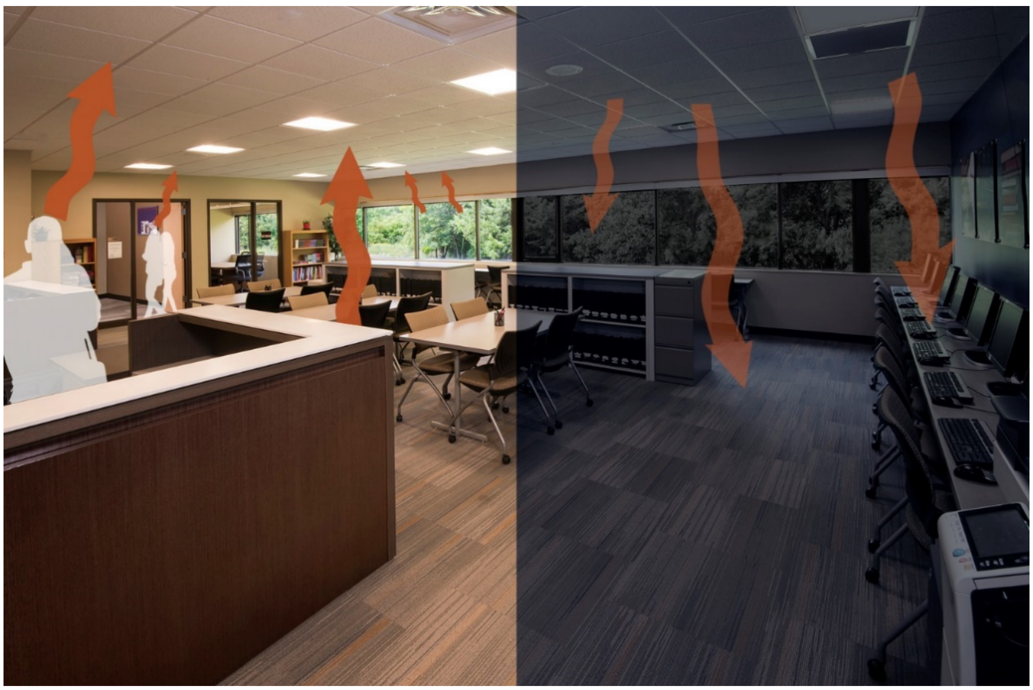
Executive Summary

Background

Phase change materials (PCMs) passively regulate air temperature by storing and releasing thermal energy. When used in buildings, PCMs can improve occupant comfort while reducing operational energy consumption, peak demand, energy costs, and greenhouse gas emissions.

Figure 1. Phase Change Material Diagram



While PCMs have been of interest in passive solar buildings for many decades, they are not widely used for non-passive buildings. However, recent advances in building products and installation strategies provide opportunities for additional market penetration, especially in retrofit applications where blanket-type PCM products can be installed above a suspended ceiling. This study investigates the impact of such installations in office and classroom settings.

The goal of this study is to assess the energy efficiency, peak demand, and occupant comfort outcomes of implementing PCM in existing buildings in Minnesota, along with evaluating this strategy's feasibility and cost-effectiveness. The project is divided into a simulation study (Phase I) and a field study (Phase II). This report provides an overview of the simulation study and findings from Phase I.

Approach

Phase I of this study included a literature review, discussion with product manufacturers, building simulation, and life cycle cost analysis. Based on an initial literature review and discussion with product manufacturers, we modeled the effect of PCMs on building energy consumption for two buildings types (office and school). We used DesignBuilder and EnergyPlus to test the effectiveness of PCM under various design and operating conditions and used the results from the models with highest heating and cooling energy savings to conduct a life cycle cost analysis of the choice to install PCM.

In combination with distilling the key challenges and opportunities for PCM market adoption from our literature review, we used the findings from our energy modeling and life cycle cost analysis to develop conclusions and recommendations for the application of PCM in Minnesota.

Results

Our modeled results show that installing PCM above suspended ceilings in existing offices and schools through non-invasive retrofits has the potential to save up to 15% of cooling energy, 50% heating electricity, and 17% of heating natural gas. This amounts to a 5% reduction in total building energy, with a peak electricity demand reduction of 4-7% (Table 1).

Table 1. Energy Savings from Phase Change Materials

Scenario	Cooling Electricity Savings	Heating Electricity Savings	Heating Natural Gas Savings	Peak kW Demand Savings	Total Electricity Savings	Total Natural Gas Savings	Total Energy Savings
Office – Highest Cooling Savings	15.2%	25.3%	-12.7%	5.4%	8.7%	-8.4%	5.0%
Office – Highest Heating Savings	12.6%	49.8%	-5.2%	6.6%	9.0%	-3.9%	5.0%
School – Highest Cooling Savings	4.7%	N/A	11.8%	5.8%	2.5%	11.8%	5.4%
School – Highest Heating Savings	1.8%	N/A	16.8%	4.2%	0.4%	16.8%	5.3%

Using Minnesota's average retail electricity prices, these operational energy savings resulted in net life cycle cost savings up to $8,820 over a 25-year study period for the 17,889 SF office (Table 2). The school scenarios are generally not shown to be cost-effective. Their lower summer occupancy results in a minimal cooling load, which minimizes the potential for electricity savings. The majority of their savings come from natural gas used for heating, which is significantly cheaper than electricity.

A key challenge in the study was the inability to vary the amount of PCM in the model, resulting in using approximately 2.2 times as much PCM as required for optimal energy savings. Since this leads to additional material first costs that are disproportionately higher than the corresponding operational energy savings, we expect cost-effectiveness to improve when the PCM quantity is right-sized. This is likely to cause the School – Highest Cooling Savings scenario to flip from negative to positive life cycle savings and reduce the simple payback of the Office – Highest Cooling Savings scenario to be under 15 years.

Table 2. PCM Life Cycle Cost Results – MN Average Utility Rates

Scenario	Net Savings (Present Value $)	Net Savings (Present Value $/SF)
Office – Highest Cooling Savings	$8,820	$0.49
Office – Highest Heating Savings	$5,748	$0.32
School – Highest Cooling Savings	- $1,612	- $0.32
School – Highest Heating Savings	- $4,220	- $0.84

Key Findings

This study shows that PCM can cost-effectively reduce energy use and peak demand in Minnesota buildings, provides initial insight into program development and implementation, and validates the need for a field study to understand the technology's real-world application potential.

PCM products can be easily installed in suspended ceilings through a non-invasive retrofit, making it an ideal candidate for utilities' CIP offerings. Under optimized operational conditions, the modeled PCMs show significant savings in Minnesota offices and schools for both heating and cooling loads throughout the year. These results can be extrapolated to other building types that have constant occupancy rates throughout the day and high internal loads. Other beneficial applications for PCM are older buildings with poorly performing thermal envelopes that operate HVAC systems at peak capacity to maintain interior temperature setpoints. The total statewide achievable annual savings potential is estimated to be 8,700,000-10,700,000 kWh of electricity and -62,000-251,000 therms of natural gas.

Conducting a field study will enable evaluation of non-energy benefits such as occupant comfort, will further our understanding of factors that couldn't be adequately captured in the simulation study, and will provide a more accurate representation of the effectiveness of PCMs under real-world conditions. The benefits of improved thermal comfort, reduced energy consumption, and shifted peak energy demand make PCMs a technology worth further exploration, as increased interest will help develop the expanding market, lowering costs and improving technological innovation.

Introduction and Background

Project Goals

The goal of this study is to demonstrate the use of phase change material (PCM) to passively regulate temperature in existing buildings in Minnesota. This includes assessing this technology's impact on energy efficiency, peak energy loads, and occupant comfort. Additional project goals are to demonstrate the feasibility, cost-effectiveness, and statewide savings potential of PCM, and use this knowledge to inform next steps for program development and widespread application.

The project is divided into a simulation study (Phase I) and a field study (Phase II). This report provides an overview of the simulation study and findings from Phase I.

Project Justification

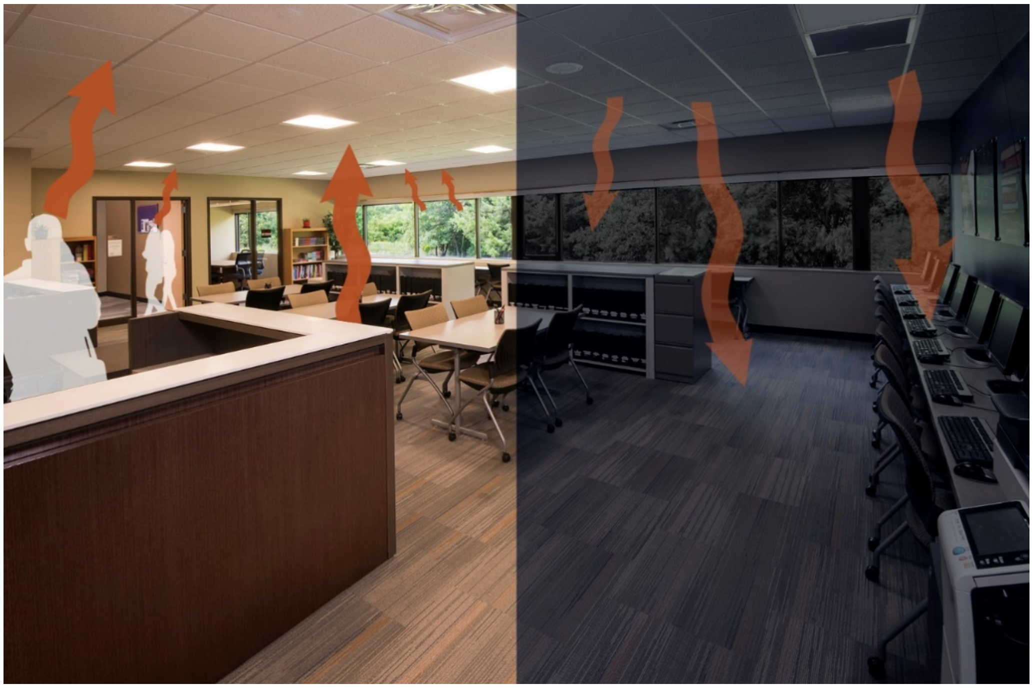
While PCMs have been of interest in passive solar buildings for many decades, recent advances in installation strategies and a focus on non-passive building by fabricators and manufacturers of the product suggest research opportunities to support further market penetration, especially in retrofit applications. Manufacturers have developed commercial PCM products suitable for installation above a suspended ceiling, offering a minimally invasive option for existing buildings. This study investigates the impact of such installations in office and classroom settings.

PCM is currently used most frequently in climates with higher cooling loads and greater diurnal temperature swings than Minnesota, as these conditions enable the material to provide passive cooling by storing heat during the day and releasing it at night using natural ventilation. Currently, published studies on the energy impact of PCMs focus on climates that are dissimilar to Minnesota's, leaving a knowledge gap in the literature. Without a cost-benefit analysis specific to Minnesota and a demonstration of the local feasibility through a pilot project or field study, building owners are unlikely to invest in this technology. This study investigates PCM's savings potential, cost-effectiveness, and ease of implementation and extrapolates results to estimate the statewide savings potential.

Phase Change Materials

Phase change materials (PCMs) passively regulate air temperature by storing and releasing thermal energy. When there is excess heat, they store energy by changing from a solid to a liquid. As their environment cools, they transition back to a solid and release the stored heat back into the air. PCMs can be engineered to undergo this phase change at a comfortable room temperature, effectively buffering temperature swings without requiring constant mechanical system engagement.

Figure 2. Phase Change Material Diagram



PCMs are used for many different applications, from refrigeration to textiles. In the building industry, PCM has drawn attention due to its ability to reduce thermal energy transfer at a level 4 to 20 times that of standard insulation (Fallahi 2013). Like concrete, PCM performs as a thermal mass, storing energy to help passively regulate thermal gains. Incorporating PCM enables buildings to achieve high thermal storage capacity with relatively low mass, allowing lightweight construction to employ passive energy conservation techniques.

For use in buildings, PCMs are available encapsulated within flexible or rigid plastic panels that can be built into a wall, ceiling, or roof assembly, laid atop a suspended ceiling, or even surface-mounted on walls or ceilings. The PCM products readily available in the Minnesota construction market are InfiniteR (a salt hydrate sold by Insolcorp) and BioPCM (a bio-based product sold by Phase Change Energy Solutions). These products are both flexible mats less than half an inch thick that can be easily laid on top of an existing suspended ceiling in a retrofit application.

Figure 3. PCM Product for Building Applications

Retrieved from https://designbuilder.co.uk/helpv6.0/#Phase_Change.htm

Benefits

Using PCM to passively regulate indoor air temperature in buildings has the potential to:

- Reduce operational energy consumption, along with its associated costs and greenhouse gas emissions.
- Reduce peak demand for electricity and shift demand to off-peak hours, which helps balance electricity supply and demand and results in lower energy rates where peak demand pricing applies.
- Improve the thermal comfort of building occupants, which can increase productivity and satisfaction.
- Contribute to building resilience, protecting human health by helping maintain safe thermal conditions when power is unavailable.
- Reduce energy demands on existing HVAC systems, decreasing wear on equipment over time (Cabeza 2015, p. 418; Auzeby 2017, p. 4074).
- Eliminate the need for the installation of costly HVAC systems in retrofit projects (Auzeby 2017).

These potential benefits, along with the ease of PCM installation within both new construction and non-invasive retrofits make them an ideal candidate for incorporation into utilities' conservation improvement program (CIP) offerings.

Literature Review

Through our review of published literature surrounding PCMs we were able to develop an understanding of the technology and its potential in Minnesota. Case studies and additional findings within the articles enabled us to validate the results of our modeling study. Articles included in the study focused on model-based results, exploring the potential of PCMs in places such as California, the United Kingdom, Phoenix, Baltimore, and other subcontinental climates (Auzeby 2017; Childs 2012; Delaney 2012; Fallahi 2013). Several studies used independent case studies to show real-world examples of PCMs and explain benefits and challenges associated with the technology (Fallahi 2013; Jelle 2017).

Several design variables that influence successful PCM implementation are identified in literature. Wall orientation, location within the wall assembly, suspended ceiling applications, seasonal variations, volume/sizing, melting temperature, and night flushing are factors that have been studied for their impact on the energy performance of PCM (Childs 2012; Lizana 2019).

Oak Ridge National Lab (ORNL) conducted a comprehensive simulation study of PCM in wall assemblies in two climate zones – Phoenix and Baltimore – using HEATING 8 code. In Phoenix, PCM was most effective when placed in the wall cavity on south and west facing walls, showing 0.32 and 0.35 kWh/m^2 annual cooling energy savings, respectively. The study also suggests that 2.4 kg/m^2 is the optimal amount of PCM on a surface for maximum cooling energy savings. Increasing the mass of PCM beyond this amount diminished savings (Childs 2012).

An EnergyPlus simulation study looked at PCM installed above suspended ceilings, embedded in wallboard and in wall insulation, and interior to the wallboard in buildings in five California climate zones. Installing PCM above suspended ceilings resulted in up to a 25% reduction in peak cooling loads. The research also concluded that PCM in wall insulation showed no significant cooling energy savings and attributed this effect to less efficient heat transfer when PCM is adjacent to an insulation layer. In addition to cost savings, PCM can also potentially reduce HVAC system sizing by up to 25%, thereby reducing first costs in new construction and in major retrofits (Southern California Edison 2012).

When PCM effectively discharges and regenerates at night, it is more effective in absorbing space loads during the day. To minimize or eliminate electricity costs associated with pre-cooling for PCM regeneration, night flushing (nighttime ventilation that takes advantage of the lower temperatures to cool the PCM) is a critical element for evaluating PCM potential in a specific application. Several simulation studies emphasize the importance of night flushing to maximize energy savings and lower energy costs in buildings with PCM (Lizana 2019; Southern California Edison 2012).

A combined simulation and field study was conducted in Arizona, where one of two identical sheds was retrofitted with PCM. In addition to simulating the PCM and non-PCM sheds using EnergyPlus, the study also gathered energy use data to validate models and conduct parametric analysis. The study found that total energy savings varied from 12 to 26% in the summer and from 9 to 29% in the winter. Peak energy use reduction was found to be between 4 and 9% (Muruganantham 2010).

Overall, the literature suggests that achieving significant energy savings with PCM in building construction is realistically possible. In their conclusions, most of the authors acknowledged the limitations of modeling explorations and the need for field study reports to observe the effects of PCMs in a real-world environment (Auzeby 2017; Childs 2012; Delaney 2012; Fallahi 2013; Jelle 2017).

Methodology

Approach

Phase I of this study is based on results obtained through literature review, discussion with product manufacturers, and building simulation. Conversations with manufacturers and knowledge gained through research informed our model inputs and allowed us to validate results against other studies. Working with the manufacturer is an essential part of design projects involving PCMs, so it was important to include this collaboration as part of our study.

Using information from our initial literature review, we modeled the effect of PCMs on building energy consumption. Based on literature review, we evaluated two different building types for ideal PCM implementation and energy saving – office and school. Since PCM requires a temperature differential to charge and discharge, a space with high occupancy and internal loads during the charging phase, and a low or no occupancy period during the discharge phase will maximize PCM's potential to save energy. For this purpose, we selected a typical open office space and a classroom with computers for further modeling analysis.

We used DesignBuilder as the graphical user interface (GUI) to build our energy models and used the EnergyPlus engine to run our simulation. Parametric testing includes variation in location, orientation of PCM, interior temperature setpoints and setbacks, effects of the economizer, and occupancy and equipment densities. The difference in annual energy use (both kilowatt-hours and therms) between each baseline and PCM scenario was used to determine the energy impact from incorporating PCM in the parametric model. We also reviewed peak kilowatt reduction and how much peak demand shifting could be achieved with PCM.

After collecting data from the model, we estimated life cycle costs (LCC) for incorporating PCM technology in the selected building types. With information gathered from the LCC and parametric modeling, we examined our research of PCMs to develop conclusions about the potential of PCM in Minnesota and an awareness of possible considerations/challenges to implementation. Strategies employed by manufacturers to address these issues were explored.

Energy Modeling Methodology

Reference Models

The first step of the simulation analysis is to develop baseline reference models. We developed reference models based on the DOE commercial prototype building models (DOE 2018). We selected the 'Medium office' and 'Secondary school' models using ASHRAE 90.1.2004 as the energy code. This energy code was selected to represent the largest group of existing commercial buildings in Minnesota. We used the weather file for zone 6A (cold humid climate), which references Rochester, Minnesota.

The DOE reference office model is a three-story building of 53,600 SF, with a 33% window-to-wall ratio (WWR) evenly distributed across all facades. We modeled the middle floor of this prototype office with a 17,888 SF floor area (Figure 4Figure 4.). The model building is conditioned by a packaged air conditioning unit with a gas furnace and direct expansion (DX) cooling. The variable air volume (VAV) terminal boxes are equipped with electric re-heat coils.

The DOE reference school model is a two-story building of 210,900 SF, with 33% ribbon windows on all facades. We modeled one zone of this prototype model with a 5017.5 SF floor area and 60% window-to-wall ratio on one façade (Figure 5). The model building is conditioned by a VAV system with hot water re-heat coils, connected to a gas fired boiler and air-cooled chiller.

Due to the complexity of building EnergyPlus models, we investigated a single floor of open office space with five HVAC zones in the office model, and a single zone classroom in the school model. We used this simplified approach to allow us to parametrically analyze multiple PCM sensitivities with relatively shorter run times for each iteration.

Figure 4. DOE Reference Office Building (DOE 2018) and Test Office Zone Model

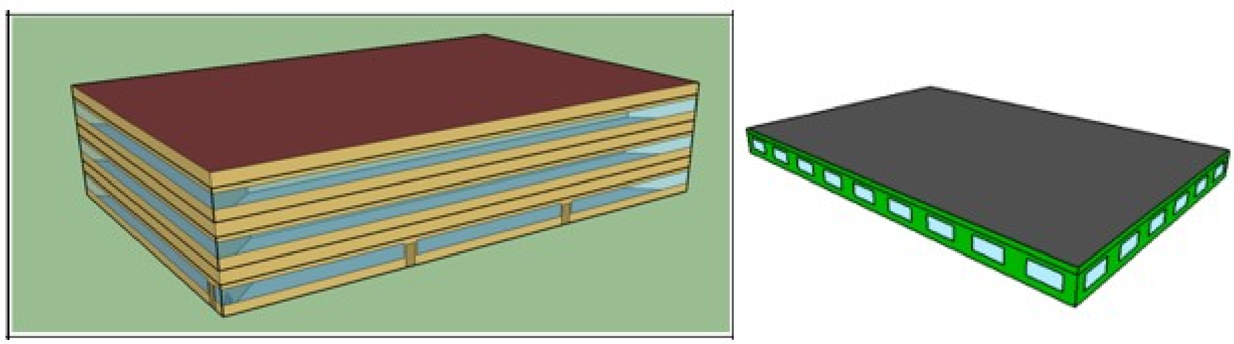


Figure 5. DOE Reference School Building (DOE 2018) and Test School Zone Model

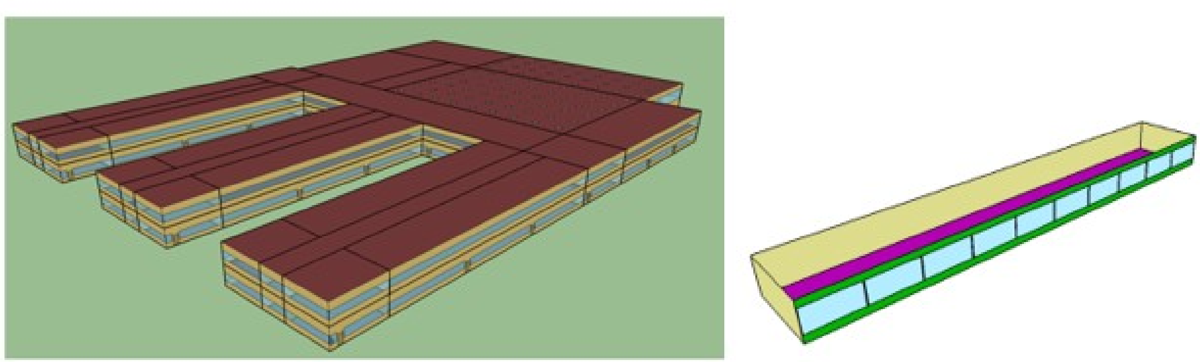


Table 3. Key Reference Model Inputs

Component	Office Model	School Model
Orientation	0°	0°
Occupancy density	100 SF/person	28.5 SF/person
Equipment density	1 W/SF	1.9 W/SF
Economizer setpoint high	65 °F	65 °F
Economizer setpoint low	40 °F	40 °F
Cooling setpoint	73.4 °F	73.4 °F
Cooling setback	75.2 °F	71.6 °F
Heating setpoint	71.6 °F	71.6 °F
Heating setback	64.4 °F	68 °F
Geometry	4 Exterior walls, single middle floor, 33% window-to-wall ratio on all façades	4 Exterior walls, single middle floor, 60% window-to-wall ratio on one façade

The following modifications from the prototypes were made to the reference models to more accurately reflect Minnesota's actual building stock:

- HVAC system efficiencies updated to be consistent with ASHRAE 90.1.2010. At least some buildings constructed to the 2004 code are likely to have replaced their HVAC systems, due to system wear and tear after over 15 years of operation. To account for some of these newer and more efficient systems, we used a higher efficiency for HVAC systems than the 90.1.2004 code requirement.
- Infiltration rates changed from 0.2 ACH to 0.3 ACH, which is more commonly observed in older buildings.
- 'Summer schedule' is included in the school model, instead of a full shut down during summer months. Since PCM technology can reduce cooling loads significantly, we assumed a partially occupied summer school schedule to estimate cooling energy savings.

After building the two reference models, we did quality checks on the results to confirm that they were performing within expected ranges. The energy use intensity for the medium office and school were 75.87 kBtu/SF and 101.40 kBtu/SF respectively, which are consistent with the DOE prototype models.

Phase Change Material in Simulated Models

Once the baseline performance was established, the next step was to introduce PCM into each model. EnergyPlus provides an object to define the properties of a PCM using a curve that progresses from solid to liquid state and back again. This EnergyPlus module uses the hysteresis effect which allows the melting and freezing process to follow separate curves (Bigladder software 2017). Thermal conductivity and density for both solid and liquid states are entered in the model.

Table 4. EnergyPlus Input Data for MaterialProperty: PhaseChangeHysterisis

Field	Units	Material
Name	n/a	InfiniteRPCM21C
Latent Heat during the Entire Phase Change Process	Btu/lb	93.66
Liquid State Thermal Conductivity	Btu-in/h-ft2-F	3.74
Liquid State Density	lb/ft3	96.14
Liquid State Specific Heat	Btu/lb-F	0.75
High Temperature Difference of Melting Curve	deltaF	1.8
Peak Melting Temperature	F	71.6
Low Temperature Difference of Melting Curve	deltaF	1.8
Solid State Thermal Conductivity	Btu-in/h-ft2-F	7.56
Solid State Density	lb/ft3	96.14
Solid State Specific Heat	Btu/lb-F	0.75
High Temperature Difference of Freezing Curve	deltaF	1.8
Peak Freezing Temperature	F	68
Low Temperature Difference of Freezing Curve	deltaF	1.8

Table 5. EnergyPlus Input Data for Material, PCM Object

Field	Units	Material
Name	n/a	InfiniteRPCM21C
Roughness	n/a	VeryRough
Thickness	inch	0.25
Conductivity	Btu-in/h-ft2-F	5.65
Density	lb/ft3	58
Specific Heat	Btu/lb-F	0.75
Thermal Absorptance	%	0.9

Field	Units	Material
Solar Absorptance	%	0.7
Visible Absorptance	%	0.7

Parametric Sensitivity Analysis

From various literature studies, we know that different building components such as envelope construction and HVAC operations modify the energy impact of installing PCM. To understand the energy impact from PCM in different implementation scenarios, we conducted a parametric sensitivity analysis. Table 6 lists the various sensitivities that were tested out in our modeling analysis.

We tested our models for variation in both physical characteristics and operational adjustments. Physical factors that could potentially influence savings from PCM include orientation, occupant density and equipment density. Although these factors have some influence on PCM design and installation, making operational adjustments in buildings is more critical to PCM implementation. We explored the impact of operational tuning in buildings to maximize savings from PCM.

Table 6. Parametric Sensitivities Modeled for Office and School

Parametric Category	Parametric Sensitivities (Office)	Parametric Sensitivities (School)
Physical Factors		
Orientation	0^o, 90^o, 180^o, 270^o	0^o, 90^o, 180^o, 270^o
Occupant density (SF/person)	-20%, -10%, 10%, 20% variation from baseline	-20%, -10%, 10%, 20% variation from baseline
Equipment density (W/SF)	-20%, -10%, 10%, 20% variation from baseline	-20%, -10%, 10%, 20% variation from baseline
Operational Factors		
Economizer setpoint – High (^{o}F)	64.4, 66.2, 68, 69.8	64.4, 66.2, 68, 69.8
Economizer setpoint - Low (^{o}F)	39.2, 41, 42.8, 44.6	39.2, 41, 42.8, 44.6
Cooling setpoint (^{o}F)	71.6, 73.4, 75.2, 77	71.6, 73.4, 75.2, 77
Cooling setback (^{o}F)	71.6, 73.4, 75.2, 77, 78.8, 80.6	71.6, 73.4, 75.2, 77, 78.8, 80.6
Heating setpoint (^{o}F)	68, 69.8, 71.6	68, 69.8, 71.6
Heating setback (^{o}F)	64.4, 66.2, 68, 69.8, 71.6	64.4, 66.2, 68, 69.8
Exterior exposure	N/A	1 to 4 exterior walls
PCM Type	75^{o}F and 71^{o}F melting points	75^{o}F and 71^{o}F melting points

Both office and school models were simulated for each sensitivity listed above. For accurate comparison, each parametric run varied from its baseline run only in the introduction of PCM. For example, the sensitivity test for the 90^{o} change in orientation included a baseline (no PCM) run and a PCM model with 90^{o} change in orientation from the reference model. This parallel approach of making changes in the baseline and PCM model allowed us to isolate the energy impact from PCM and eliminate the effect of any confounding factors.

We used a stepped approach for arriving at the design conditions with the highest heating or cooling energy savings for each building type. In this approach, we ran all possible combinations of sensitivities within each parametric category (listed in Table 6). The goal was to identify the sensitivities which resulted in the highest heating savings and highest cooling savings within each of the eleven parametric categories. Then, the runs with highest savings in each category were combined in the reference model to arrive at the building conditions with the highest cooling and highest heating energy savings. The results from this process are two optimized design strategies for each building type that achieve the highest percentage reduction in cooling and heating energy use (highest heating and highest cooling energy savings).

Due to the computationally intensive nature of this exercise, we used a Python script called the Batch Runner to speed up the process without losing modeling accuracy. Batch Runner allows us to execute multiple parametric runs in parallel by specifying parametric values in an Excel input file. It uses this data in combination with a specified .IDF input file to execute multiple runs simultaneously on the cloud. Since EnergyPlus is an advanced software with long run times, Batch Runner enabled us to do the parametric sensitivity analysis in an efficient manner.

Modeling Limitations

It is worth noting that there are limitations to conducting a study of PCMs through computer-aided simulation packages, which may have impacted the achieved results. Most commercially available modeling software does not have the ability to model PCMs with complete accuracy.

Amount of PCM

The key limitation of the study is the inability to specify the required amount of PCM in the model. PCM could only be added to 100% of a selected surface in the energy modeling software (in this case, the suspended ceilings). Therefore, the amount of PCM in the model could not be 'right-sized' for the loads in the building, and we were unable to parametrically vary the amount of PCM. In practice, 100% coverage will not be possible due to conflicts with ceiling fixtures. For PCM to be cost-effective, it is critical to identify the right amount to be used in a space, based on loads. As with other energy-saving technologies, there is a point of diminishing returns when the product is oversized.

Although sizing depends on local climate, space loads and product application, energy savings from oversizing PCM is not beneficial to the return on investment. A simulation study conducted for Phoenix, AZ suggests that 0.49 lb/SF is the optimal amount of PCM for maximum energy savings when used in exterior walls. Beyond this point, increasing PCM does not lead to increased saving, and the cooling energy savings remains constant (Childs 2012, p. 33). The point of diminishing returns could not be evaluated in the energy model due to the inability to vary the amount of PCM modeled.

The material specified in our model is at 1.1 lb/SF, which implies that the model currently employs 2.24 times the required amount of PCM. Right sizing the amount of PCM will greatly improve its cost-effectiveness.

Location of PCM

Standard modeling packages cannot capture the impact of PCM when embedded in the wall assembly. The modeling algorithms lack sophistication to capture the effect of PCM that is adjacent to insulation. Investigating the effect of PCM orientation in eliminating unwanted solar heat gain was one of our first sensitivity tests. However, all the parametric combinations yielded little savings from PCM in wall assemblies. A similar drawback has been documented in other literature studies as well, where EnergyPlus models show nominal impact from PCM in wall assemblies but saw significant energy use reduction when PCM is used in suspended ceilings. The study found that the effect of PCM near a material with poor heat transfer properties, such as insulation, is not captured in the energy model (Southern California Edison 2012). However, PCM in the suspended ceiling is directly adjacent to return air in the plenum, and the heat transfer mechanisms between the PCM layer and return air stream are more accurately calculated.

Lack of Comparable Results

One of the main challenges of the study was the lack of literature on PCM performance in cold climates. We were unable to make a direct comparison between our modeling results to that of other complete studies, since the other studies have not been conducted in a cold climate zone like Minnesota. To compare our modeling results to available literature as a quality control measure, we changed the location and weather file of our model to a location where literature study results or field data was available. This helped us compare results in a similar climate, and we found our results closely aligned to other studies (Southern California Edison 2012). After verifying that our models performed similarly, we reverted our models back to the Minnesota weather file and conducted the sensitivity analysis.

Impact of Seasonal Variation

Since PCM is a dynamic material, the energy performance is closely tied to external temperature variations. This means that to achieve optimum performance, the building controls should be adjusted seasonally to respond to prevailing weather conditions. A constant internal setpoint does not maximize the energy savings potential from PCM, which is a limitation in the model. Although the model can vary internal setpoints for heating and cooling seasons, it lacks the sophistication of a building automation system (BAS) that can make real time building control adjustments based on prevailing weather conditions.

Introducing night flushing to discharge the PCM on days when diurnal temperature swings allow is critical to reducing cooling costs. Buildings can benefit from night flushing during the shoulder season, and on summer days with nighttime temperature drops. This eliminates the need for mechanical pre-cooling and helps the PCM discharge during unoccupied hours. We analyzed night flushing for a two-week period in July by setting an indoor temperature limit, below which night flushing is activated in the model. The results showed that night flushing maximized cooling energy savings from PCM at 15.8%. Since the activation temperature needs to be adjusted based on outdoor air temperature, we could not estimate the annual savings in the model by using this method. This hurdle will be addressed in the field study with buildings managed by a BAS.

Non-Energy Benefits

The energy model did not account for other significant benefits of PCMs that don't include a numerical decrease in energy consumption. For example, by maintaining a more stable indoor temperature, the PCM reduces HVAC system cycling, which in turn reduces wear and tear on the system. This reduction in system cycling cannot be predicted with modeling tools but can be measured on site.

Less variation in indoor temperature also improves thermal comfort for the occupants, which was not evaluated with simulation. This is especially relevant for schools, many of which are at partial occupancy during the cooling season. PCM can effectively lower indoor temperatures in these spaces in the absence of a mechanical cooling system. Thermal comfort from PCM will be included in the site study component of the study with a pre-retrofit and post-retrofit comfort evaluation surveys.

Life Cycle Cost Methodology

Life cycle cost analyses were conducted using the U.S. Department of Energy's Building Life Cycle Cost (BLCC) Program for each of the four models with highest heating and cooling energy savings (two office and two school) described in the Parametric Sensitivity Analysis section above. BLCC is a publicly available tool developed by the National Institute of Standards and Technology (NIST) and used to evaluate alternative designs that have higher initial costs but lower operating costs over the project life than the lowest initial cost design. Embedded in the software are the latest Federal Energy Management Program (FEMP) discount factors and energy price escalation rates for U.S. Census regions, rate types, and fuel types. Our analysis also follows the FEMP guidance of conducting a constant dollar analysis using an end-of-year discounting convention. Table 7 lists the other assumptions used for the life cycle cost analysis.

Table 7. Life Cycle Cost Assumptions

Variable	Input	Source
Length of study period	25 years	FEMP Handbook 135
Real discount rate	3.0%	FEMP 2019 Discount Rates
Electricity price/kWh	$0.1063	U.S. EIA – average retail commercial price in MN (2019) [a,b]
Natural gas price/therm	$0.683	U.S. EIA – average retail commercial price in MN (2018) [b]
Annual demand charge for electricity	$0	Included in average retail price (see Utility Rates discussion below)
Annual demand charge for natural gas	$0	Included in average retail price
Installed cost/SF of PCM	$3.00	PCM distributer
Annual utility rebate for PCM	$0	Testing cost-effectiveness without rebates
Residual value of PCM at end of study period	95%	Conservative estimate based on literature review and PCM distributer [c]

a) Uses most recent EIA data, available through October 2019
b) Represents total prices paid by end users, inclusive of all tax, delivery, commodity, demand, and other charges
c) Unintended amount of crystallization leads to degradation of PCM caused by changes in the amount of water in the salt hydrate mixture. Selected product prevents this effect through additives and a non-permeable encapsulation.

When comparing a project alternative to a base case, BLCC calculates the total life cycle cost of each option and presents the net savings from implementing the project alternative. The net savings are shown in present-value dollars, representing the savings achieved over the study period in excess of the amount that would have been earned from investing the same funds at the minimum acceptable rate of return (i.e. the discount rate). While BLCC also calculates supplementary measures (savings-to-investment ratio, adjusted internal rate of return, simple payback, and discounted payback), these measures were not used to evaluate cost-effectiveness in this study.[1]

[1] As described in NIST's Life-Cycle Costing Manual (Handbook 135), "payback is best used as a screening method for identifying single project alternatives that are so clearly economical that the time and expense of a full LCCA is not warranted" (6-9). The savings-to-investment ratio and adjusted internal rate of return are always consistent with the net savings in demonstrating whether a project alternative is cost-effective or not, but generally do not indicate which project alternative has the lowest life cycle cost.

Utility Rates

The Minnesota average retail commercial electricity price shown in Table 7 combines energy (kWh) and demand (kW) charges into a single dollar per kilowatt-hour price. Using this blended rate for life cycle cost analysis provides a reasonable estimate of average savings, especially when the percentage of energy savings and demand savings are roughly equivalent. However, since each utility's rate structures assign different weights to energy versus demand charges, using utility-specific electricity prices provides a more accurate representation of the range of savings achievable through implementing PCM in Minnesota commercial buildings. Therefore, in addition to using the Minnesota average electricity price, we tested the general commercial rate structures for Minnesota's five largest electric utilities (Xcel Energy, Minnesota Power, Connexus Energy, Dakota Electric Association, and Otter Tail Power), shown in Table 8.

Table 8. Minnesota Electric Utility Rates

Utility and Rate Case [a]	Energy Charge ($/kWh)	Demand Charge ($/kW)
Connexus Energy General Commercial [b]	First 400 kWh/kW: $0.0667 Over 400 kWh/kW: $0.0567	June-Sept: $14.45 Oct-May: $10.30
Dakota Electric General Service [c]	First 200 kWh/kW: $0.0776 Next 200 kWh/kW: $0.0676 Over 400 kWh/kW: $0.0576	June-Aug: $12.26 Sept-May: $9.16
Minnesota Power General Service [d]	$0.07619	$6.50
Otter Tail Power General Service - Secondary [e]	June-Sept: $0.07123 Oct-May: $0.07469	June-Sept: $4.60 Oct-May: $2.36
Xcel Energy General Service [f]	$0.03407	June-Sept: $14.79 Oct-May: $10.49

a) The rate cases used in this table (e.g. General Service) were selected based on the maximum demand requirements of the modeled buildings.
b) Rates effective January 1, 2017.
c) Rates effective November 18, 2019.
d) Rates effective December 1, 2018.
e) Rates effective June 1, 2019. Includes a per/kW Facilities Charge in the Demand Charge.
f) Rates effective June 1, 2019.

Life Cycle Cost Analysis Limitations

Many of the constraints identified in the Modeling Limitations section also impact the cost-effectiveness of PCM:

- Like the model, the life cycle cost analysis assumes 100% coverage of the suspended ceiling, despite this being both impractical and far past the point of diminishing returns identified in the literature. The potential cost-effectiveness impacts of right-sizing the PCM are described in the Life Cycle Cost Analysis Results.
- Since the energy model could not quantify reduced HVAC system cycling due to the PCM passively regulating temperature, cost savings associated with reduced maintenance and extended lifetime are not included in the life cycle cost analysis.
- The life cycle cost analysis does not include any potential improvements in employee productivity or student learning due to increased thermal comfort. A 2011 study indicated a reduction in performance of 4% at cooler temperatures and 6% at warmer ones (Lan 2011). Since the cost of employee salaries far exceed both construction costs and operational energy costs, even small improvements in productivity have the potential to greatly impact net savings (World Green Building Council 2014).

Additionally, the cost analysis focused on using PCM as a retrofit in buildings that retain their existing heating and cooling systems. It did not explore installing PCM in new buildings – which could potentially result in downsizing the mechanical system – nor did it consider the impacts on existing buildings that do not have cooling systems. In Minnesota, many schools are adding cooling systems to address the increased cooling degree days at the beginning and end of the school year. If PCM can improve thermal comfort enough to prevent the need for mechanical cooling, the avoided cost of this system could be factored into the life cycle cost analysis.

Results

Energy Savings from PCM

Our modeling approach identified operating parameters with highest savings potential for PCM applications in two variations of office and school models. Building design and operational factors influence heating and cooling energy use differently. We were able to identify trends that influenced energy savings associated with PCM by optimizing individually for heating and cooling. The optimized design is the individual design condition with the highest percentage reduction in annual cooling (Highest Cooling Savings) or heating energy use (Highest Heating Savings). Table 9 shows the sensitivities with the highest cooling and heating energy savings within each parametric category for office and school models. Appendix A includes energy use reduction from each sensitivity run in the different parametric categories for both office and school models.

We tested two types of PCM with 75°F and 71°F melting points. The PCM with 71°F melting point provided higher heating and cooling energy savings.

Table 9. Office and School Models – Sensitivities for Highest Cooling and Heating Energy Savings

Parametric Category	Office – Highest Cooling Savings	Office – Highest Heating Savings	School – Highest Cooling Savings	School – Highest Heating Savings
Orientation	90°	90°	0°	0°
Occupant density (SF/person)	10% increase over baseline	20% decrease over baseline	20% increase over baseline	20% decrease over baseline
Equipment density (W/SF)	10% increase over baseline	10% decrease over baseline	20% increase over baseline	20% decrease over baseline
Economizer setpoint - High (°F)	69.8	64.94	66.2	64.94
Economizer setpoint – Low (°F)	44.6	40	44.6	40
Cooling setpoint (°F)	73.4	73.4	73.4	71.6
Cooling setback (°F)	77	77	77	77
Heating setpoint (°F)	71.6	68	69.8	71.6
Heating setback (°F)	66.2	64.4	69.8	68
Exterior exposure	Internal floor (adiabatic roof) with four exterior walls	Internal floor (adiabatic roof) with four exterior walls	Internal floor (adiabatic roof) with one exterior wall	Internal floor (adiabatic roof) with one exterior wall

The four final models each achieve a 5% reduction in total energy consumption. Table 10 shows the energy savings breakdown for each of the optimized scenarios, including the reduction in the annual peak electricity demand.

In the office model, the energy savings is from electricity, since both electric cooling and re-heat systems were assumed. The design for optimized cooling showed reductions of 15.2% cooling kWh and 25.3% heating kWh. Optimized for heating, the model showed 12.6% and 49.8% reductions in cooling and heating kWh, respectively.

The savings in the school model is primarily from natural gas, since the school operate on a regular (fully occupied) schedule during the winter months. During summer months, the building operates on a partially occupied schedule, and the associated cooling savings are low. The design for optimized cooling showed 4.7% and 11.8% reductions in cooling kWh and heating therms, respectively. Optimized for heating, the model showed 1.8% reduction in kWh and a 16.8% reduction in therms.

Table 10. Energy Savings from PCM

Scenario	Cooling Electricity Savings	Heating Electricity Savings [a]	Heating Natural Gas Savings [b]	Peak kW Demand Savings	Total Electricity Savings	Total Natural Gas Savings	Total Energy Savings
Office – Highest Cooling Savings	**15.2%**	25.3%	-12.7%	**5.4%**	8.7%	-8.4%	5.0%
Office – Highest Heating Savings	**12.6%**	49.8%	-5.2%	**6.6%**	9.0%	-3.9%	5.0%
School – Highest Cooling Savings	4.7%	N/A	11.8%	**5.8%**	2.5%	**11.8%**	5.4%
School – Highest Heating Savings	1.8%	N/A	16.8%	**4.2%**	0.4%	**16.8%**	5.3%

a) School model does not use electricity for space heating
b) Office model shows a small penalty in gas space heating

The optimization process identified building characteristics and operational patterns that lead to the highest heating and cooling energy savings from PCM. Table 11 shows the range of savings for each sensitivity tested in the different parametric categories. Variations in physical characteristics of buildings such as orientation, occupant and equipment densities did not lead to significant variation in energy use. The energy savings range was found to be less than 2% for all sensitivities involving physical characteristics, except for gas savings from orientation in the school model.

In contrast, operational adjustments in buildings had a more significant variation in energy use. For example, the heating setpoint and setback adjustments can reduce gas use between 8-49% in offices. Similarly, cooling setback and setpoint management were also found to have a significant impact on savings from PCM. The results show that PCM can be an effective energy savings technology in many typical commercial buildings, but managing operating conditions is critical to maximizing savings.

Table 11. Range of Energy Savings from Sensitivities Tested for Office and School

Parametric Category	Office – Cooling kWh (%)	Office – Heating kWh (%)	School – Cooling kWh (%)	School – Heating therms (%)
Orientation	12.7-13.4	26.5-27.5	2.9-4.4	3.9-10
Occupant density (SF/person)	12.2-13.0	26.3-27.0	4.1-4.6	8.8-10.8
Equipment density (W/SF)	12.5-12.7	26.2-26.8	4.2-4.6	9.8-10.3
Economizer setpoint – High and low (°F)	12.5-13.5	N/A	4.4-4.5	NA
Cooling setpoint and setback(°F)	3.4-17.4	17.2-27.4	2.5-4.6	8.5-12.5
Heating setpoint and setback (°F)	10.8-12.8	8.1-48.9	4.4-4.5	8.2-10

Office – Highest Cooling Savings

Figure 6. Annual electricity use in baseline vs. office PCM model with highest cooling energy savings

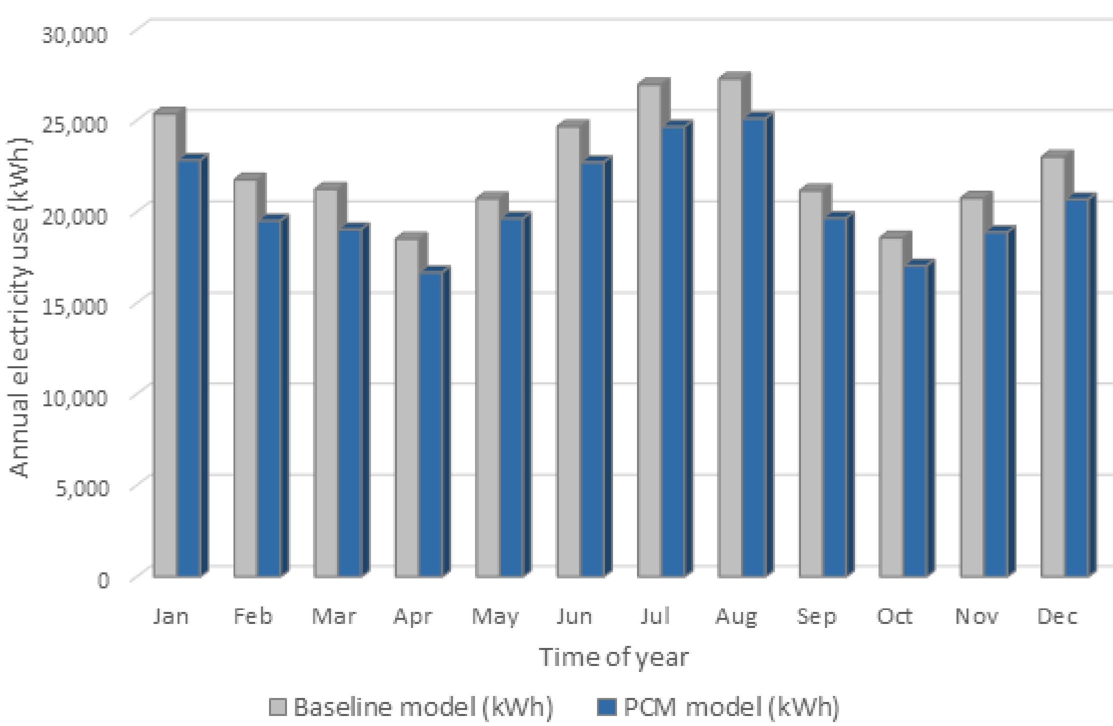


Figure 7. Annual gas use in baseline vs. office PCM model with highest cooling energy savings

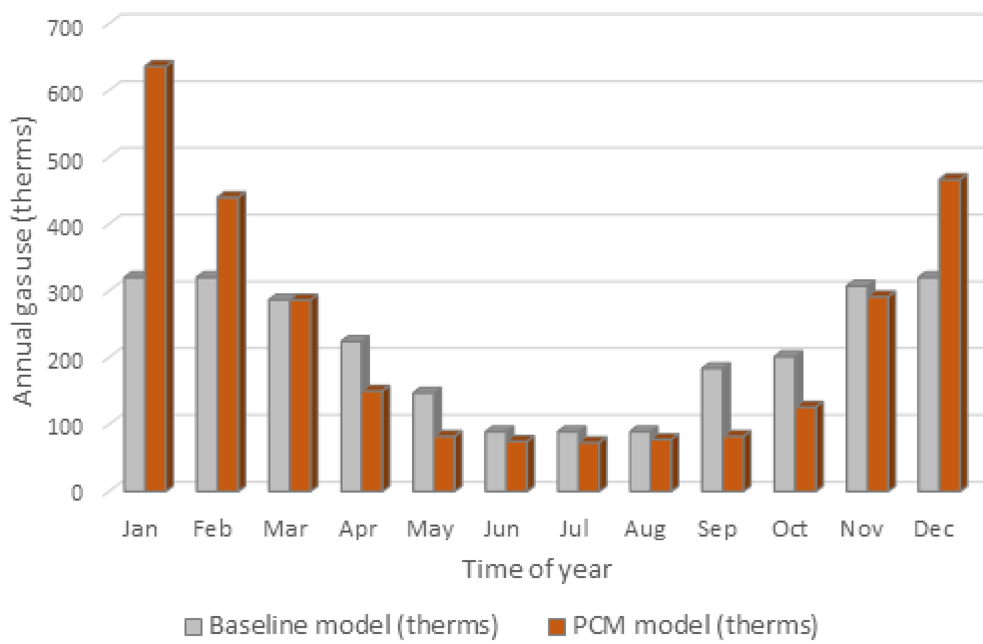
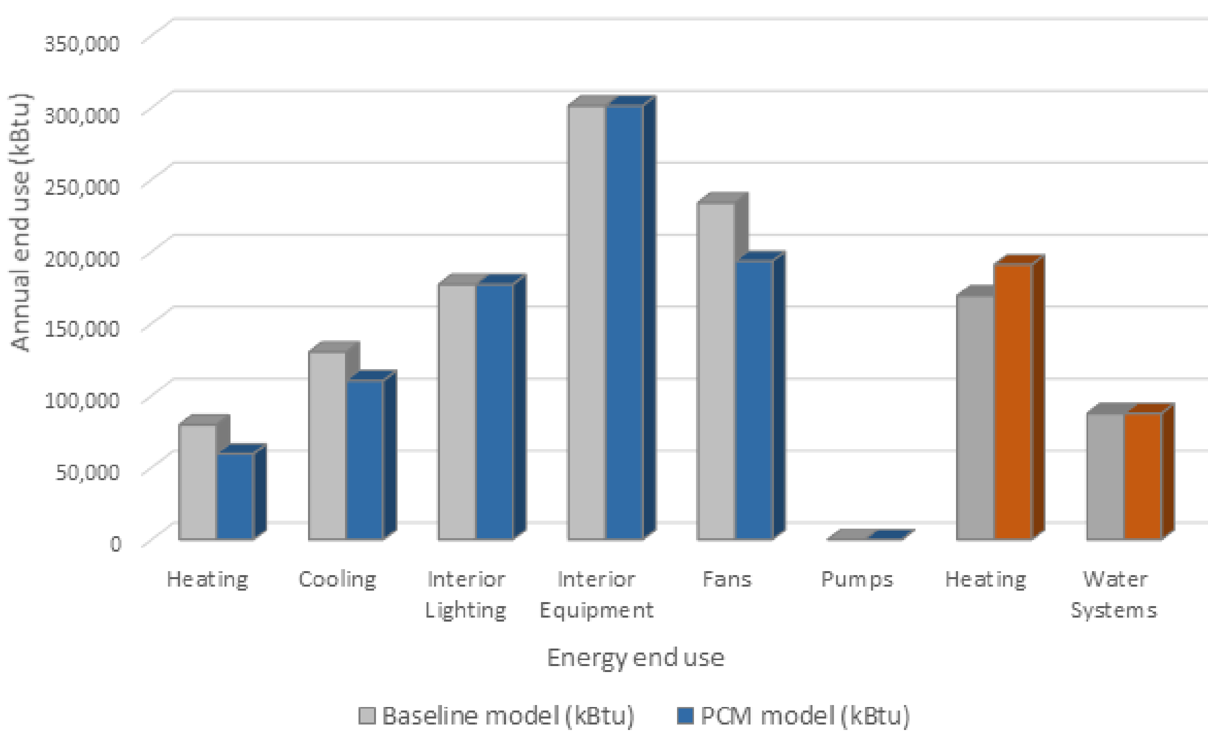


Figure 8. Annual end use comparison for baseline vs. office PCM model with highest cooling energy savings



Annual electricity and gas use for the optimized cooling scenario in office buildings is shown in Figure 6 and Figure 7, respectively. Electricity use reduction from incorporating PCM is observed throughout the year in the model, since both cooling and heating are electric end uses. This scenario predicted an overall 8.7% reduction in total electricity use. The gas use increased from December to February but decreased over the rest of the year. In the heating season, PCM absorbs heat energy in the space which drives up the heating loads. This finding suggests that buildings will benefit from introducing pre-heat during unoccupied hours to charge the PCM, which will help maintain the indoor temperature during occupied hours and reduce gas usage during peak pricing hours. Figure 8 shows annual end energy distribution with lower electricity use for re-heat, cooling and fans, but higher gas heating use.

Office – Highest Heating Savings

Figure 9. Annual electricity use in baseline vs. office PCM model with highest heating energy savings

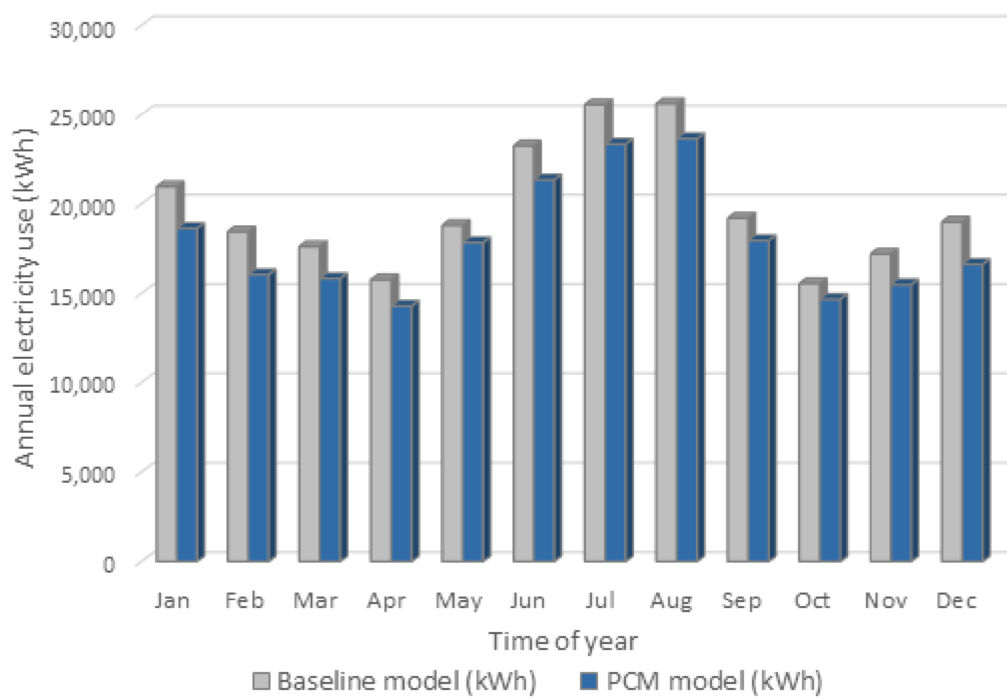


Figure 10. Annual gas use in baseline vs. office PCM model with highest heating energy savings

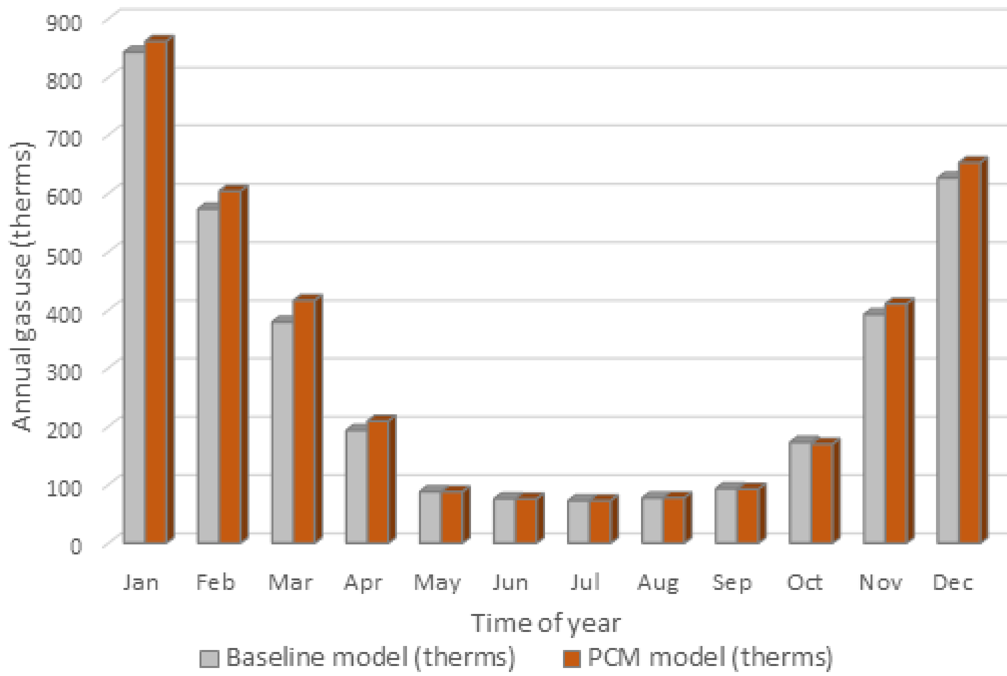
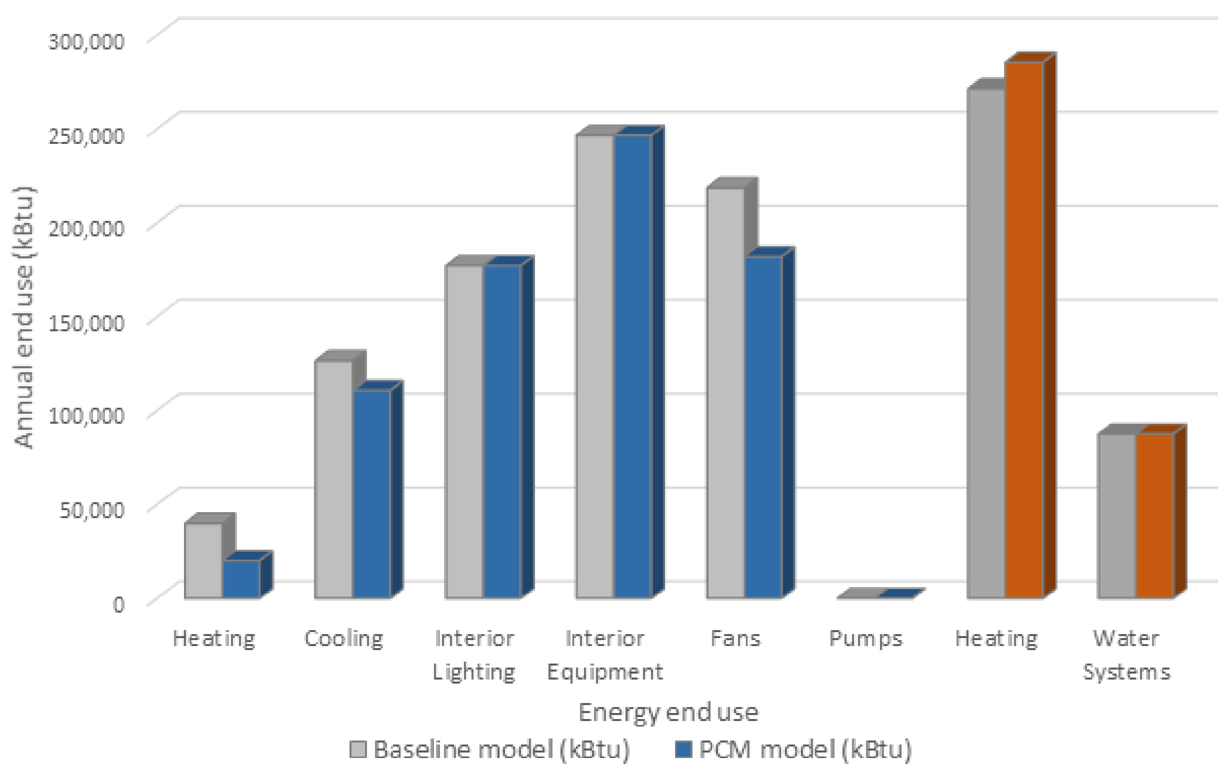


Figure 11. Annual end use comparison for baseline vs. office PCM model with highest heating energy savings



Annual electricity and gas use for the optimized heating scenario in office buildings is shown in Figure 9 and Figure 10, respectively. As in the optimized cooling scenario, electricity use reduction is observed throughout the year from incorporating PCM in the model with an overall 9% reduction in total electricity use. The gas use increased during the heating season, which suggests that buildings will benefit from introducing pre-heat during unoccupied hours to charge the PCM. Preheating during off-peak hours will help maintain indoor temperature during occupied hours and reduce gas usage during peak pricing hours. Figure 11 shows annual end energy distribution with lower electricity use for re-heat, cooling and fans, but higher gas heating use.

Night Flushing

Night flushing or night ventilation is the process of cooling down a building at night with additional ventilation, which may be natural or mechanical (Blondeau 1997). Using natural ventilation for night flushing is a no cost method of discharging PCM during summer nights to maximize its ability to absorb heat during the following day.

Night flushing using natural ventilation needs sufficient diurnal swing in outdoor air temperatures, so the PCM can discharge at night after a summer day. The effect of night flushing could not be sufficiently captured in annual simulation in the model. So, we explored a two-week period from July 11 and 24, when the outdoor air temperature is ideal for night flushing. This period was identified by reviewing the Typical Meteorological Year 3 (TMY3) weather data for a two-week period with a diurnal swing.

We tested night flushing in the office model to evaluate its effect on the charging and discharging process of PCM. We set the model to activate night ventilation when the zone temperature was above 62.6^{o}F, allowing lower temperature outside air to pre-cool the space. This pre-cooling process will discharge the PCM in preparation for the cooling load during the following day. The cooling temperature setpoint and setback were set to 75.2^{o}F and 78.8^{o}F respectively, in this test case.

As shown in Figure 12, PCM effectively controlled the zone temperature in a narrower range of 71F to 76.5F during the day, compared to the baseline case where the zone temperature drifted between 71F and 79F. Daytime temperatures were lower in the PCM case than in the baseline case, effectively shifting and reducing the load during the afternoon 1:00 – 5:00 p.m. peak hours. This indicates that the mechanical systems can operate over a wider temperature range which saves energy, while the PCM enables stable indoor temperature control. The results also indicate higher thermal comfort and less cycling of the mechanical system due to PCM in the space.

Figure 12. Zone 5 Mean Air Temperature

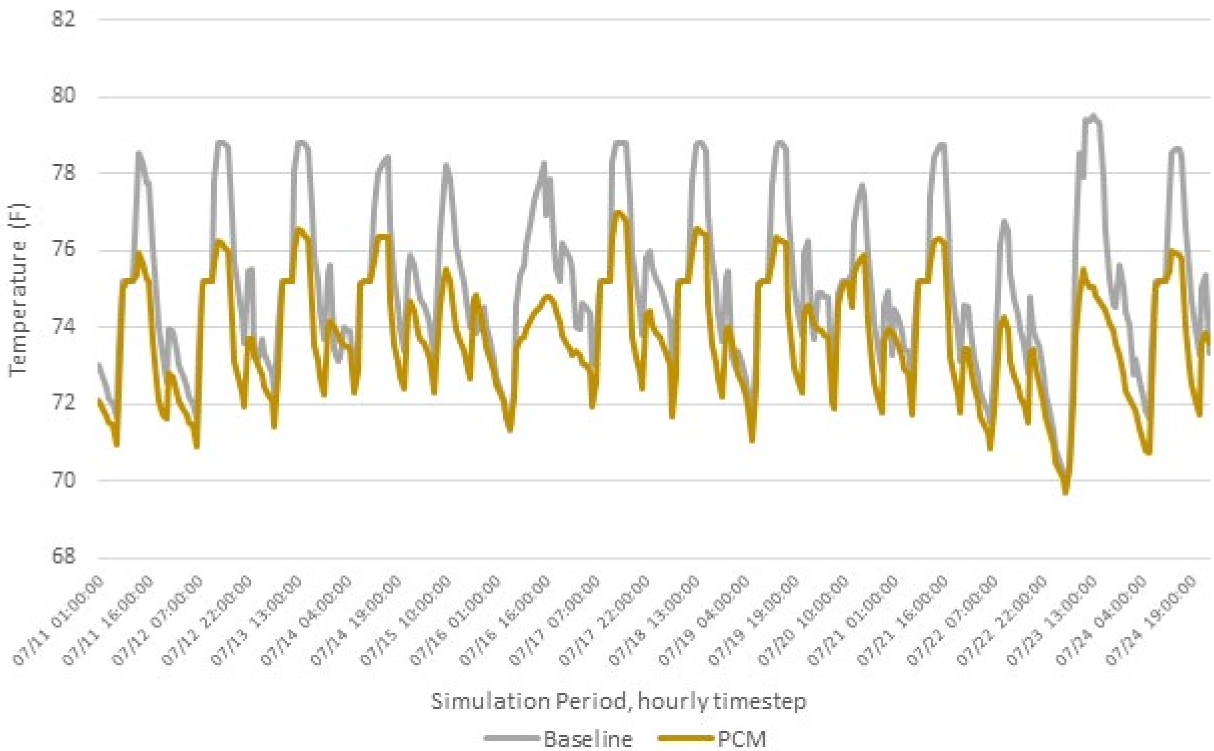
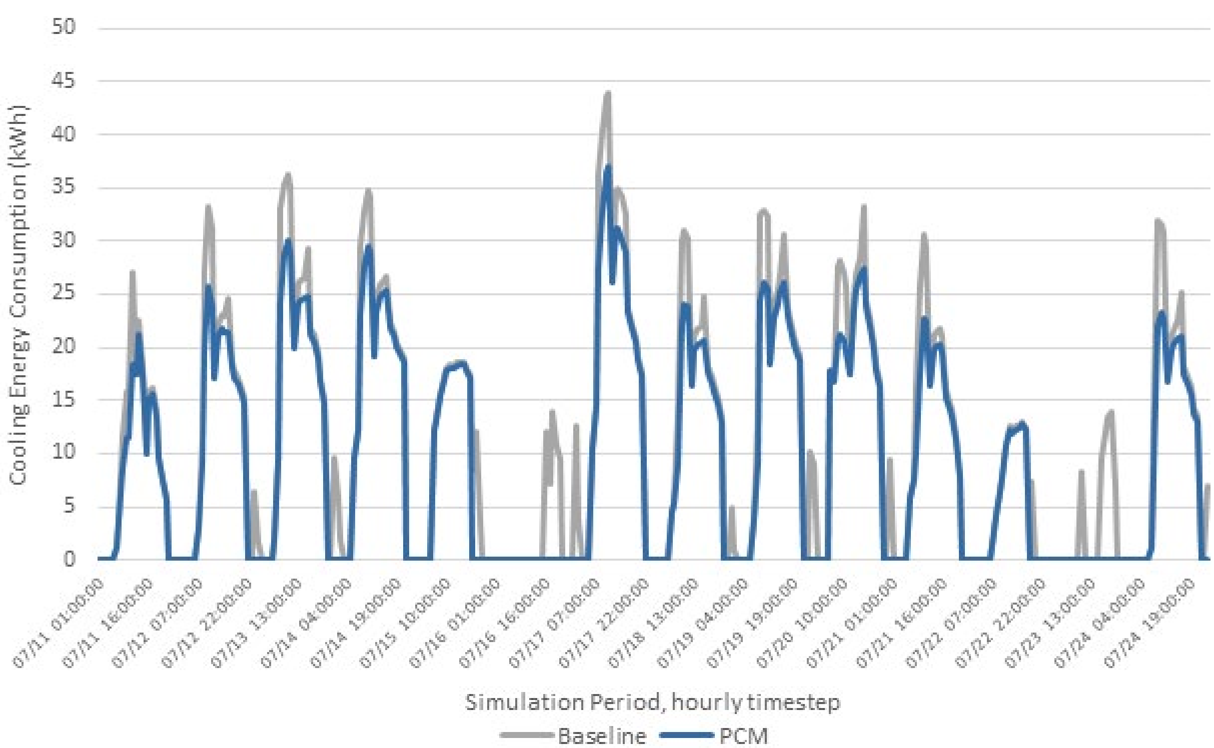
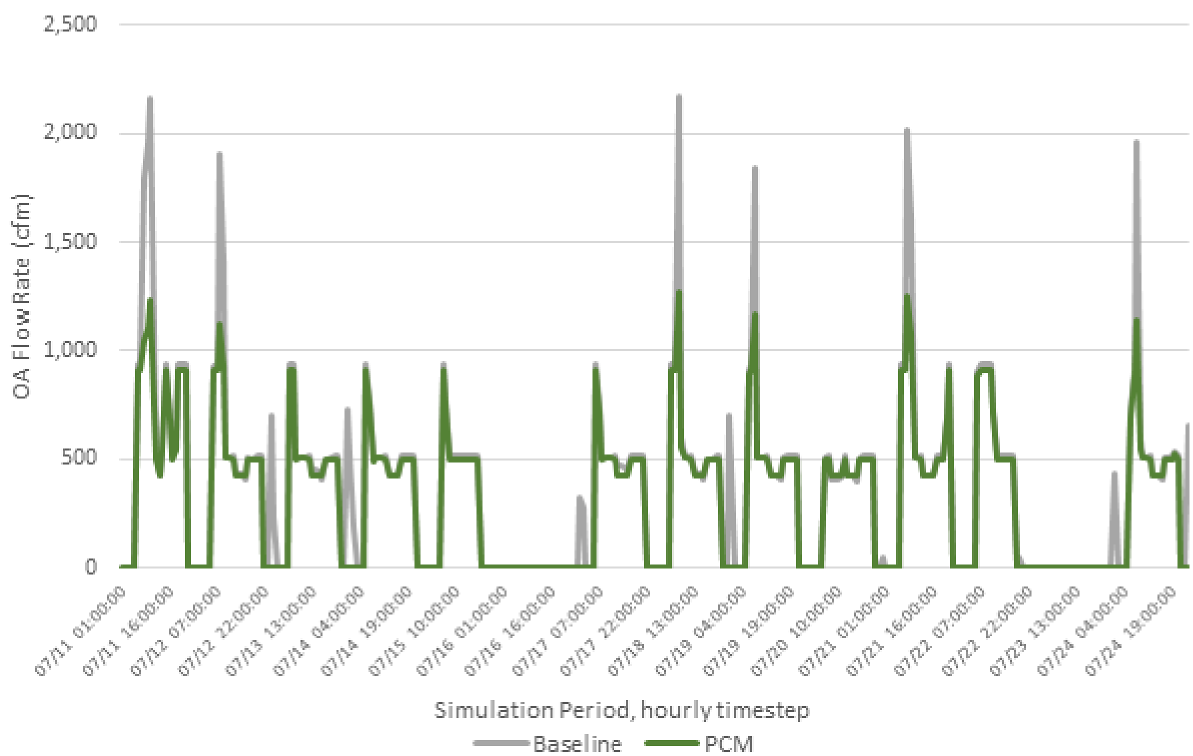


Figure 13. AHU Cooling Coil Electric Energy



As shown in Figure 13, incorporating PCM effectively reduced cooling energy usage during the daytime compared to the baseline case. For some periods (e.g. July 16 1:00 – 5:00 p.m. and July 23 1:00 – 5:00 p.m.), the air handling unit in the PCM case shows a complete shut down without the need for mechanical cooling, whereas the baseline case showed spikes calling for active mechanical cooling. For the two-week simulation period, total cooling energy use was reduced by 15.8% in the PCM case. Figure 14 shows that mechanical ventilation was reduced from 5:00 – 9:00 a.m. for the PCM case, as the space did not need as much pre-cooling (economizing) because of lower zone temperatures.

Figure 14. Zone 5 Mechanical Ventilation Flow Rate



On summer days without a diurnal swing in outdoor air temperatures, night flushing with mechanical cooling is still a cost-effective method of discharging the PCM. Buildings can benefit from pre-cooling the space at off-peak fuel pricing hours and save cooling energy cost during peak-priced daytime periods.

School – Highest Cooling Savings

Figure 15. Annual electricity use in baseline vs. school PCM model with highest cooling energy savings

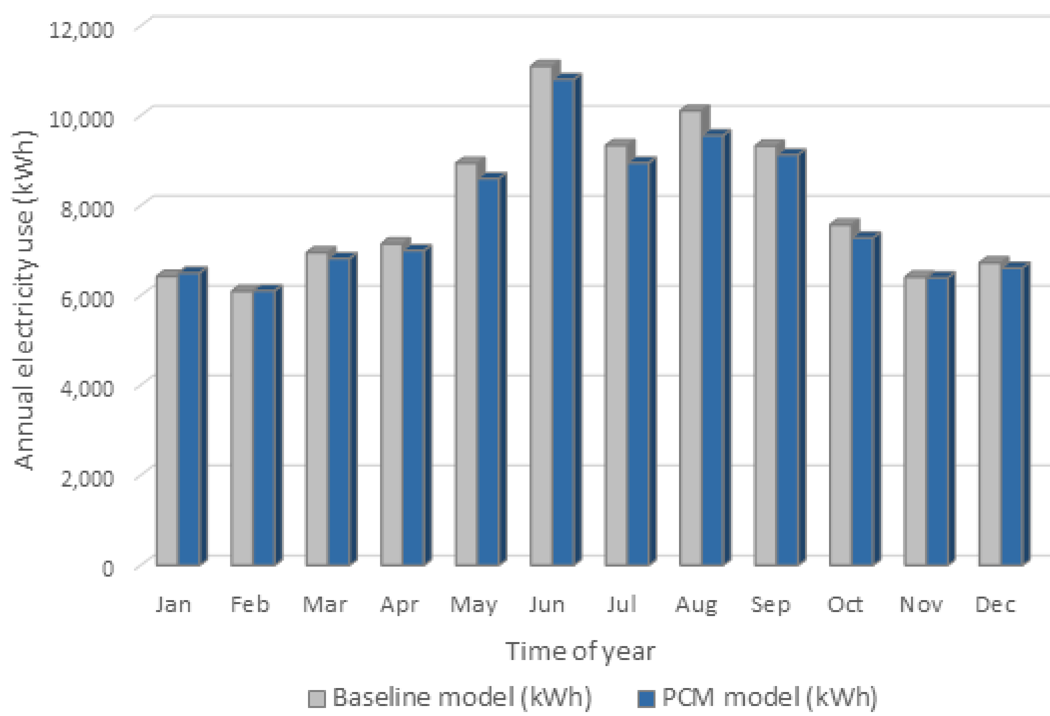


Figure 16. Annual gas use in baseline vs. school PCM model with highest cooling energy savings

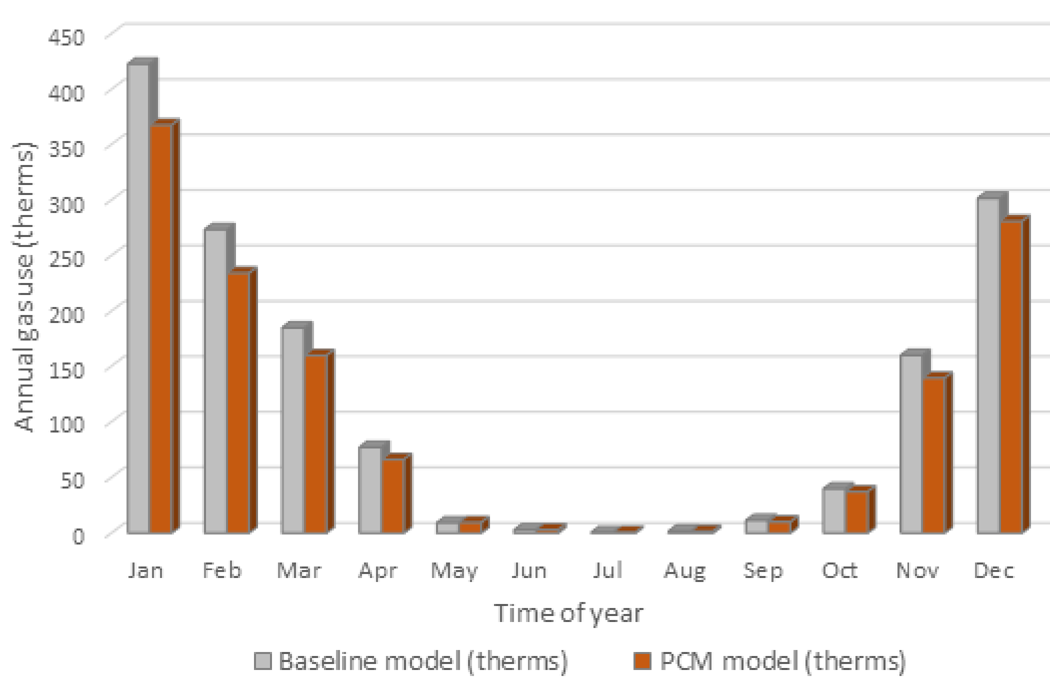
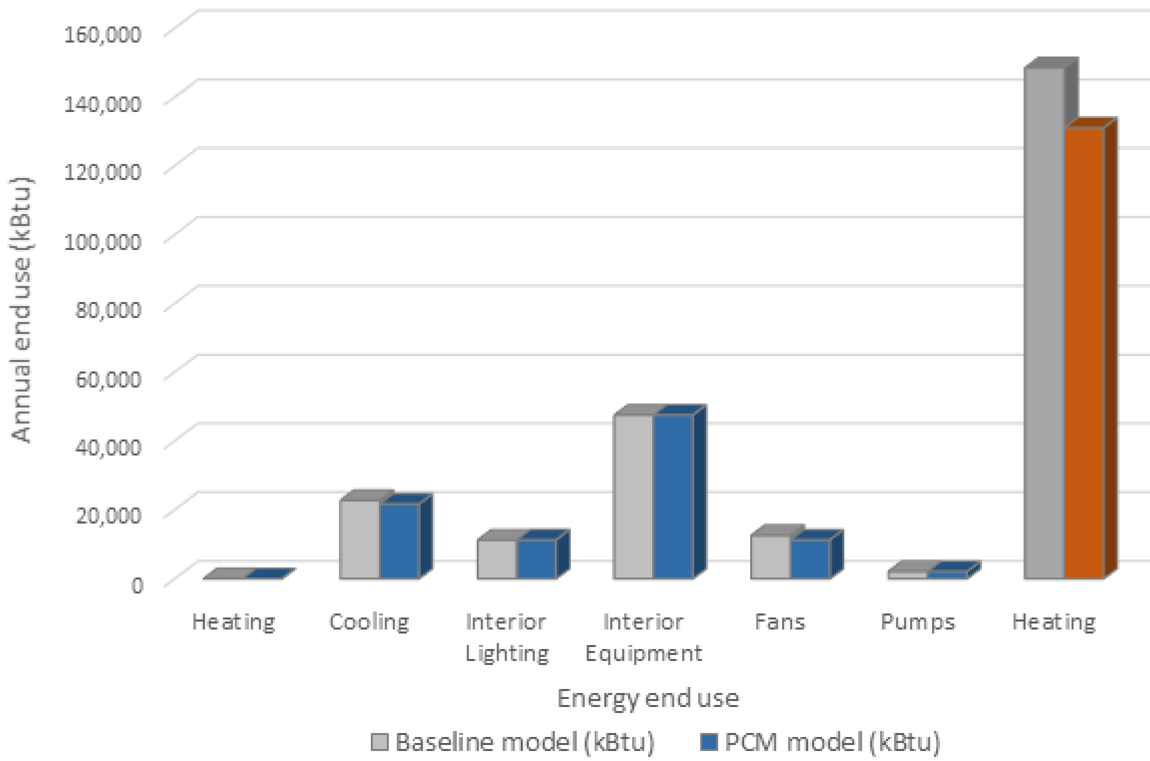


Figure 17. Annual end use comparison in school with highest cooling energy savings



Annual electricity and gas use for the optimized cooling scenario in school buildings is shown in Figure 15 and Figure 16, respectively. Electricity use reduction is observed throughout the year from incorporating PCM, except for a small increase in January. Overall, a 2.5% reduction in total electricity use was observed in this model. School buildings that operate at partial or peak capacity during summer months will maximize the cooling energy savings from PCM. The gas use decreased throughout the year, leading to an 11.8% reduction in heating gas use. Figure 17 shows annual end energy distribution with lower electricity and gas consumption for all end uses.

School – Highest Heating Savings

Figure 18. Annual electricity use in baseline vs. school PCM model with highest heating energy savings

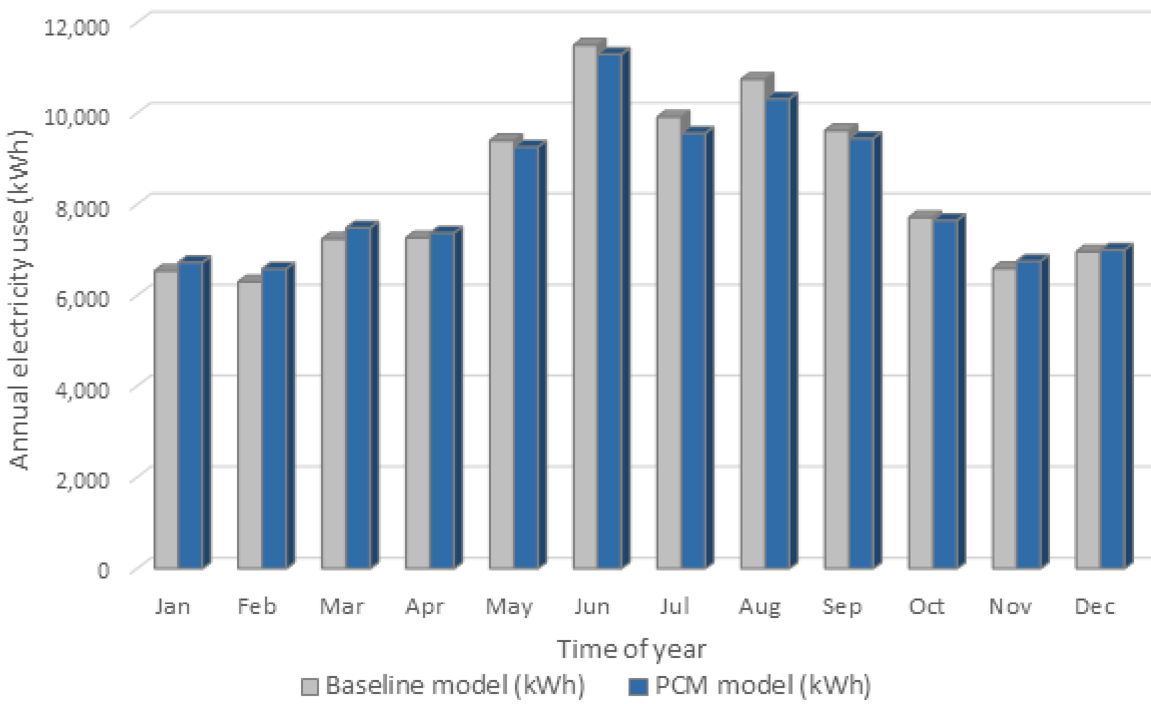


Figure 19. Annual gas use in baseline vs. school PCM model with highest heating energy savings

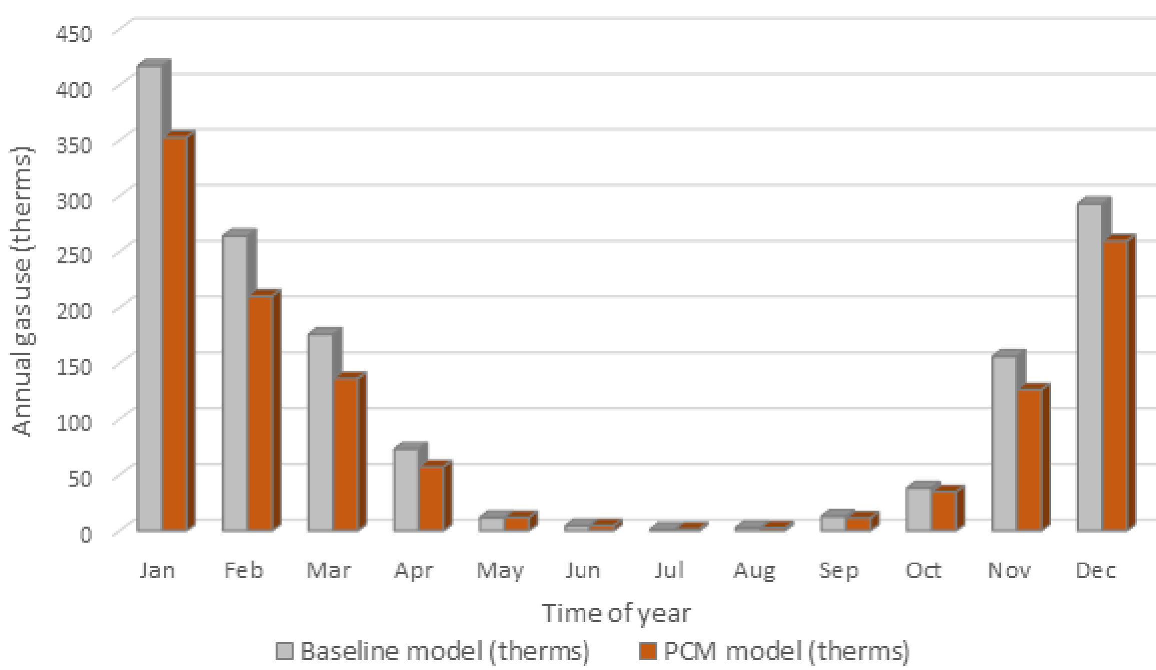
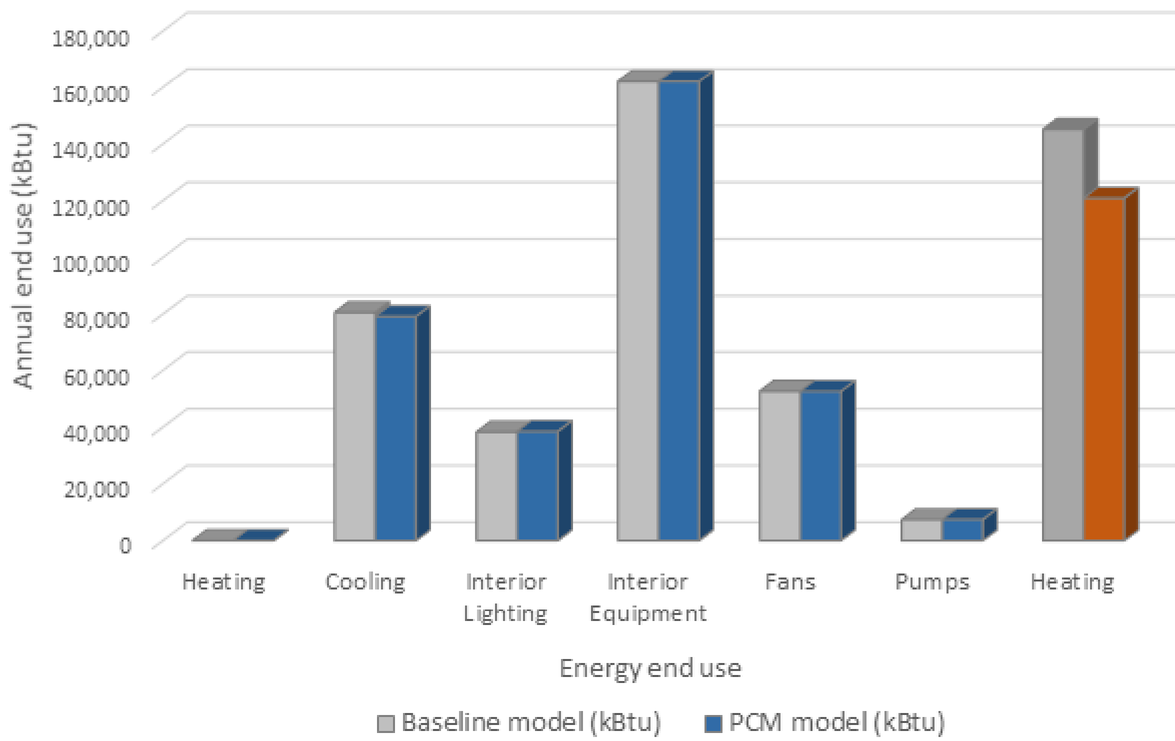


Figure 20. Annual end use comparison in school with highest heating energy savings



Annual electricity and gas use for the optimized heating scenario in school buildings is shown in Figure 18 and Figure 19, respectively. The heating energy use decreased throughout the year, leading to a 16.8% reduction in gas use. Schools that only use heating for space conditioning can benefit greatly from installing PCM. In this scenario, electricity use increased during the heating season, but overall, a 0.4% reduction in electricity use is observed. Figure 20 shows annual end energy distribution with lower electricity and gas use for heating and cooling end uses.

Life Cycle Cost Analysis Results

Results from the energy models were used to analyze the life cycle costs of each of the four final scenarios. The office scenarios include 17,889 SF of PCM with an estimated installed cost of $53,667. The school scenarios include 5,018 SF of PCM with an estimated installed cost of $15,053.

The life cycle cost analysis compares the initial cost of the PCM to the annual energy cost savings, along with the residual value of the PCM at the end of the 25-year study period. Net savings are shown in present-value dollars, representing the savings achieved over the study period in excess of the amount that would have been earned from investing the same funds at the minimum acceptable rate of return (i.e. the discount rate). A positive value for net savings indicates that the strategy is cost-effective, while strategies with negative values are not cost-effective.

Using Minnesota's average retail electricity prices, the life cycle cost analysis shows positive net savings in the two office scenarios but not in the school scenarios (Table 12), despite the two building types achieving similar overall energy use reductions. This difference in cost-effectiveness can be attributed to several factors:

- The biggest factor is the use of electricity for reheat in the office. The school achieves most of its heating savings through natural gas reduction. Since natural gas is relatively inexpensive in comparison to electricity, it takes longer to pay back.
- The cooling savings are higher in the office since it operates at constant occupancy throughout the year, while the school only operates at a partial-occupancy summer schedule from June through September.

Table 12. PCM Life Cycle Cost Results – MN Average Utility Rates

Scenario	Net Savings (Present Value $)	Net Savings (Present Value $/SF)
Office – Highest Cooling Savings	$8,820	$0.49
Office – Highest Heating Savings	$5,748	$0.32
School – Highest Cooling Savings	- $1,612	- $0.32
School – Highest Heating Savings	- $4,220	- $0.84

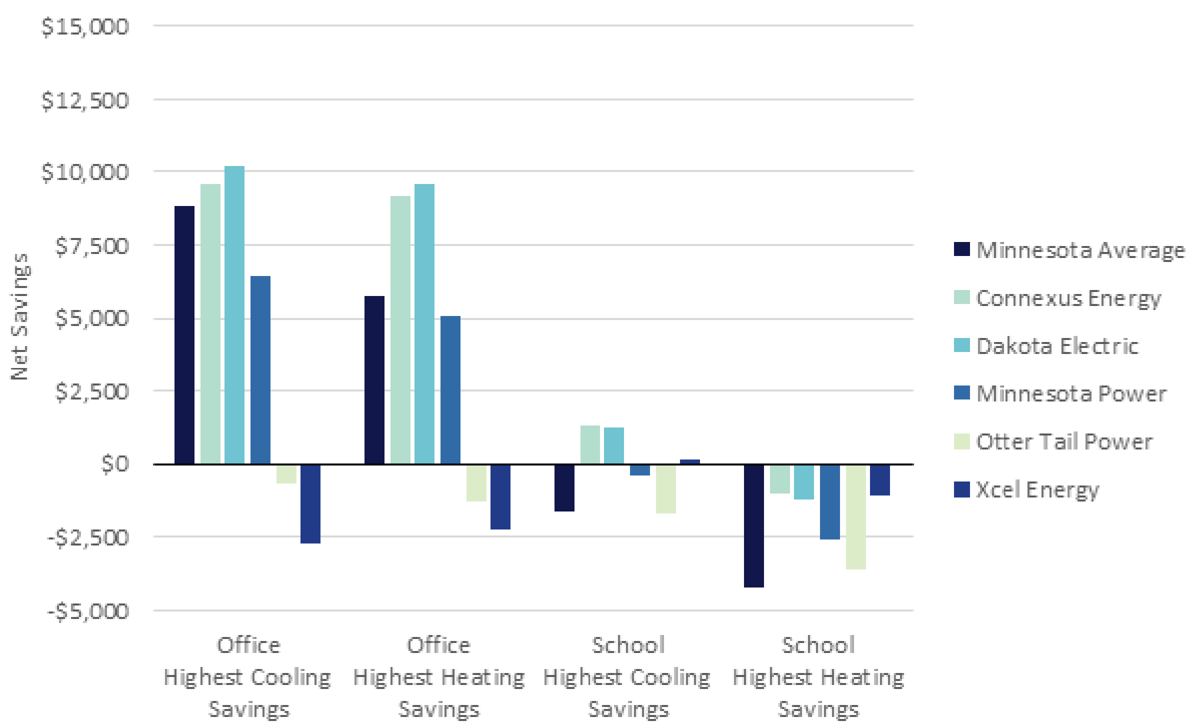
In addition to using Minnesota's average electricity prices to calculate net savings, we also tested the general commercial rate structures for Minnesota's five largest electric utilities (Xcel Energy, Minnesota Power, Connexus Energy, Dakota Electric Association, and Otter Tail Power). Since these rate structures assign different weights to total energy (kWh) versus demand (kW), they have a significant impact on cost-effectiveness, representing the range of savings achievable through implementing PCM in Minnesota.

As shown in Table 13 and Figure 21, the School – Highest Heating Savings scenario is the only scenario that is not cost-effective under any of the studied rate structures. The other three scenarios are cost-effective under most of the studied rate structures, though the net savings vary significantly. In general, buildings served by utilities with higher overall rates (e.g. Dakota Electric and Connexus Energy) will achieve the greatest net savings from implementing PCM. Secondarily, schools served by utilities whose rates are weighted more heavily toward demand (e.g. Connexus) will achieve the greatest net savings, since the two school scenarios attain higher demand savings than overall electricity savings.

Table 13. PCM Net Savings by Electric Utility

Scenario	Connexus Energy	Dakota Electric	Minnesota Power	Otter Tail Power	Xcel Energy
Office – Highest Cooling Savings	$9,577	$10,232	$6,475	- $697	- $2,720
Office – Highest Heating Savings	$9,193	$9,615	$5,103	- $1,291	- $2,225
School – Highest Cooling Savings	$1,329	$1,225	- $376	- $1,668	$142
School – Highest Heating Savings	- $972	- $1,203	- $2,552	- $3,600	- $1,103

Figure 21. PCM Net Savings by Electric Utility



A major limitation of the energy modeling study was the inability to vary the amount of PCM in the model, resulting in using approximately 2.2 times as much PCM as required for optimal energy savings (see Modeling Limitations). This led to additional material first costs that are disproportionately higher than the corresponding operational energy savings. To test the potential cost-effectiveness impacts of right-sizing the PCM, we ran a life cycle cost analysis that assumes 80% of the energy savings can be achieved using 45% of the PCM (Childs 2012, p. 25). Using the Minnesota average electricity rates, this would cause the School – Highest Cooling Savings scenario to flip from not cost-effective (net savings of -$1,612) to cost-effective (net savings of $1,590) and would increase net savings from $8,820 to $17,317 for the Office – Highest Cooling Savings scenario, reducing the simple payback to 14 years. For Xcel Energy customers, this would flip the least cost-effective scenario (Office – Highest Cooling Savings) from not cost-effective (net savings of -$2,720) to cost-effective with a net savings of $7,493.

Additionally, these results do not include rebates, which could increase the net savings by a modest amount. Incorporating a $400/kW and $5/therm rebate[2] to the Office Highest Heating Savings scenario (MN average electricity prices) would increase the net savings from $5,748 to $7,380. The full set of reports produced by the BLCC tool are available in Appendix B: Life Cycle Cost Analysis Reports.

[2] Based on Xcel Energy's Custom Efficiency rebate program for businesses

Discussion of Results

This study shows that PCM can cost-effectively reduce energy use and peak demand in Minnesota buildings and defines operating parameters to maximize savings in offices and schools. This section extrapolates these findings to determine PCM's statewide savings potential, emphasizes the need for a field study, and describes practical considerations for integrating PCM into Minnesota's building sector.

Minnesota Savings Potential

Minnesota's Next Generation Energy Act of 2007 established a statewide energy savings goal of 1.5 percent of gross annual retail electricity and natural gas sales. To understand PCM's potential to help meet these goals, we estimated the savings from applying this technology to buildings across the state.

To estimate potential savings from PCM energy conservation programs, we extrapolated the energy savings from our study to applicable buildings in the entire state of Minnesota. We used the Commercial Building Energy Consumption Survey (CBECS) 2003 data for West North Central region to extrapolate estimated floor space in 2021 for Minnesota and identified the building types most likely to benefit from PCM using findings from our literature review and modeling analysis. We focused on building types that are likely to have constant daytime occupancy and high internal loads. We arrived at 675,000,000 SF for offices, nursing, non-refrigerated warehouses, inpatient healthcare, food service and public safety building types (grouped as office building types) and 568,000,000 SF for education and public assembly (grouped as educational building types). We estimated a market penetration for PCM between 1-3% in these building types.

Finally, we applied savings estimates from the sensitivity analysis to the eligible building area in Minnesota. We applied savings percentages to cooling, heating and fan end uses in the Minnesota sub-dataset. From our modeling study, office building types show between 12.6-15.2% electric cooling savings, 25.3-49.8% electric heating savings, 16.8-17.4% fan energy savings, and a 5.0-12.7% increase in natural gas consumption (due to the PCM absorbing heat that would otherwise contribute to space heating). This translates to a 7,670,000 – 8,480,000 kWh reduction in electricity and a 331,181 – 130,386 therm increase in natural gas in office building types statewide.

For education and public assembly building types, our modeling study shows between 1.8 – 4.7% electric cooling savings, 0.025 - 10.6% electric fan energy savings, and 11.8-16.8% heating gas savings. This translates to 227,000 – 3,020,000 kWh savings and 269,000 – 381,000 therm savings in educational buildings statewide.

The total statewide achievable annual savings potential is between 8,700,000 – 10,700,000 kWh of electricity and between -62,000 – 251,000 therms of natural gas.

Simulation versus Field Measurement

The greatest barrier to implementation of PCM in Minnesota is the limited knowledge available due to lack of field studies on PCM performance in colder climates. While many studies backed by simulation exist surrounding the effectiveness of PCM, there is a possibility of gaining more accurate and specific information from a full-scale field test (Childs 2012). In fact, most articles reviewed for this study mentioned a need for further exploration to field validate the simulation data. Delaney writes:

> More simulations are needed to better understand the effects of varying parameters. A parametric simulation study can help identify the climate, building type, PCM properties, and HVAC system to theoretically optimize performance. However, such a study must also include laboratory or field validation. Development of a systematic approach (as opposed to a custom simulation-based approach or contractor's best guess) would be constructive in selecting a PCM best suitable for each application (Delaney 2012, p. 3.166).

The field studies that do exist focus on Southern climates, creating a need for further exploration of colder climates like Minnesota. Since a large part of the literature surrounding PCM focuses on these Southern climates, there is a need for detailed exploration into the varied parameters of Northern climates. Many of these parameters are complex when simulated, thus a field study would be a useful way to explore variations between them (Fallahi 2013). The lack of climate-specific guidelines for PCM selection creates uncertainty and acts as a barrier to market expansion; if field research could show the long-term economic benefits, interest in PCM could increase, driving down costs and increasing product innovation (Jelle 2017).

Considerations for Market Adoption

Incorporating PCM has a minimal impact on standard architectural and construction practices, allowing for a smoother integration of the technology into the market. The primary barriers to market adoption of PCM in Minnesota are the lack of knowledge about the technology, the expertise required to optimize PCM's design, and the up-front costs.

Design Considerations

Though optimizing PCM's application within a building design currently requires access to technical expertise, the product itself can be easily incorporated into standard architectural assemblies and details. Available PCM products allow for design flexibility; the varied forms and types enable it to be incorporated into a building in several ways. While above-the-ceiling applications remain the least invasive, PCM can also be installed as a component within wall and roof assemblies and can even be integrated as an additive within other construction materials, such as gypsum wallboard, concrete, and paint. As the thickness of the PCM is not believed to have an impact on its effectiveness in terms of energy conservation (Childs 2012, pp. 15-16), applications can remain relatively thin and lightweight, eliminating the need for additional structural support and minimizing increases to assembly thicknesses.

The two PCM products discussed in this report, InfiniteR and BioPCM, are 0.25” and 0.5” thick, respectively, and can be incorporated into ceiling, wall, or roof assemblies.

With minimal impact on architectural assemblies and details, the primary design considerations for PCM are determining the optimal application (e.g. wall, ceiling, roof), selecting an appropriate product, determining the optimal coverage, and evaluating potential impacts on mechanical system sizing (for new construction applications). Currently, this is typically done in consultation with PCM distributers that provide rules-of-thumb for product selection and sizing and may provide specialized energy modeling services to help optimize savings. Due to the complexity of simulating PCM’s impacts, it would require a significant time investment for energy modelers that haven’t worked with it before. This challenge could be overcome through the development of guidance materials for energy modelers and/or the development of a systematic, product-agnostic approach to PCM design that negates the need for custom simulations for each project.

The following sections include general information about the primary design considerations for incorporating PCM into new construction or existing buildings.

Building Eligibility

Designers should first determine whether the building characteristics make it a good candidate for PCM. As we’ve seen in this study, buildings with constant daytime occupancy and higher internal loads are likely to see the greatest energy savings from incorporating PCM in Minnesota’s climate. Computer labs and office spaces with high internal equipment loads are good examples of this, with high internal heat loads during the day that can be released at night when the computers are off. Other space types are less suitable for PCM. For example, hospitals often have strict ventilation requirements that can interfere with the charging and discharging process of the PCM (Delaney 2012, p. 3.170).

A building automation system is also critical to successfully integrating PCM in a commercial building. From this study, it is apparent that seasonal adjustments to temperature setpoints, setbacks and economizing when possible are critical to maximize savings from PCM.

Product Selection

The three main types of PCMs available for use in building construction are: bio-based, paraffin derived from petroleum, and nonorganic salt hydrates. These PCMs are typically encapsulated in plastic vessels of various shapes and sizes through a process called macroencapsulation. PCMs can also be microencapsulated (through a chemical process of coating small amounts of PCM) and mixed into products like gypsum wallboard and concrete; these forms are better suited to new construction than retrofits.

The PCM products that are currently readily available in the Minnesota construction market are InfiniteR and BioPCM. Each of these products can be obtained in Minnesota through direct contact with their respective distributer and can be easily installed in retrofit applications above a suspended ceiling.

InfiniteR

InfiniteR, distributed by Insolcorp, is a 0.25-inch-thick, salt hydrate PCM product made using natural minerals such as clay, salt, and water. Unlike paraffins, which are created as a by-product of a fossil fuel, InfiniteR does not require fossil fuels to produce the raw materials beyond extraction, helping to lower the environmental impact of the product when compared to paraffins. Salt hydrates are generally cost-efficient and have a high latent heat storage capacity. They are also inherently nonflammable, unlike paraffins which may require flame retardant additives that can lead to lower thermal conductivity (Fallahi 2013, p. 1). InfiniteR has an NFPA Class A Fire Rating without the need for flame retardants.

With salt hydrates it is important to be aware of the lifespan of the product since repeated phase change cycles can lead to a lower efficiency as the mixture separates. This process can be countered through thickened mixtures and proper nucleating materials (Jelle 2017), as well as by preventing changes in the moisture content of the PCM mixture. Insolcorp offers a 25-year warranty for their products and expect minimal degradation of efficiency (conservative estimate, 5%) over the life of the product (Insolcorp 2018). In an eight-year field exposure test, InfiniteR showed no degradation (Insolcorp 2018).

Depending on the mixture, salt hydrates also have the potential to contain toxic, corrosive materials, which can lead to degradation of their encapsulating material if incompatible and can also be a concern if the encapsulating material gets punctured. Insolcorp claims that InfiniteR uses non-toxic ingredients and plastic vessels to avoid degradation of the material and conform to building safety standards.

BioPCM

BioPCM, produced by Phase Change Energy Solutions (PCES), is a bio-based PCM manufactured using plant by-products. The 0.5-inch-thick ENRG blankets were the form of BioPCM considered in this report due to their ease of installation. Bio-based PCMs can be naturally produced with minimal greenhouse gases emissions (Fallahi 2013, p. 13). Organic PCMs are non-toxic, experience little volume change between phases, and are naturally fire-resistant (PureTemp 2019). The fire rating of ENRG Blanket applications of BioPCM meets or exceeds ASTM E84, UL 723 and ASTM E800-0 99 standards (PCES 2018).

Most bio-based PCMs do not experience phase segregation – which causes a separation of the material components over time and alters its melting point – meaning they should perform over their lifespan without degradation (Jelle 2017, p. 60). It is also worth noting that many organic PCMs have low hysteresis, meaning the melting and freezing temperature curves are relatively similar (Cabeza 2015, p. 415). While this characteristic is helpful for more accurately predicting energy savings, the actual impact of hysteresis on savings varies based on building conditions and is not well-studied (Childs 2012, p. 33). BioPCM is claimed to have a useful life of over one hundred years for indoor applications (PCES 2018). The packaging for this product is plastic, minimizing the chance of corrosion from the PCM itself, although exterior applications of the material may cause the packaging to degrade. PCES offers a recycling program at end-of-life for both the plastic container and the raw PCM.

Although organic PCMs are often more expensive than inorganic alternatives, BioPCM and InfiniteR offer comparable prices.

Selecting the Phase Change Temperature

PCMs are engineered to change phase when they reach a specific temperature range, which is often identified by its midpoint. Standard phase change midpoints range from 73-81°F for BioPCM and 66-84°F for InfiniteR. It is generally safe to assume that the optimal midpoint temperature should be close in value to the ideal interior setpoint temperature, which will allow the PCM to fully freeze and thaw (Childs 2012, pp. 16-17). However, incorporating additional project-specific considerations can help maximize PCM's energy and/or cost savings potential.

A primary design consideration for any PCM project is the local climate and site conditions; the outside air temperature, shade conditions, and solar absorptivity of the exterior walls will impact which energy loads to focus on and which PCM midpoint temperature to select (Childs 2012, p. 16). Since Minnesota's climate requires both heating and cooling, the midpoint temperature of the PCM must be selected to consider both heating loads and cooling loads (Childs 2012, p. 8). Higher melting points will tend to be more efficient during cooling scenarios.

The building's energy sources may also play a role in determining the ideal midpoint temperature. If a more expensive heating fuel like propane is used, it may be more cost-effective to optimize the PCM for the higher cost of heating loads, even if the energy savings would be higher for cooling loads. Our life cycle cost analysis demonstrates this; the scenarios that are optimized for cooling (electricity) are more cost-effective than the scenarios optimized for heating (primarily natural gas). On the other hand, owners motivated by carbon reductions can optimize the midpoint temperature to address the most carbon-intensive fuel source.

Product Acquisition

PCM products can be obtained through a similar process as other construction materials. Both Insolcorp and PCES have websites that provide product data and a contact form for building owners or contractors to request a price quote. Company representatives are available to provide product selection guidance and assist in ordering. Manufacturing for both companies occurs in North Carolina.

Insolcorp provides an additional product acquisition option through partnership with a company called D.I. Pathways. Instead of purchasing the product themselves, building owners pay a fixed monthly fee for PCM upgrades that are owned and installed by D.I. Pathways.

Constructability

PCM building products are designed for ease of installation within standard new construction practices and through non-invasive retrofits. Many products are dimensioned to fit within standard construction measurements (Delaney 2012, p. 3.163). In wall applications, PCM products the width of stud spacing can be mechanically attached to the studs prior to installing the interior gypsum wallboard (Figure 22).

Retrofits in suspended ceilings can be achieved with minimal disturbance of the existing space by removing a ceiling tile, laying the blanket-type product on the surrounding tiles, and replacing the ceiling tile. Unlike thermal insulation or air sealing, continuous application of PCM is not critical. This enables people without special training to complete the installation, which reduces costs.

Figure 22. Installation of PCM in Ceiling and Wall Applications

Retrieved from [Environmental Technology Solutions webpage]

Operations and Maintenance

Many energy conservation measures require the active participation of facility managers to achieve ongoing savings, whether through building controls or regular equipment maintenance. As a passive strategy that is anticipated to outlive most buildings, PCM products generally do not require maintenance. However, facilities personnel can maximize PCM's effectiveness by ensuring the interior setpoint temperature remains consistent with the intended range, as unintentional variations in the setpoint temperature will have a negative impact on potential savings (Childs 2012, p. 30). Since PCMs are dynamic, their effectiveness increases when setpoints are adjusted seasonally to respond to prevailing weather conditions. This can be automated using a BAS that can make real time building control adjustments.

Facility operators can also use the BAS to reduce cooling costs by introducing night flushing to discharge the PCM on days when diurnal temperature swings allow during the shoulder season and on summer days with nighttime temperature drops. This eliminates the need for mechanical pre-cooling and helps the PCM discharge during unoccupied hours. When night flushing is not an option because the overnight temperature will not fall below the freezing point of the PCM, mechanical assistance may be needed to charge or discharge the PCM.

Due to the potential for building operations to impact energy savings from PCM and the lack of familiarity with this technology, guidance should be incorporated into building operator training and included in the building operations manual. This guidance should list the optimized setpoint temperatures, describe the reasons for these setpoints and the potential impacts of changing them, and establish a building-specific procedure for night flushing.

Cost

The blanket-type PCM products available in Minnesota have a similar install cost around $3.00 per square foot (Insolcorp 2018; Scott Queen, phone conversation with authors, November 18, 2019). When comparing initial costs to operational energy savings, PCM's cost-effectiveness is dependent on the quantity of PCM installed, the magnitude of energy and demand savings, and the price of the displaced energy. As shown in the life cycle cost analysis, some applications will be cost-effective and others will not. Other variables such as eliminating or downsizing a new HVAC system or improving occupant satisfaction and productivity can improve PCM's cost-effectiveness.

Current PCM distributers also offer pricing models that reduce costs. PCES provide a 10% discount for projects over 50,000 SF and 25-40% discounts for repeat business. Insolcorp lowers risk and upfront costs by pairing with D.I. Pathways to offer a monthly subscription plan, where building owners pay a fixed monthly fee to lease PCM for their space. This reduces the financial risk to the owner, since the company assumes risk for the product in the case of underperformance on energy savings. While this model was not evaluated in our life cycle cost analysis, it has potential to increase PCM's cost-effectiveness in Minnesota.

A final cost consideration is the ongoing development of the PCM market; growth in market demand will help drive down costs and encourage further explorations into increased efficiency (Fallahi 2013, p. 8).

Conclusions and Recommendations

This study shows that PCM can cost-effectively reduce energy use and peak demand in Minnesota buildings, provides initial insight into implementation, and validates the need for a field study to understand the technology's real-world application potential. The remainder of this section discusses the potential implications of these outcomes for Minnesota's CIPs.

PCM Program Potential

PCM products can be easily installed in suspended ceilings through a non-invasive retrofit, making it a candidate for a broad utility CIP offering. A PCM program could be marketed both to architects working on renovation projects and to facility managers looking to reduce their energy costs and improve occupant comfort. Typically comprised of lightweight materials, PCM can be installed in both lightweight and heavy construction without requiring additional structural support. Additionally, PCM can be an effective option for older masonry buildings where implementing insulation or air sealing strategies would change how the exterior walls handle moisture and could comprise their structural integrity. Due to this widespread applicability, a PCM program would be equally applicable to the portfolios of investor-owned utilities, cooperative utilities and municipal utilities, and has the potential to contribute toward the State's 1.5% energy savings goal.

Although PCM is currently used most frequently in climates with higher cooling loads and greater diurnal temperature swings than Minnesota, our study results suggest that buildings in Minnesota's climate can benefit significantly from incorporating PCMs. Under optimized conditions, the modeled PCMs show significant savings in Minnesota offices and schools for both heating and cooling loads throughout the year, amounting to a 5% reduction in total building energy, and peak load reductions between 4 and 7%. Using Minnesota's current utility rates, PCM has the potential to achieve life cycle cost savings over a 25-year study period. Our research suggests more savings may be possible when PCM design, field implementation, and management practices for cold climates are better understood.

Significant energy savings are possible from incorporating PCM in both new and existing commercial buildings across the state of Minnesota. Beyond the studied office and school building types, any building with constant daytime occupancy and high internal loads is likely to benefit from PCM application.

Many new energy saving technologies in buildings are based on control systems. While building controls offer a high degree of flexibility for building management, they can also lack persistence over time. Controls-based measures are frequently overwritten or disabled in BAS programming by facilities personnel, leading to low measure persistence and loss of energy savings over time (Gunasingh 2019). PCM technology is not susceptible to error from human intervention since it is not directly controlled by a programming logic. Energy savings from PCM is likely to have high persistence over the measure life, which is critical for the success of utility energy efficiency programs.

There are non-energy benefits to the PCM strategy as well. It contributes to the resilience of the State's building stock and protects human comfort by providing a passive method of regulating indoor temperature. PCM can increase passive survivability when power is unavailable, and – with the projected increase in cooling loads across the state – can provide an alternative for adding air conditioning in buildings that do not have it currently.

Guidelines for achieving maximum benefits from PCM include:

- **Optimize PCM design for electricity savings.** Although PCM can be used to achieve both electricity and natural gas reductions, it is more likely to be cost-effective when optimized for electricity due to the relatively low cost of natural gas.
- **Prioritize buildings with high savings potential.** Building types that will benefit most from PCM retrofits include: buildings with electric heating, cooling load dominated buildings, data centers and buildings with high internal loads, and older buildings with leaky envelopes and minimal insulation which typically have high energy use intensities due to the mechanical system's inability to maintain temperature setpoints.
- **Evaluate cost-effectiveness within your service territory.** PCM is more likely to be cost-effective for customers with electricity rates at or higher than the statewide average of $0.1063/kWh (including both energy and demand charges). Since PCM reduces both electricity consumption and peak demand – though at different rates for different building types – demand pricing structures also impact life cycle cost savings.

With these model-based conclusions providing a foundation, the recommended next step for program development is a field study to demonstrate PCM's real-world potential.

Field Study Recommendations

The literature review and energy modeling analysis conducted for Phase I of this study validate the need for the Phase II field study, which can be used to test variables that cannot be tested in a modeling environment and to demonstrate the technology's real-world potential before making significant investments.

The lack of field studies on PCM performance in colder climates is one of the greatest barriers to implementation of PCM in Minnesota. Most of the published literature acknowledges the limitations of modeling explorations and calls for field studies to observe the effects of PCM in a real-world environment (Auzeby 2017; Childs 2012; Delaney 2012; Fallahi 2013; Jelle 2017).

Our study also supports this recommendation, finding that although EnergyPlus is adept at predicting the effect of PCMs in suspended ceilings, modeling tools have several limitations that can be resolved in a real-world application. The Phase II field study will be designed to further our understanding of factors that influence PCM's impacts that couldn't be adequately captured in the simulation study, including:

- **Optimizing the amount of PCM based on building loads.** While the model required PCM to be added to 100% of a surface (e.g. a suspended ceiling), a field study application will optimize the volume of PCM to more cost-effectively meet the building loads.

- **Identifying best practices for optimizing seasonal performance.** As a dynamic material, PCM can be optimized to respond to outdoor weather conditions through the real-time building controls adjustments in the BAS. This effect, which could not be sufficiently captured in the energy model, could result in additional energy and cost savings. The model predicted energy savings based on a heating and cooling setpoint schedule that was applied to the entire year. The field study will explore varying setpoints and setbacks seasonally to maximize the heating and cooling savings from PCM.
- **Evaluating the impact of PCM on occupant comfort.** PCM improves thermal comfort by reducing indoor air temperature fluctuations. Quantifying this impact through a pre- and post-retrofit occupant satisfaction survey could help make PCM more attractive to building owners and could identify a target market of spaces with thermal comfort challenges.
- **Measuring the impacts of PCM on HVAC system cycling.** PCM reduces HVAC system cycling by maintaining a more stable indoor temperature. By measuring this reduction, we can estimate additional cost savings associated with reduced HVAC maintenance and extended lifetime.
- **Evaluating the PCM design, procurement, and installation process for Minnesota buildings.** Evaluating the time and expertise required for PCM design and installation – in addition to any unintended impacts on the space or occupants – will inform the feasibility of near-term market adoption in Minnesota and identify potential barriers to overcome.

In combination with the Phase I literature review and modeling study, findings from the Phase II field study will help inform the development of a systematic approach for incorporating PCMs into Minnesota buildings, helping to inform future program development.

Future Work

Over the course of this study, we encountered several topics worthy of further exploration. One future study idea is to evaluate the potential of PCM as a low-cost retrofit option to provide thermal comfort in buildings without a cooling system (e.g. many schools) rather than completing a major renovation to install mechanical cooling. This approach could be translated into a program for low-income households, where PCM could protect human health by providing passive temperature regulation in homes with inadequate air conditioning.

PCM could also be explored as a strategy for new construction in Minnesota, using the same blanket-type products evaluated here or other products – such as PCM that is microencapsulated in gypsum wallboard or concrete. Using PCM in new construction has the potential to achieve additional cost savings by reducing HVAC system sizing but would require additional engineering expertise to implement.

Another future research topic is a comparison of PCM's embodied carbon – the sum of all the greenhouse gas emissions attributed to the materials throughout their life cycle (extracting from the ground, manufacturing, construction, maintenance, and end of life/disposal) – to its operational carbon savings. A study that evaluated embodied versus operational energy for a wall plaster containing microencapsulated, paraffin-based PCM found the product's operational energy savings over a 50-year time period did not balance its high embodied energy content (Carbonaro 2015). However, our literature review did not find this type of analysis for the PCM products (bio-based or salt hydrate PCMs microencapsulated in plastic) or applications (laid above suspended ceiling) included in our study.

Overall, PCM's benefits of improved thermal comfort, reduced energy consumption, and shifted peak energy demand make it a technology worth further exploration, as increased interest will help develop the expanding market, lowering costs and improving technological innovation.

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Appendix A: Energy Modeling Results

Energy End Use Breakdown

The following graphs illustrate the electricity and natural gas end use breakdown for the four optimized models (which represent the highest cooling savings and highest heating savings for office and school).

Figure 23. Comparison of Electricity End Use Breakdown for Office – Highest Cooling Savings (left: Baseline model, right: PCM model)

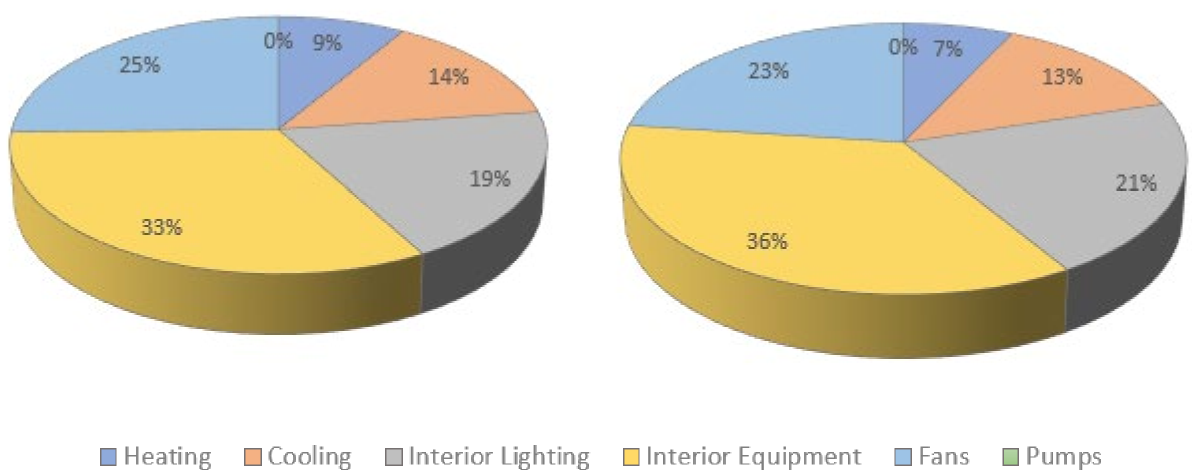


Figure 24. Comparison of Gas End Use Breakdown for Office – Highest Cooling Savings (left: Baseline model, right PCM model)

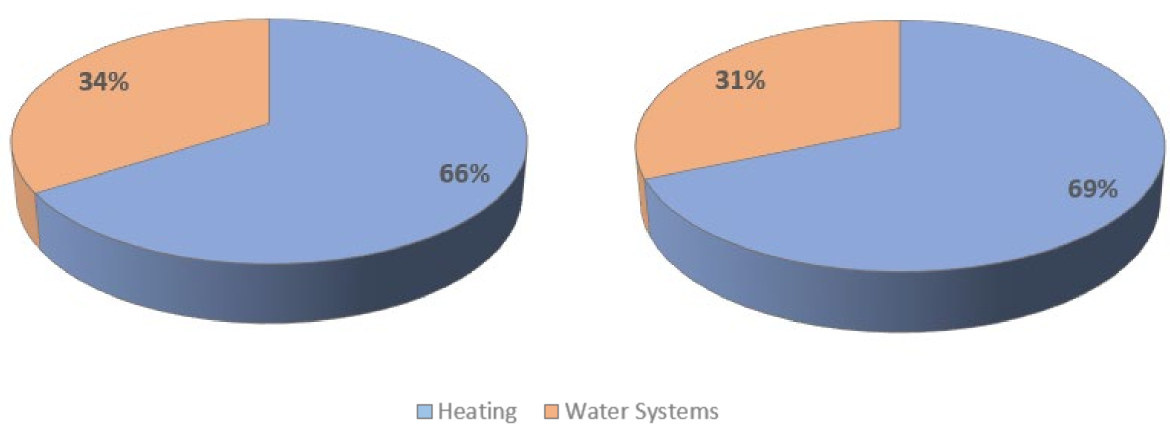


Figure 25. Comparison of Electricity End Use Breakdown for Office – Highest Heating Savings (left: Baseline model, right: PCM model)

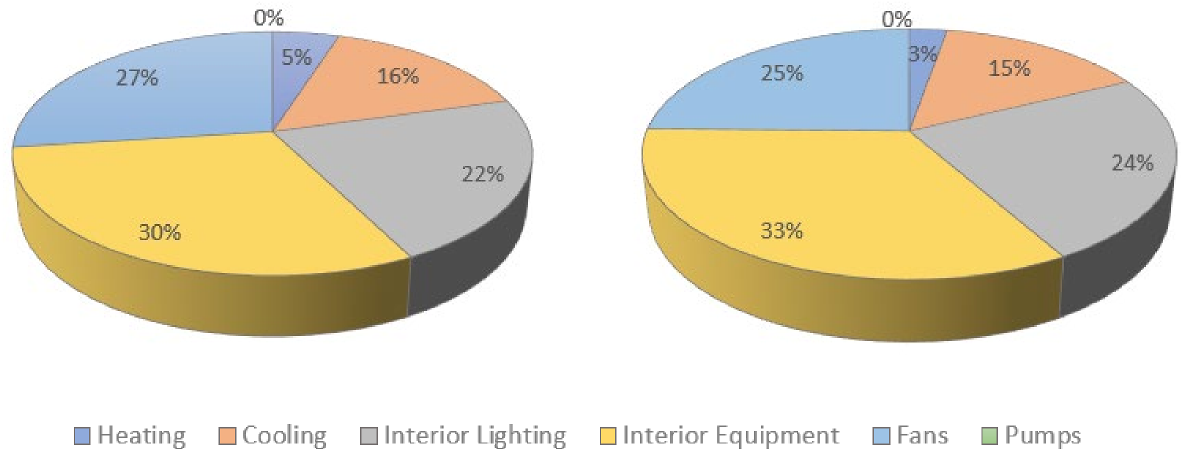


Figure 26. Comparison of Gas End Use Breakdown for Office – Highest Heating Savings (left: Baseline model, right: PCM model)

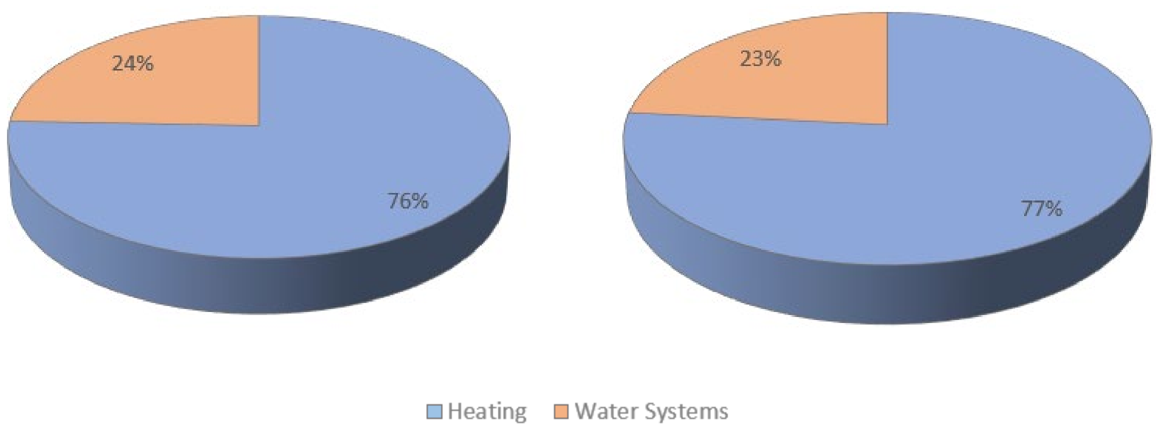


Figure 27. Comparison of Electricity End Use Breakdown for School – Highest Cooling Savings (left: Baseline model, right: PCM model)

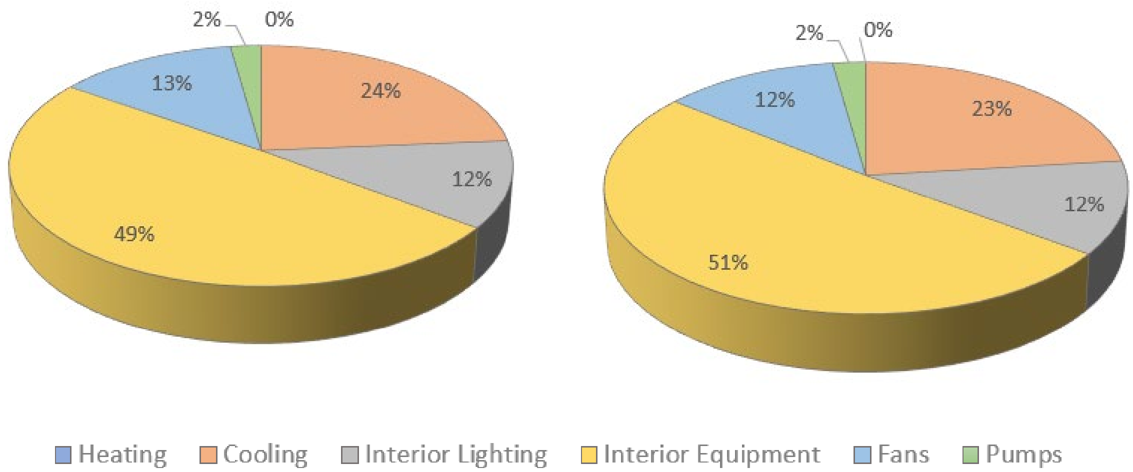
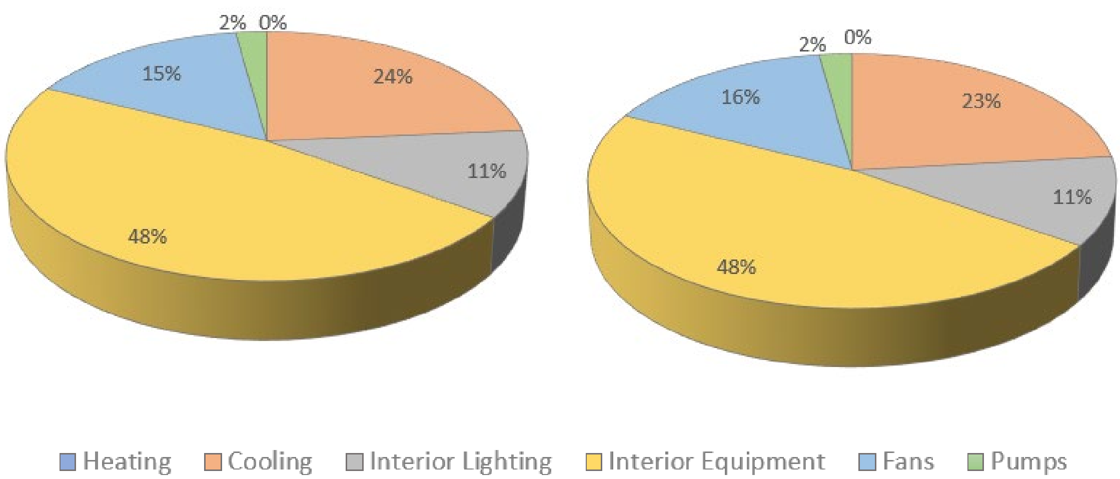


Figure 28. Comparison of Electricity End Use Breakdown for School – Highest Heating Savings (left: Baseline model, right: PCM model)



The school model natural gas use is 100% space heating in both the baseline and PCM models, hence individual pie charts are not shown.

Sensitivity Analysis

The following tables list the baseline and PCM modeled results for the sensitivity analysis for the office and school prototypes.

In the office model, the input parameters in Table 14 were the initial values for the sensitivity analysis.

Table 14. Initial Input Parameters for Office Sensitivity Analysis

Parameter	Value
Orientation	0°
Occupant Density (SF/person)	100
Equipment Density (W/SF)	1.0
Econ High (°F)	65
Econ Low (°F)	40
Cool Setpoint (°F)	73.4
Cool Setback (°F)	75.2
Heat Setpoint (°F)	71.6
Heat Setback (°F)	64.4
Envelope Exposure	Middle floor, four exterior walls, roof adiabatic
PCM Location	False ceiling

Table 15. Office Model Orientation Sensitivity Analysis

Orientation	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Heating End Use (kWh)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Heating End Use (kWh)	PCM Electric Peak (W)	Cooling kWh Savings	Heating kWh Savings	Peak kW Savings	Total Elec Savings
0º	253,909	36,555	1,997	22,141	112,786	232,368	31,928	2,183	16,243	104,514	12.66%	26.64%	7.33%	8.48%
90º	256,196	37,235	1,995	22,473	113,988	233,545	32,262	2,181	16,296	107,470	13.36%	27.49%	5.72%	8.84%
180º	253,760	36,576	2,003	22,051	112,789	232,276	31,932	2,188	16,208	104,518	12.70%	26.50%	7.33%	8.47%
270º	255,742	37,187	1,999	22,398	114,093	233,309	32,247	2,184	16,307	107,464	13.28%	27.19%	5.81%	8.77%

Table 16. Office Model Occupant Density Sensitivity Analysis

Occupant Density (SF/person)	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Heating End Use (kWh)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Heating End Use (kWh)	PCM Electric Peak (W)	Cooling kWh Savings	Heating kWh Savings	Peak kW Savings	Total Elec Savings
80	257,813	38,219	2,435	20,943	118,638	235,943	33,561	2,647	15,297	108,815	12.19%	26.96%	8.28%	8.48%
90	255,575	37,292	2,192	21,595	115,391	233,876	32,659	2,390	15,803	106,428	12.42%	26.82%	7.77%	8.49%
100	253,909	36,555	1,997	22,141	112,786	232,368	31,928	2,183	16,243	104,514	12.66%	26.64%	7.33%	8.48%
110	252,622	35,957	1,839	22,614	110,642	231,234	31,334	2,014	16,616	103,065	12.86%	26.52%	6.85%	8.47%
120	251,647	35,461	1,707	23,047	108,847	230,392	30,841	1,872	16,977	102,058	13.03%	26.34%	6.24%	8.45%

Table 17. Office Model Equipment Density Sensitivity Analysis

Equip Density (W/SF)	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Heating End Use (kWh)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Heating End Use (kWh)	PCM Electric Peak (W)	Cooling kWh Savings	Heating kWh Savings	Peak kW Savings	Total Elec Savings
0.8	235,865	34,672	2,181	26,256	106,153	214,714	30,340	2,356	19,236	99,164	12.49%	26.74%	6.58%	8.97%
0.9	244,685	35,612	2,090	24,099	109,477	223,288	31,103	2,272	17,649	101,822	12.66%	26.77%	6.99%	8.74%
1.0	253,909	36,555	1,997	22,141	112,786	232,368	31,928	2,183	16,243	104,514	12.66%	26.64%	7.33%	8.48%
1.1	263,613	37,557	1,902	20,259	116,131	242,053	32,783	2,093	14,886	107,448	12.71%	26.52%	7.48%	8.18%
1.2	273,728	38,568	1,806	18,491	119,504	252,210	33,696	2,002	13,647	110,424	12.63%	26.20%	7.60%	7.86%

Table 18. Office Model Economizer High Limit and Low Limit Setpoints Sensitivity Analysis

Econ High (°F)	Econ Low (°F)	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Heating End Use (kWh)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Heating End Use (kWh)	PCM Electric Peak (W)	Cooling kWh Savings	Heating kWh Savings	Peak kW Savings	Total Elec Savings
64.4	39.2	254,051	36,684	1,998	22,182	112,786	232,530	32,087	2,184	16,251	104,514	12.53%	26.74%	7.33%	8.47%
64.4	41	254,272	36,811	1,997	22,145	112,786	232,603	32,111	2,183	16,244	104,514	12.77%	26.65%	7.33%	8.52%
64.4	42.8	254,535	36,953	1,996	22,124	112,786	232,713	32,160	2,183	16,236	104,514	12.97%	26.61%	7.33%	8.57%
64.4	44.6	254,946	37,203	1,995	22,090	112,786	232,898	32,275	2,182	16,223	104,514	13.25%	26.56%	7.33%	8.65%
66.2	39.2	253,386	36,184	1,998	22,115	112,786	232,018	31,646	2,184	16,236	104,514	12.54%	26.58%	7.33%	8.43%
66.2	41	253,604	36,311	1,997	22,077	112,786	232,092	31,670	2,183	16,230	104,514	12.78%	26.48%	7.33%	8.48%
66.2	42.8	253,867	36,453	1,996	22,056	112,786	232,202	31,720	2,183	16,222	104,514	12.98%	26.45%	7.33%	8.53%
66.2	44.6	254,279	36,703	1,995	22,022	112,786	232,387	31,835	2,182	16,209	104,514	13.26%	26.40%	7.33%	8.61%
68	39.2	252,906	35,879	1,998	22,046	112,785	231,646	31,349	2,184	16,222	104,515	12.63%	26.42%	7.33%	8.41%
68	41	253,123	36,007	1,997	22,008	112,785	231,719	31,373	2,183	16,215	104,515	12.87%	26.32%	7.33%	8.46%
68	42.8	253,387	36,149	1,996	21,987	112,785	231,829	31,423	2,183	16,207	104,515	13.07%	26.29%	7.33%	8.51%
68	44.6	253,799	36,399	1,995	21,953	112,785	232,015	31,538	2,182	16,194	104,515	13.36%	26.23%	7.33%	8.58%
69.8	39.2	252,535	35,733	1,998	21,959	112,785	231,380	31,170	2,184	16,204	104,518	12.77%	26.21%	7.33%	8.38%
69.8	41	252,752	35,861	1,997	21,922	112,785	231,453	31,194	2,183	16,197	104,518	13.01%	26.12%	7.33%	8.43%
69.8	42.8	253,016	36,003	1,996	21,900	112,785	231,564	31,244	2,183	16,189	104,518	13.22%	26.08%	7.33%	8.48%
69.8	44.6	253,429	36,253	1,995	21,866	112,785	231,749	31,359	2,182	16,176	104,518	13.50%	26.02%	7.33%	8.55%

Table 19. Office Model Cooling Setpoint and Setback Sensitivity Analysis

Cool Setpoint (°F)	Cool Setback (°F)	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Heating End Use (kWh)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Heating End Use (kWh)	PCM Electric Peak (W)	Cooling kWh Savings	Heating kWh Savings	Peak kW Savings	Total Elec Savings
71.6	71.6	279,515	40,760	1,668	30,067	118,986	265,068	39,385	1,739	23,152	117,564	3.37%	23.00%	1.20%	5.17%
71.6	73.4	276,562	39,806	1,686	28,890	117,793	261,003	37,348	1,744	22,352	117,184	6.17%	22.63%	0.52%	5.63%
71.6	75.2	275,015	39,143	1,685	28,274	117,553	259,159	36,251	1,744	22,015	116,709	7.39%	22.14%	0.72%	5.77%
71.6	77	274,106	38,685	1,686	27,942	117,394	258,355	35,730	1,744	21,866	117,474	7.64%	21.75%	-0.07%	5.75%
71.6	78.8	273,504	38,336	1,686	27,746	117,394	258,230	35,647	1,743	21,850	117,478	7.01%	21.25%	-0.07%	5.58%
71.6	80.6	273,054	38,040	1,685	27,614	117,301	258,230	35,647	1,743	21,850	117,478	6.29%	20.88%	-0.15%	5.43%
73.4	71.6	257,962	37,980	1,975	23,432	113,133	238,635	35,081	2,179	17,017	98,979	7.63%	27.37%	12.51%	7.49%
73.4	73.4	255,416	37,250	1,998	22,640	112,870	234,333	33,112	2,184	16,450	104,131	11.11%	27.34%	7.74%	8.25%
73.4	75.2	253,909	36,555	1,997	22,141	112,786	232,368	31,928	2,183	16,243	104,514	12.66%	26.64%	7.33%	8.48%
73.4	77	253,106	36,110	1,997	21,926	112,775	231,672	31,430	2,183	16,180	104,517	12.96%	26.21%	7.32%	8.47%
73.4	78.8	252,632	35,775	1,997	21,824	112,774	231,574	31,348	2,183	16,175	104,517	12.37%	25.88%	7.32%	8.34%
73.4	80.6	252,331	35,525	1,997	21,772	112,774	231,574	31,348	2,183	16,175	104,517	11.76%	25.71%	7.32%	8.23%
75.2	71.6	244,773	35,994	2,238	20,084	99,622	228,729	32,391	2,450	15,606	87,608	10.01%	22.30%	12.06%	6.55%
75.2	73.4	241,093	35,133	2,268	19,126	102,884	223,333	30,101	2,461	14,925	90,602	14.32%	21.96%	11.94%	7.37%
75.2	75.2	239,312	34,461	2,268	18,644	104,928	220,625	28,641	2,460	14,633	92,151	16.89%	21.51%	12.18%	7.81%
75.2	77	238,340	33,967	2,268	18,459	105,038	219,724	28,065	2,461	14,569	92,170	17.38%	21.07%	12.25%	7.81%
75.2	78.8	237,833	33,629	2,267	18,406	105,039	219,612	27,974	2,461	14,566	92,763	16.82%	20.86%	11.69%	7.66%
75.2	80.6	237,530	33,380	2,267	18,383	105,040	219,612	27,974	2,461	14,566	92,763	16.20%	20.76%	11.69%	7.54%
77	71.6	240,150	34,751	2,339	19,190	93,450	227,950	31,981	2,459	15,531	87,608	7.97%	19.07%	6.25%	5.08%
77	73.4	235,323	33,714	2,378	18,119	95,660	221,902	29,308	2,470	14,796	87,608	13.07%	18.34%	8.42%	5.70%
77	75.2	233,179	33,001	2,380	17,661	98,319	218,765	27,581	2,470	14,488	87,608	16.42%	17.96%	10.89%	6.18%
77	77	231,855	32,396	2,379	17,473	99,526	217,713	26,931	2,470	14,419	87,608	16.87%	17.48%	11.97%	6.10%
77	78.8	231,150	31,993	2,379	17,423	99,614	217,601	26,855	2,470	14,415	87,608	16.06%	17.27%	12.05%	5.86%
77	80.6	230,754	31,723	2,379	17,406	99,618	217,583	26,841	2,470	14,415	87,608	15.39%	17.19%	12.06%	5.71%

Table 20. Office Model Heating Setpoint and Setback Sensitivity Analysis

Heat Setpoint (°F)	Heat Setback (°F)	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Heating End Use (kWh)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Heating End Use (kWh)	PCM Electric Peak (W)	Cooling kWh Savings	Heating kWh Savings	Peak kW Savings	Total Elec Savings
71.6	64.4	253,909	36,555	1,997	22,141	112,786	232,368	31,928	2,183	16,243	104,514	12.66%	26.64%	7.33%	8.48%
71.6	66.2	261,162	37,532	1,946	25,364	112,786	238,578	32,739	2,166	18,655	104,514	12.77%	26.45%	7.33%	8.65%
71.6	68	272,941	39,072	1,880	32,133	112,786	249,472	34,325	2,145	24,140	104,514	12.15%	24.87%	7.33%	8.60%
71.6	69.8	291,755	40,739	1,783	45,338	112,786	267,407	36,010	2,094	36,747	104,514	11.61%	18.95%	7.33%	8.35%
71.6	71.6	321,068	42,813	1,650	67,568	112,785	300,175	37,999	1,964	62,071	104,520	11.24%	8.14%	7.33%	6.51%
69.8	64.4	244,549	36,096	2,115	14,206	109,246	223,830	31,687	2,265	8,193	101,872	12.21%	42.33%	6.75%	8.47%
69.8	66.2	252,339	37,124	2,058	17,755	109,246	230,338	32,538	2,244	10,799	101,872	12.35%	39.18%	6.75%	8.72%
69.8	68	264,846	38,661	1,987	25,251	109,246	241,716	34,153	2,222	16,777	101,872	11.66%	33.56%	6.75%	8.73%
69.8	69.8	284,707	40,261	1,879	39,358	109,246	259,870	35,801	2,167	29,652	101,872	11.08%	24.66%	6.75%	8.72%
69.8	71.6	317,093	42,745	1,726	63,795	109,094	295,540	38,118	2,030	57,100	101,634	10.82%	10.49%	6.84%	6.80%
68	64.4	241,221	36,073	2,177	11,137	109,246	221,365	31,691	2,299	5,695	101,872	12.15%	48.87%	6.75%	8.23%
68	66.2	249,408	37,123	2,116	15,072	109,246	228,190	32,561	2,276	8,565	101,872	12.29%	43.17%	6.75%	8.51%
68	68	262,237	38,660	2,038	22,863	109,246	239,617	34,191	2,251	14,613	101,872	11.56%	36.09%	6.75%	8.63%
68	69.8	283,206	40,256	1,919	37,895	109,246	258,306	35,837	2,192	27,941	101,872	10.98%	26.27%	6.75%	8.79%
68	71.6	315,381	42,720	1,758	62,342	109,094	293,924	38,116	2,052	55,560	101,634	10.78%	10.88%	6.84%	6.80%

Figure 29. Sensitivity analysis results for office cooling energy savings

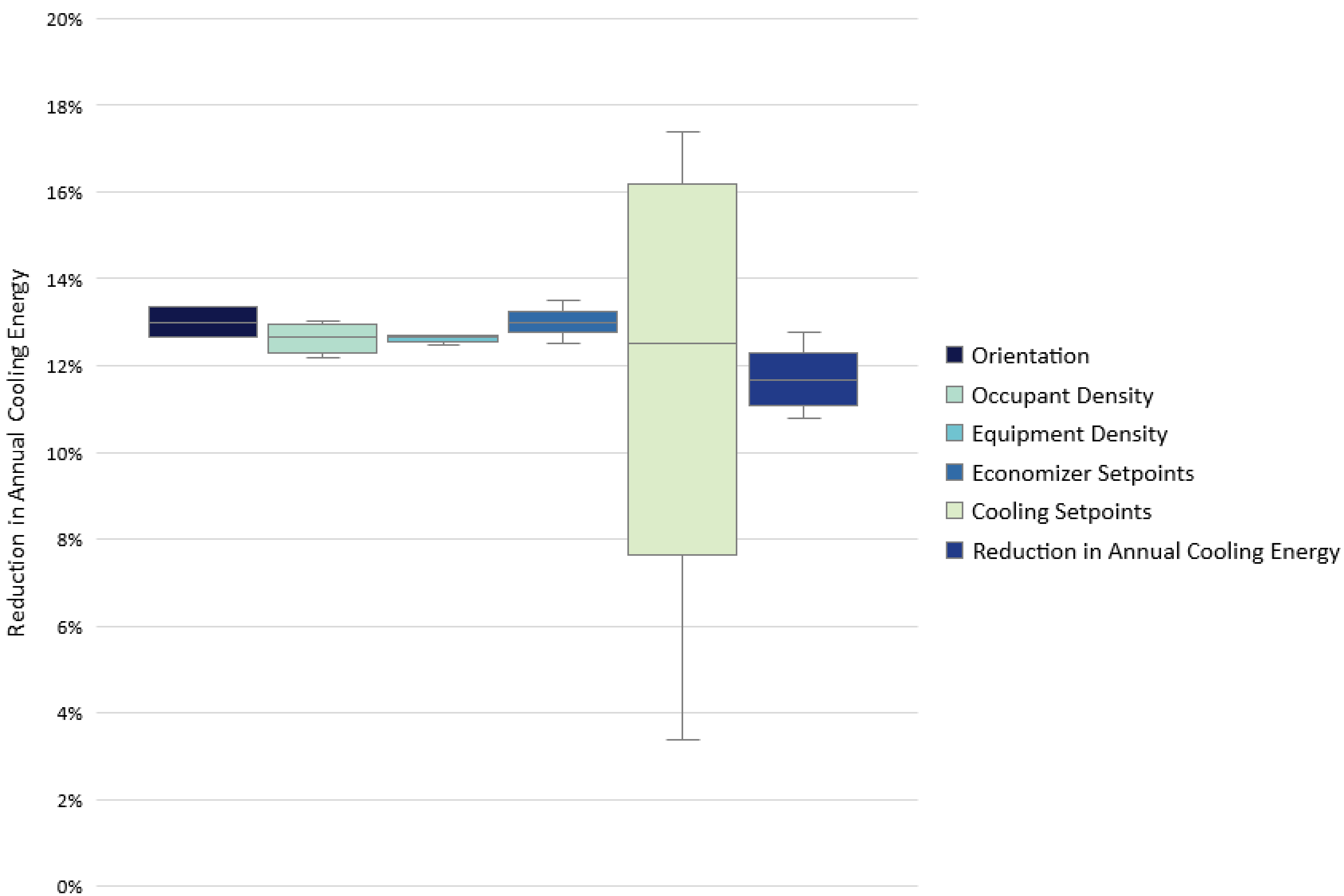
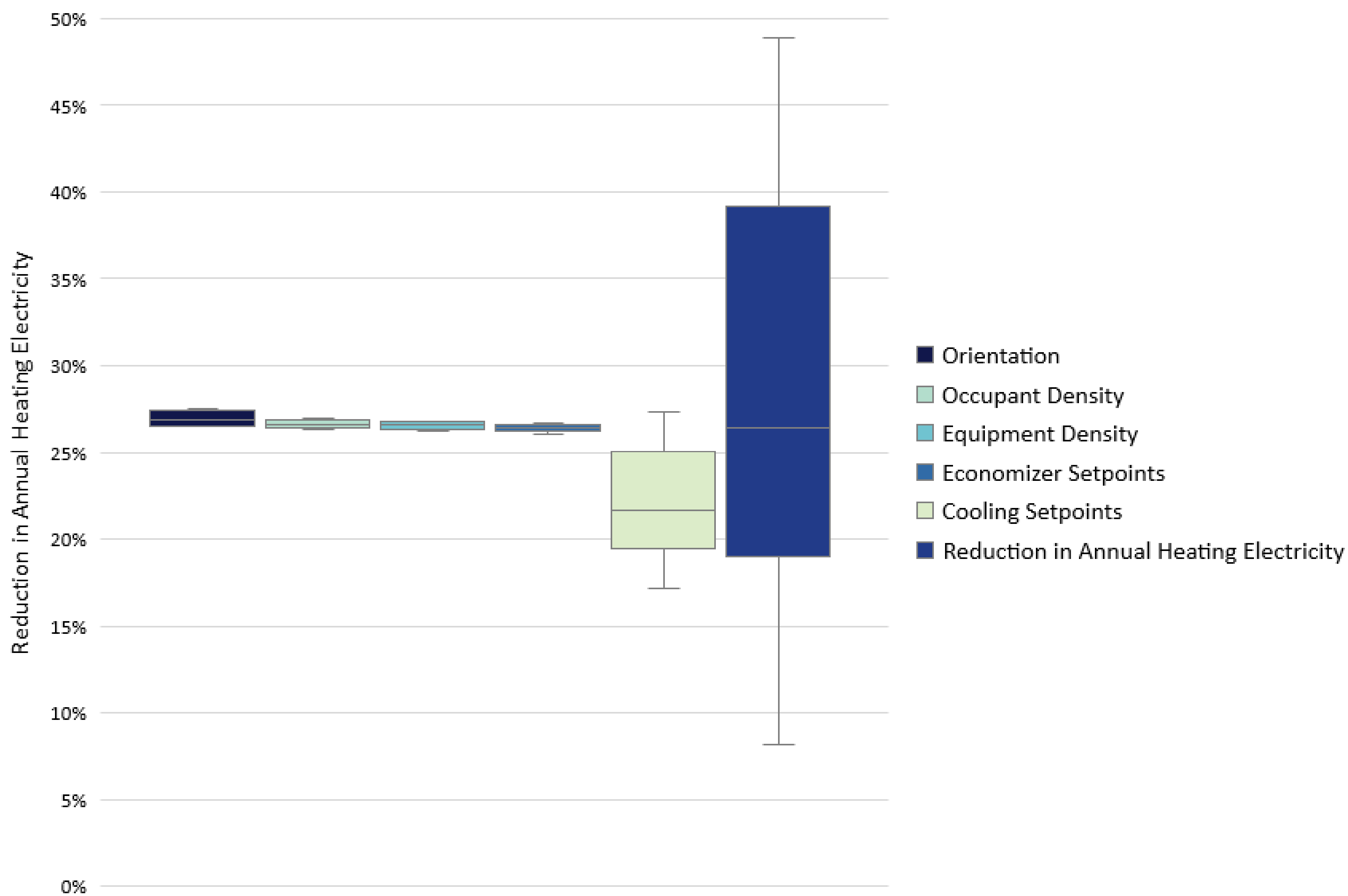


Figure 30. Sensitivity analysis results for office heating electricity savings



In the school model, the input parameters in Table 21 were the initial values for the sensitivity analysis.

Table 21. Initial Input Parameters for School Sensitivity Analysis

Parameter	Value
Orientation	0º (south window)
Occupant Density (SF/person)	28.5
Equipment Density (W/SF)	1.9
Econ High (ºF)	65
Econ Low (ºF)	40
Cool Setpoint (ºF)	73.4
Cool Setback (ºF)	71.6
Heat Setpoint (ºF)	71.6
Heat Setback (ºF)	68
Envelope Exposure	Middle floor, four exterior walls, roof adiabatic
PCM Location	False ceiling

Table 22. School Model Orientation Sensitivity Analysis

Orientation	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Electric Peak (W)	Cooling kWh Savings	Heating therm Savings	Peak kW Savings
0º	86,800	21,472	2,055	55,399	84,603	20,519	1,850	50,109	4.44%	9.97%	9.55%
90º	87,698	22,016	2,320	57,672	85,496	21,097	2,199	56,885	4.18%	5.20%	1.37%
180º	83,974	20,258	2,468	54,730	82,819	19,677	2,367	51,284	2.87%	4.06%	6.30%
270º	87,666	21,979	2,317	57,939	85,833	21,099	2,227	58,000	4.00%	3.88%	-0.11%

Table 23. School Model Occupant Density Sensitivity Analysis

Occupant Density (SF/person)	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Electric Peak (W)	Cooling kWh Savings	Heating therm Savings	Peak kW Savings
22.8	90,552	22,563	2,292	57,026	88,541	21,632	2,090	53,694	4.13%	8.82%	5.84%
25.65	88,508	21,987	2,164	55,556	86,357	21,024	1,959	52,813	4.38%	9.45%	4.94%
28.5	86,800	21,472	2,055	55,399	84,603	20,519	1,850	50,109	4.44%	9.97%	9.55%
31.35	85,492	21,065	1,969	55,153	83,255	20,118	1,765	49,715	4.50%	10.39%	9.86%
34.2	84,364	20,705	1,895	54,896	82,095	19,758	1,691	49,376	4.57%	10.75%	10.05%

Table 24. School Model Equipment Density Sensitivity Analysis

Equip Density (W/SF)	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Electric Peak (W)	Cooling kWh Savings	Heating therm Savings	Peak kW Savings
1.52	77,334	20,824	2,178	50,915	75,192	19,942	1,965	47,213	4.24%	9.81%	7.27%
1.71	82,064	21,141	2,115	52,974	79,892	20,228	1,907	48,165	4.32%	9.85%	9.08%
1.9	86,800	21,472	2,055	55,399	84,603	20,519	1,850	50,109	4.44%	9.97%	9.55%
2.09	91,600	21,825	1,997	56,654	89,375	20,821	1,794	51,644	4.60%	10.14%	8.84%
2.28	96,377	22,174	1,939	58,103	94,186	21,146	1,739	53,659	4.64%	10.32%	7.65%

Table 25. School Model Economizer High Limit and Low Limit Sensitivity Analysis

Econ High (°F)	Econ Low (°F)	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Electric Peak (W)	Cooling kWh Savings
64.4	39.2	86,826	21,499	2,055	55,399	84,635	20,553	1,850	50,109	4.40%
64.4	41	86,914	21,580	2,055	55,399	84,713	20,623	1,850	50,109	4.43%
64.4	42.8	87,026	21,679	2,055	55,399	84,816	20,714	1,850	50,109	4.45%
64.4	44.6	87,306	21,929	2,055	55,399	85,072	20,940	1,850	50,109	4.51%
66.2	39.2	86,707	21,380	2,055	55,399	84,515	20,433	1,850	50,109	4.43%
66.2	41	86,795	21,460	2,055	55,399	84,593	20,503	1,850	50,109	4.46%
66.2	42.8	86,907	21,560	2,055	55,399	84,697	20,594	1,850	50,109	4.48%
66.2	44.6	87,187	21,810	2,055	55,399	84,953	20,821	1,850	50,109	4.54%
68	39.2	86,669	21,341	2,055	55,399	84,486	20,404	1,850	50,109	4.39%
68	41	86,757	21,422	2,055	55,399	84,564	20,474	1,850	50,109	4.42%
68	42.8	86,868	21,521	2,055	55,399	84,667	20,565	1,850	50,109	4.44%
68	44.6	87,149	21,771	2,055	55,399	84,923	20,791	1,850	50,109	4.50%
69.8	39.2	86,667	21,340	2,055	55,399	84,491	20,408	1,850	50,109	4.37%
69.8	41	86,755	21,420	2,055	55,399	84,569	20,478	1,850	50,109	4.40%
69.8	42.8	86,867	21,519	2,055	55,399	84,672	20,569	1,850	50,109	4.42%
69.8	44.6	87,147	21,770	2,055	55,399	84,928	20,796	1,850	50,109	4.47%

Table 26. School Model Cooling Setpoint and Setback Sensitivity Analysis

Cool Setpoint (ºF)	Cool Setback (ºF)	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Electric Peak (W)	Cooling kWh Savings	Heating therm Savings	Peak kW Savings
71.6	71.6	90,393	22,629	2,041	57,098	89,628	21,950	1,787	51,774	3.00%	12.45%	9.32%
71.6	73.4	90,341	22,610	2,041	57,089	89,585	21,935	1,786	52,089	2.98%	12.48%	8.76%
71.6	75.2	90,346	22,615	2,041	57,089	89,572	21,932	1,787	51,030	3.02%	12.49%	10.61%
71.6	77	90,346	22,615	2,041	57,089	89,572	21,932	1,787	51,030	3.02%	12.49%	10.61%
71.6	78.8	90,346	22,615	2,041	57,089	89,572	21,932	1,787	51,030	3.02%	12.49%	10.61%
71.6	80.6	90,346	22,615	2,041	57,089	89,572	21,932	1,787	51,030	3.02%	12.49%	10.61%
73.4	71.6	86,800	21,472	2,055	55,399	84,603	20,519	1,850	50,109	4.44%	9.97%	9.55%
73.4	73.4	86,601	21,397	2,054	55,363	84,509	20,488	1,850	50,109	4.25%	9.96%	9.49%
73.4	75.2	86,592	21,394	2,054	55,363	84,507	20,488	1,850	50,109	4.24%	9.96%	9.49%
73.4	77	86,592	21,394	2,054	55,363	84,507	20,488	1,850	50,109	4.24%	9.96%	9.49%
73.4	78.8	86,592	21,394	2,054	55,363	84,507	20,488	1,850	50,109	4.24%	9.96%	9.49%
73.4	80.6	86,592	21,394	2,054	55,363	84,507	20,488	1,850	50,109	4.24%	9.96%	9.49%
75.2	71.6	84,025	20,517	2,063	52,213	81,736	19,570	1,886	51,784	4.61%	8.61%	0.82%
75.2	73.4	83,712	20,382	2,063	52,315	81,612	19,530	1,885	48,432	4.18%	8.62%	7.42%
75.2	75.2	83,646	20,357	2,063	52,315	81,600	19,526	1,885	48,432	4.09%	8.62%	7.42%
75.2	77	83,646	20,357	2,063	52,315	81,600	19,526	1,885	48,432	4.09%	8.62%	7.42%
75.2	78.8	83,646	20,357	2,063	52,315	81,600	19,526	1,885	48,432	4.09%	8.62%	7.42%
75.2	80.6	83,646	20,357	2,063	52,315	81,600	19,526	1,885	48,432	4.09%	8.62%	7.42%
77	71.6	82,268	19,832	2,066	52,316	80,757	19,195	1,890	51,546	3.21%	8.54%	1.47%
77	73.4	81,894	19,671	2,066	51,896	80,587	19,133	1,889	49,103	2.74%	8.55%	5.38%
77	75.2	81,755	19,615	2,065	51,896	80,546	19,120	1,889	47,046	2.52%	8.54%	9.35%
77	77	81,742	19,609	2,065	51,896	80,540	19,118	1,889	47,046	2.50%	8.54%	9.35%
77	78.8	81,742	19,609	2,065	51,896	80,540	19,118	1,889	47,046	2.50%	8.54%	9.35%
77	80.6	81,742	19,609	2,065	51,896	80,540	19,118	1,889	47,046	2.50%	8.54%	9.35%

Table 27. School Model Heating Setpoint and Setback Sensitivity Analysis

Heat Setpoint (°F)	Heat Setback (°F)	Baseline Electric Use (kWh)	Baseline Cooling End Use (kWh)	Baseline Heating End Use (therm)	Baseline Electric Peak (W)	PCM Electric Use (kWh)	PCM Cooling End Use (kWh)	PCM Heating End Use (therm)	PCM Electric Peak (W)	Cooling kWh Savings	Heating therm Savings	Peak kW Savings
68	64.4	86,423	21,330	1,803	55,411	84,306	20,385	1,656	50,060	4.43%	8.15%	9.66%
68	66.2	86,429	21,335	1,810	55,411	84,310	20,388	1,660	50,060	4.44%	8.28%	9.66%
68	68	86,440	21,341	1,820	55,411	84,315	20,392	1,667	50,060	4.45%	8.42%	9.66%
68	69.8	86,464	21,352	1,835	55,411	84,326	20,397	1,681	50,060	4.47%	8.42%	9.66%
69.8	64.4	86,560	21,383	1,907	55,407	84,404	20,431	1,727	50,063	4.45%	9.43%	9.65%
69.8	66.2	86,566	21,386	1,912	55,407	84,409	20,435	1,729	50,063	4.45%	9.57%	9.65%
69.8	68	86,575	21,392	1,921	55,407	84,417	20,441	1,734	50,063	4.44%	9.73%	9.65%
69.8	69.8	86,597	21,402	1,936	55,407	84,430	20,448	1,746	50,063	4.46%	9.78%	9.65%
71.6	64.4	86,788	21,463	2,043	55,399	84,596	20,513	1,843	50,109	4.43%	9.80%	9.55%
71.6	66.2	86,792	21,466	2,047	55,399	84,598	20,515	1,845	50,109	4.43%	9.87%	9.55%
71.6	68	86,800	21,472	2,055	55,399	84,603	20,519	1,850	50,109	4.44%	9.97%	9.55%
71.6	69.8	86,816	21,479	2,068	55,399	84,611	20,523	1,862	50,109	4.45%	9.93%	9.55%

Table 28. School Model One Exterior Wall Sensitivity Analysis

One Exterior Wall: Construction Type	Cooling kWh Savings	Heating therm Savings	Peak kW Savings
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.76%	10.52%	9.72%
PCM Wall	4.84%	9.44%	6.90%

Table 29. School Model Two Exterior Walls Sensitivity Analysis

Wall 1 Construction Type	Wall 2 Construction Type	Cooling kWh Savings	Heating therm Savings	Peak kW Savings
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.66%	10.64%	9.38%
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	4.77%	9.65%	6.52%
PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.72%	10.20%	11.29%
PCM Wall	PCM Wall	4.77%	9.25%	4.97%

Table 30. School Model Three Exterior Walls Sensitivity Analysis

Wall 1 Construction Type	Wall 2 Construction Type	Wall 3 Construction Type	Cooling kWh Savings	Heating therm Savings	Peak kW Savings
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.67%	10.52%	9.66%
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	4.74%	9.54%	6.92%
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.78%	10.12%	10.88%
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	PCM Wall	4.73%	9.17%	5.34%
PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.75%	10.15%	10.56%
PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	4.72%	9.19%	5.28%
PCM Wall	PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.78%	9.74%	6.94%
PCM Wall	PCM Wall	PCM Wall	4.70%	8.85%	9.86%

Table 31. School Model Four Exterior Walls Sensitivity Analysis

Wall 1 Construction Type	Wall 2 Construction Type	Wall 3 Construction Type	Wall 4 Construction Type	Cooling kWh Savings	Heating therm Savings	Peak kW Savings
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.44%	9.97%	9.55%
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	4.30%	9.10%	5.02%
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.37%	9.63%	7.05%
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	PCM Wall	4.26%	8.77%	3.69%
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.01%	8.28%	9.69%
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	3.70%	7.55%	10.52%
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	3.88%	8.00%	9.68%
90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	PCM Wall	PCM Wall	3.58%	7.32%	9.23%
PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.39%	9.62%	11.23%
PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	4.26%	8.76%	3.69%
PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	4.34%	9.29%	5.56%
PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	PCM Wall	4.19%	8.47%	9.54%
PCM Wall	PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	3.88%	8.01%	9.60%
PCM Wall	PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	PCM Wall	3.57%	7.33%	9.21%
PCM Wall	PCM Wall	PCM Wall	90.1-2004 CZ6 Steel-Framed Wall R-13+R-3.8c.i. U-0.084	3.77%	7.75%	10.39%
PCM Wall	PCM Wall	PCM Wall	PCM Wall	3.47%	7.09%	9.23%

Figure 31. Sensitivity analysis results for school cooling energy savings

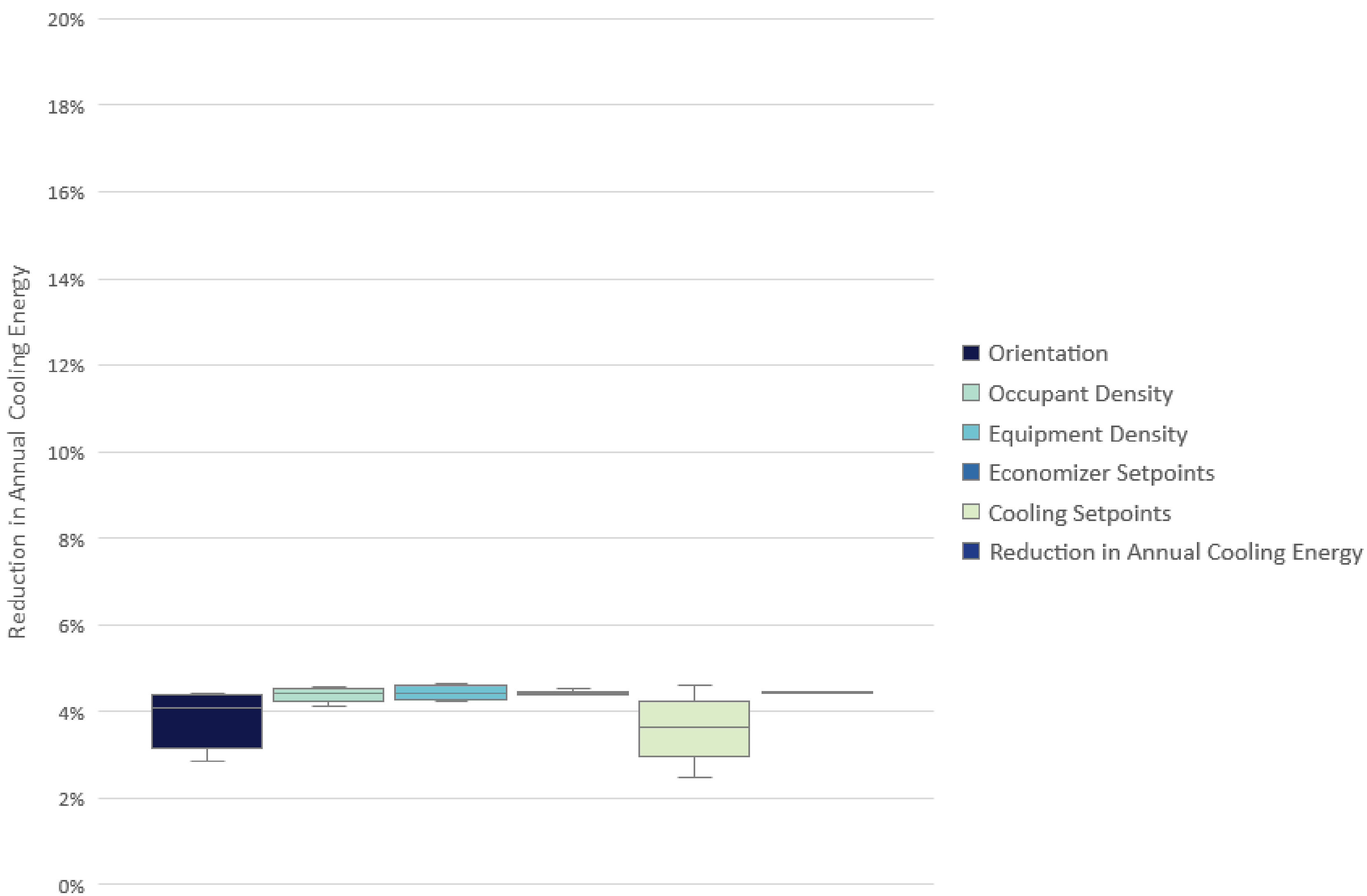
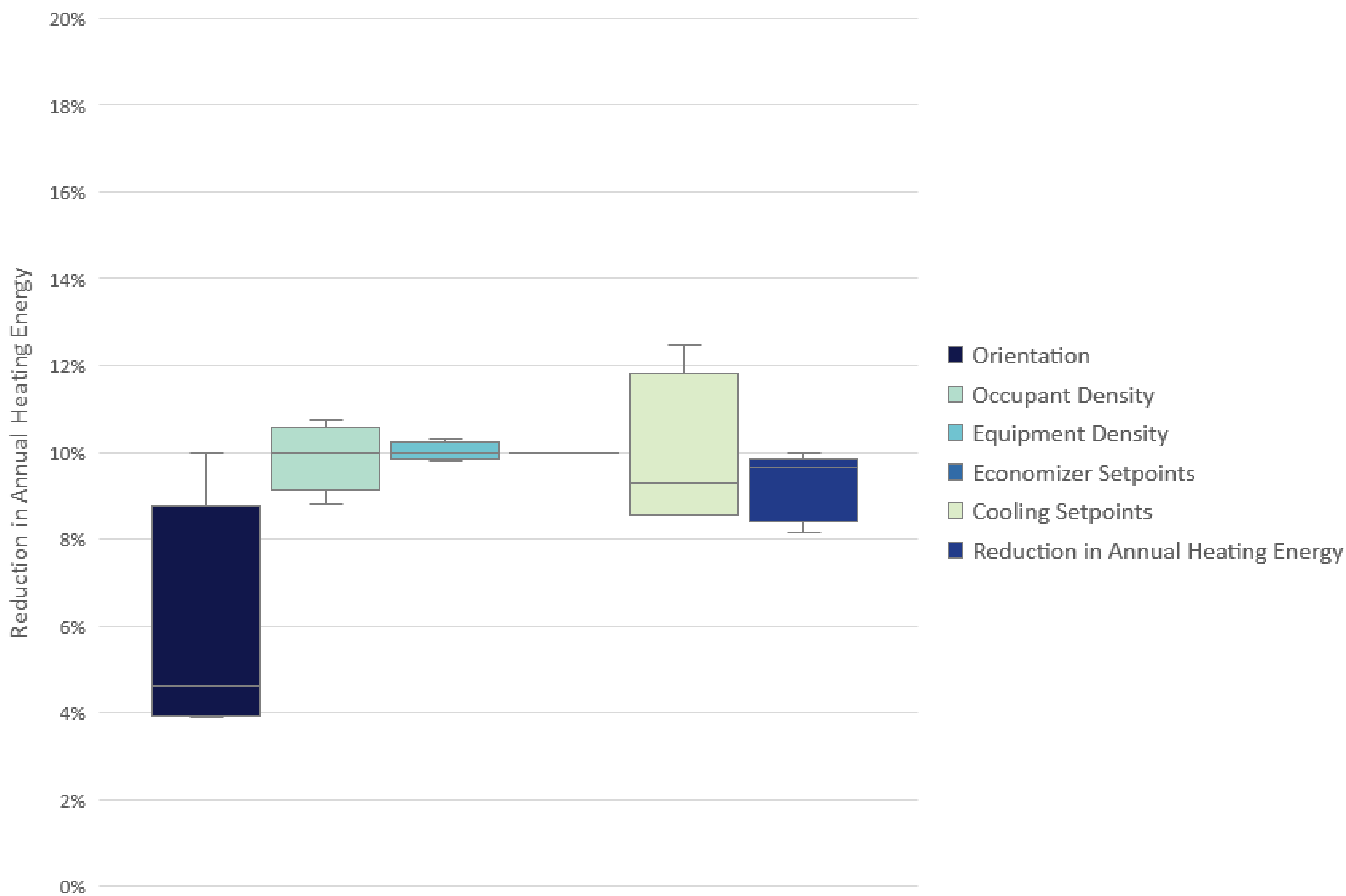


Figure 32. Sensitivity analysis results for school heating energy savings



Appendix B: Life Cycle Cost Analysis Reports

Office Highest Cooling Savings – MN Average Rates

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office best cooling scenario.xml
Date of Study:	Fri Jan 17 11:20:26 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$505,580	$467,444	$38,136
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
Subtotal (for Future Cost Items)	$505,580	$443,093	$62,487
Total PV Life-Cycle Cost	$505,580	$496,760	$8,820

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$38,136
- Increased Total Investment	$29,316

Net Savings $8,820

Savings-to-Investment Ratio (SIR)

SIR = 1.30

Adjusted Internal Rate of Return

AIRR = 4.09%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 25

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	270,153.0 kWh	246,523.0 kWh	23,630.0 kWh	590,733.8 kWh
Natural Gas	2,570.0 Therm	2,785.0 Therm	-215.0 Therm	-5,374.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	921.8 MBtu	841.2 MBtu	80.6 MBtu	2,015.7 MBtu
Natural Gas	257.0 MBtu	278.5 MBtu	-21.5 MBtu	-537.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO2	210,154.53 kg	191,772.53 kg	18,382.00 kg	459,537.34 kg
SO2	523.25 kg	477.48 kg	45.77 kg	1,144.16 kg
NOx	438.63 kg	400.27 kg	38.37 kg	959.14 kg
Natural Gas				
CO2	13,574.16 kg	14,709.74 kg	-1,135.58 kg	-28,388.77 kg
SO2	109.55 kg	118.71 kg	-9.16 kg	-229.11 kg
NOx	11.39 kg	17.34 kg	-5.95 kg	-148.70 kg
Total:				
CO2	223,728.69 kg	206,482.28 kg	17,246.42 kg	431,148.57 kg
SO2	632.79 kg	596.19 kg	36.60 kg	915.06 kg
NOx	450.02 kg	417.60 kg	32.42 kg	810.44 kg

Office Highest Cooling Savings – Reduced PCM (MN Average)

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office best cooling scenario.xml
Date of Study:	Tue Feb 04 12:51:14 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$24,150	-$24,150
Future Costs:			
Energy Consumption Costs	$505,580	$475,071	$30,509
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$10,958	$10,958
	------------	------------	------------
Subtotal (for Future Cost Items)	$505,580	$464,113	$41,467
	------------	------------	------------
Total PV Life-Cycle Cost	$505,580	$488,263	$17,317

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$30,509
- Increased Total Investment	$13,192

Net Savings $17,317

Savings-to-Investment Ratio (SIR)

SIR = 2.31

Adjusted Internal Rate of Return

AIRR = 6.51%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 14

Discounted Payback occurs in year 18

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	270,153.0 kWh	251,249.0 kWh	18,904.0 kWh	472,587.1 kWh
Natural Gas	2,570.0 Therm	2,742.0 Therm	-172.0 Therm	-4,299.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	921.8 MBtu	857.3 MBtu	64.5 MBtu	1,612.5 MBtu
Natural Gas	257.0 MBtu	274.2 MBtu	-17.2 MBtu	-430.0 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO2	210,154.53 kg	195,448.93 kg	14,705.60 kg	367,629.87 kg
SO2	523.25 kg	486.63 kg	36.61 kg	915.33 kg
NOx	438.63 kg	407.94 kg	30.69 kg	767.31 kg
Natural Gas				
CO2	13,574.16 kg	14,482.63 kg	-908.47 kg	-22,711.01 kg
SO2	109.55 kg	116.88 kg	-7.33 kg	-183.29 kg
NOx	11.39 kg	17.07 kg	-5.68 kg	-142.01 kg
Total:				
CO2	223,728.69 kg	209,931.56 kg	13,797.13 kg	344,918.86 kg
SO2	632.79 kg	603.51 kg	29.28 kg	732.05 kg
NOx	450.02 kg	425.01 kg	25.01 kg	625.31 kg

Office Highest Cooling Savings – Connexus Energy

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office best cooling scenario.xml
Date of Study:	Mon Jan 20 17:00:59 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$330,486	$307,665	$22,821
Energy Demand Charges	$214,979	$198,907	$16,072
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
	------------	------------	------------
Subtotal (for Future Cost Items)	$545,465	$482,221	$63,244
	------------	------------	------------
Total PV Life-Cycle Cost	$545,465	$535,888	$9,577

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$38,893
- Increased Total Investment	$29,316

Net Savings $9,577

Savings-to-Investment Ratio (SIR)

SIR = 1.33

Adjusted Internal Rate of Return

AIRR = 4.17%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 25

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	270,153.0 kWh	246,523.0 kWh	23,630.0 kWh	590,733.8 kWh
Natural Gas	2,570.0 Therm	2,785.0 Therm	-215.0 Therm	-5,374.9 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	921.8 MBtu	841.2 MBtu	80.6 MBtu	2,015.7 MBtu
Natural Gas	257.0 MBtu	278.5 MBtu	-21.5 MBtu	-537.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO2	210,154.53 kg	191,772.53 kg	18,382.00 kg	459,537.34 kg
SO2	523.25 kg	477.48 kg	45.77 kg	1,144.16 kg
NOx	438.63 kg	400.27 kg	38.37 kg	959.14 kg
Natural Gas				
CO2	13,574.16 kg	14,709.74 kg	-1,135.58 kg	-28,388.77 kg
SO2	109.55 kg	118.71 kg	-9.16 kg	-229.11 kg
NOx	11.39 kg	17.34 kg	-5.95 kg	-148.70 kg
Total:				
CO2	223,728.69 kg	206,482.28 kg	17,246.42 kg	431,148.57 kg
SO2	632.79 kg	596.19 kg	36.60 kg	915.06 kg
NOx	450.02 kg	417.60 kg	32.42 kg	810.44 kg

Office Highest Cooling Savings – Dakota Electric

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office best cooling scenario.xml
Date of Study:	Mon Jan 20 16:59:01 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$370,280	$344,382	$25,898
Energy Demand Charges	$181,591	$167,941	$13,650
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
	------------	------------	------------
Subtotal (for Future Cost Items)	$551,870	$487,972	$63,899
	------------	------------	------------
Total PV Life-Cycle Cost	$551,870	$541,639	$10,232

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$39,548
- Increased Total Investment	$29,316

Net Savings $10,232

Savings-to-Investment Ratio (SIR)

SIR = 1.35

Adjusted Internal Rate of Return

AIRR = 4.24%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 24

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	270,153.0 kWh	246,523.0 kWh	23,630.0 kWh	590,733.8 kWh
Natural Gas	2,570.0 Therm	2,785.0 Therm	-215.0 Therm	-5,374.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	921.8 MBtu	841.2 MBtu	80.6 MBtu	2,015.7 MBtu
Natural Gas	257.0 MBtu	278.5 MBtu	-21.5 MBtu	-537.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO_2	210,154.53 kg	191,772.53 kg	18,382.00 kg	459,537.34 kg
SO_2	523.25 kg	477.48 kg	45.77 kg	1,144.16 kg
NO_x	438.63 kg	400.27 kg	38.37 kg	959.14 kg
Natural Gas				
CO_2	13,574.16 kg	14,709.74 kg	-1,135.58 kg	-28,388.77 kg
SO_2	109.55 kg	118.71 kg	-9.16 kg	-229.11 kg
NO_x	11.39 kg	17.34 kg	-5.95 kg	-148.70 kg
Total:				
CO_2	223,728.69 kg	206,482.28 kg	17,246.42 kg	431,148.57 kg
SO_2	632.79 kg	596.19 kg	36.60 kg	915.06 kg
NO_x	450.02 kg	417.60 kg	32.42 kg	810.44 kg

Office Highest Cooling Savings – Minnesota Power

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM cooling

General Information

File Name:	
Date of Study:	Wed Jan 29 21:26:09 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$372,491	$345,996	$26,495
Energy Demand Charges	$116,958	$107,661	$9,296
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
	------------	------------	------------
Subtotal (for Future Cost Items)	$489,448	$429,307	$60,142
	------------	------------	------------
Total PV Life-Cycle Cost	$489,448	$482,974	$6,475

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$35,791
- Increased Total Investment	$29,316

Net Savings $6,475

Savings-to-Investment Ratio (SIR)

SIR = 1.22

Adjusted Internal Rate of Return

AIRR = 3.83%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 25

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	270,153.0 kWh	246,523.0 kWh	23,630.0 kWh	590,733.8 kWh
Natural Gas	2,570.0 Therm	2,785.0 Therm	-215.0 Therm	-5,374.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	921.8 MBtu	841.2 MBtu	80.6 MBtu	2,015.7 MBtu
Natural Gas	257.0 MBtu	278.5 MBtu	-21.5 MBtu	-537.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO_2	210,154.53 kg	191,772.53 kg	18,382.00 kg	459,537.34 kg
SO_2	523.25 kg	477.48 kg	45.77 kg	1,144.16 kg
NO_x	438.63 kg	400.27 kg	38.37 kg	959.14 kg
Natural Gas				
CO_2	13,574.16 kg	14,709.74 kg	-1,135.58 kg	-28,388.77 kg
SO_2	109.55 kg	118.71 kg	-9.16 kg	-229.11 kg
NO_x	11.39 kg	17.34 kg	-5.95 kg	-148.70 kg
Total:				
CO_2	223,728.69 kg	206,482.28 kg	17,246.42 kg	431,148.57 kg
SO_2	632.79 kg	596.19 kg	36.60 kg	915.06 kg
NO_x	450.02 kg	417.60 kg	32.42 kg	810.44 kg

Office Highest Cooling Savings – Otter Tail Power

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office best cooling scenario.xml
Date of Study:	Mon Jan 20 17:02:05 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$359,226	$334,698	$24,528
Energy Demand Charges	$58,463	$54,371	$4,092
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
	------------	------------	------------
Subtotal (for Future Cost Items)	$417,688	$364,718	$52,970
	------------	------------	------------
Total PV Life-Cycle Cost	$417,688	$418,385	-$697

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$28,619
- Increased Total Investment	$29,316

Net Savings -$697

Savings-to-Investment Ratio (SIR)

SIR = 0.98

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 2.90%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	270,153.0 kWh	246,523.0 kWh	23,630.0 kWh	590,733.8 kWh
Natural Gas	2,570.0 Therm	2,785.0 Therm	-215.0 Therm	-5,374.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	921.8 MBtu	841.2 MBtu	80.6 MBtu	2,015.7 MBtu
Natural Gas	257.0 MBtu	278.5 MBtu	-21.5 MBtu	-537.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO_2	210,154.53 kg	191,772.53 kg	18,382.00 kg	459,537.34 kg
SO_2	523.25 kg	477.48 kg	45.77 kg	1,144.16 kg
NO_x	438.63 kg	400.27 kg	38.37 kg	959.14 kg
Natural Gas				
CO_2	13,574.16 kg	14,709.74 kg	-1,135.58 kg	-28,388.77 kg
SO_2	109.55 kg	118.71 kg	-9.16 kg	-229.11 kg
NO_x	11.39 kg	17.34 kg	-5.95 kg	-148.70 kg
Total:				
CO_2	223,728.69 kg	206,482.28 kg	17,246.42 kg	431,148.57 kg
SO_2	632.79 kg	596.19 kg	36.60 kg	915.06 kg
NO_x	450.02 kg	417.60 kg	32.42 kg	810.44 kg

Office Highest Cooling Savings – Xcel Energy

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office best cooling scenario.xml
Date of Study:	Mon Jan 20 16:55:03 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$186,343	$176,130	$10,213
Energy Demand Charges	$219,464	$203,080	$16,383
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
	------------	------------	------------
Subtotal (for Future Cost Items)	$405,806	$354,860	$50,947
	------------	------------	------------
Total PV Life-Cycle Cost	$405,806	$408,527	-$2,720

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$26,596
- Increased Total Investment	$29,316

Net Savings -$2,720

Savings-to-Investment Ratio (SIR)

SIR = 0.91

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 2.60%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	270,153.0 kWh	246,523.0 kWh	23,630.0 kWh	590,733.8 kWh
Natural Gas	2,570.0 Therm	2,785.0 Therm	-215.0 Therm	-5,374.9 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	921.8 MBtu	841.2 MBtu	80.6 MBtu	2,015.7 MBtu
Natural Gas	257.0 MBtu	278.5 MBtu	-21.5 MBtu	-537.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO_2	210,154.53 kg	191,772.53 kg	18,382.00 kg	459,537.34 kg
SO_2	523.25 kg	477.48 kg	45.77 kg	1,144.16 kg
NO_x	438.63 kg	400.27 kg	38.37 kg	959.14 kg
Natural Gas				
CO_2	13,574.16 kg	14,709.74 kg	-1,135.58 kg	-28,388.77 kg
SO_2	109.55 kg	118.71 kg	-9.16 kg	-229.11 kg
NO_x	11.39 kg	17.34 kg	-5.95 kg	-148.70 kg
Total:				
CO_2	223,728.69 kg	206,482.28 kg	17,246.42 kg	431,148.57 kg
SO_2	632.79 kg	596.19 kg	36.60 kg	915.06 kg
NO_x	450.02 kg	417.60 kg	32.42 kg	810.44 kg

Office Highest Cooling Savings – Reduced PCM (Xcel Energy)

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office best cooling scenario.xml
Date of Study:	Wed Mar 11 17:16:36 CDT 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$24,150	-$24,150
Future Costs:			
Energy Consumption Costs	$186,343	$178,767	$7,575
Energy Demand Charges	$219,464	$206,354	$13,110
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$10,958	$10,958
	------------	------------	------------
Subtotal (for Future Cost Items)	$405,806	$374,164	$31,643
	------------	------------	------------
Total PV Life-Cycle Cost	$405,806	$398,314	$7,493

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$20,685
- Increased Total Investment	$13,192

Net Savings $7,493

Savings-to-Investment Ratio (SIR)

SIR = 1.57

Adjusted Internal Rate of Return

AIRR = 4.87%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 21

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	270,153.0 kWh	251,249.0 kWh	18,904.0 kWh	472,587.1 kWh
Natural Gas	2,570.0 Therm	2,785.0 Therm	-215.0 Therm	-5,374.9 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	921.8 MBtu	857.3 MBtu	64.5 MBtu	1,612.5 MBtu
Natural Gas	257.0 MBtu	278.5 MBtu	-21.5 MBtu	-537.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO2	210,154.53 kg	195,448.93 kg	14,705.60 kg	367,629.87 kg
SO2	523.25 kg	486.63 kg	36.61 kg	915.33 kg
NOx	438.63 kg	407.94 kg	30.69 kg	767.31 kg
Natural Gas				
CO2	13,574.16 kg	14,709.74 kg	-1,135.58 kg	-28,388.77 kg
SO2	109.55 kg	118.71 kg	-9.16 kg	-229.11 kg
NOx	11.39 kg	17.34 kg	-5.95 kg	-148.70 kg
Total:				
CO2	223,728.69 kg	210,158.68 kg	13,570.02 kg	339,241.10 kg
SO2	632.79 kg	605.34 kg	27.45 kg	686.23 kg
NOx	450.02 kg	425.28 kg	24.75 kg	618.62 kg

Office Highest Heating Savings – MN Average Rates

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office\office best heating scenario.xml
Date of Study:	Fri Jan 17 15:21:10 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$462,018	$426,953	$35,065
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
	------------	------------	------------
Subtotal (for Future Cost Items)	$462,018	$402,603	$59,415
	------------	------------	------------
Total PV Life-Cycle Cost	$462,018	$456,270	$5,748

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$35,065
- Increased Total Investment	$29,316

Net Savings $5,748

Savings-to-Investment Ratio (SIR)

SIR = 1.20

Adjusted Internal Rate of Return

AIRR = 3.74%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 25

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	237,001.0 kWh	215,725.0 kWh	21,276.0 kWh	531,885.4 kWh
Natural Gas	3,590.0 Therm	3,731.0 Therm	-141.0 Therm	-3,524.9 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	808.7 MBtu	736.1 MBtu	72.6 MBtu	1,814.9 MBtu
Natural Gas	359.0 MBtu	373.1 MBtu	-14.1 MBtu	-352.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO2	184,365.28 kg	167,814.48 kg	16,550.80 kg	413,758.63 kg
SO2	459.04 kg	417.83 kg	41.21 kg	1,030.18 kg
NOx	384.81 kg	350.26 kg	34.54 kg	863.59 kg
Natural Gas				
CO2	18,961.57 kg	19,706.30 kg	-744.73 kg	-18,617.75 kg
SO2	153.03 kg	159.04 kg	-6.01 kg	-150.25 kg
NOx	15.91 kg	23.23 kg	-7.32 kg	-182.92 kg
Total:				
CO2	203,326.85 kg	187,520.79 kg	15,806.07 kg	395,140.88 kg
SO2	612.06 kg	576.86 kg	35.20 kg	879.93 kg
NOx	400.71 kg	373.49 kg	27.23 kg	680.67 kg

Office Highest Heating Savings – With Rebate (MN Average)

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office\office best heating scenario.xml
Date of Study:	Fri Jan 24 09:08:25 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$50,680	-$50,680
Future Costs:			
Energy Consumption Costs	$462,018	$426,953	$35,065
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$22,995	$22,995
Subtotal (for Future Cost Items)	$462,018	$403,958	$58,060
Total PV Life-Cycle Cost	$462,018	$454,638	$7,380

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$35,065
- Increased Total Investment	$27,685

Net Savings $7,380

Savings-to-Investment Ratio (SIR)

SIR = 1.27

Adjusted Internal Rate of Return

AIRR = 3.98%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 25

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	237,001.0 kWh	215,725.0 kWh	21,276.0 kWh	531,885.4 kWh
Natural Gas	3,590.0 Therm	3,731.0 Therm	-141.0 Therm	-3,524.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	808.7 MBtu	736.1 MBtu	72.6 MBtu	1,814.9 MBtu
Natural Gas	359.0 MBtu	373.1 MBtu	-14.1 MBtu	-352.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO_2	184,365.28 kg	167,814.48 kg	16,550.80 kg	413,758.63 kg
SO_2	459.04 kg	417.83 kg	41.21 kg	1,030.18 kg
NO_x	384.81 kg	350.26 kg	34.54 kg	863.59 kg
Natural Gas				
CO_2	18,961.57 kg	19,706.30 kg	-744.73 kg	-18,617.75 kg
SO_2	153.03 kg	159.04 kg	-6.01 kg	-150.25 kg
NO_x	15.91 kg	23.23 kg	-7.32 kg	-182.92 kg
Total:				
CO_2	203,326.85 kg	187,520.79 kg	15,806.07 kg	395,140.88 kg
SO_2	612.06 kg	576.86 kg	35.20 kg	879.93 kg
NO_x	400.71 kg	373.49 kg	27.23 kg	680.67 kg

Office Highest Heating Savings – Connexus Energy

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office\office best heating scenario.xml
Date of Study:	Wed Jan 22 13:40:25 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$308,411	$287,136	$21,275
Energy Demand Charges	$199,529	$182,295	$17,234
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
	------------	------------	------------
Subtotal (for Future Cost Items)	$507,939	$445,080	$62,860
	------------	------------	------------
Total PV Life-Cycle Cost	$507,939	$498,747	$9,193

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$38,509
- Increased Total Investment	$29,316

Net Savings $9,193

Savings-to-Investment Ratio (SIR)

SIR = 1.31

Adjusted Internal Rate of Return

AIRR = 4.13%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 25

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	237,001.0 kWh	215,725.0 kWh	21,276.0 kWh	531,885.4 kWh
Natural Gas	3,590.0 Therm	3,731.0 Therm	-141.0 Therm	-3,524.9 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	808.7 MBtu	736.1 MBtu	72.6 MBtu	1,814.9 MBtu
Natural Gas	359.0 MBtu	373.1 MBtu	-14.1 MBtu	-352.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO2	184,365.28 kg	167,814.48 kg	16,550.80 kg	413,758.63 kg
SO2	459.04 kg	417.83 kg	41.21 kg	1,030.18 kg
NOx	384.81 kg	350.26 kg	34.54 kg	863.59 kg
Natural Gas				
CO2	18,961.57 kg	19,706.30 kg	-744.73 kg	-18,617.75 kg
SO2	153.03 kg	159.04 kg	-6.01 kg	-150.25 kg
NOx	15.91 kg	23.23 kg	-7.32 kg	-182.92 kg
Total:				
CO2	203,326.85 kg	187,520.79 kg	15,806.07 kg	395,140.88 kg
SO2	612.06 kg	576.86 kg	35.20 kg	879.93 kg
NOx	400.71 kg	373.49 kg	27.23 kg	680.67 kg

Office Highest Heating Savings – Dakota Electric

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office\office best heating scenario.xml
Date of Study:	Wed Jan 22 13:39:23 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$344,252	$319,936	$24,316
Energy Demand Charges	$168,252	$153,636	$14,616
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
	------------	------------	------------
Subtotal (for Future Cost Items)	$512,504	$449,222	$63,282
	------------	------------	------------
Total PV Life-Cycle Cost	$512,504	$502,889	$9,615

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$38,932
- Increased Total Investment	$29,316

Net Savings $9,615

Savings-to-Investment Ratio (SIR)

SIR = 1.33

Adjusted Internal Rate of Return

AIRR = 4.18%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 25

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	237,001.0 kWh	215,725.0 kWh	21,276.0 kWh	531,885.4 kWh
Natural Gas	3,590.0 Therm	3,731.0 Therm	-141.0 Therm	-3,524.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	808.7 MBtu	736.1 MBtu	72.6 MBtu	1,814.9 MBtu
Natural Gas	359.0 MBtu	373.1 MBtu	-14.1 MBtu	-352.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO_2	184,365.28 kg	167,814.48 kg	16,550.80 kg	413,758.63 kg
SO_2	459.04 kg	417.83 kg	41.21 kg	1,030.18 kg
NO_x	384.81 kg	350.26 kg	34.54 kg	863.59 kg
Natural Gas				
CO_2	18,961.57 kg	19,706.30 kg	-744.73 kg	-18,617.75 kg
SO_2	153.03 kg	159.04 kg	-6.01 kg	-150.25 kg
NO_x	15.91 kg	23.23 kg	-7.32 kg	-182.92 kg
Total:				
CO_2	203,326.85 kg	187,520.79 kg	15,806.07 kg	395,140.88 kg
SO_2	612.06 kg	576.86 kg	35.20 kg	879.93 kg
NO_x	400.71 kg	373.49 kg	27.23 kg	680.67 kg

Office Highest Heating Savings – Minnesota Power

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office\office best heating scenario.xml
Date of Study:	Wed Jan 22 13:38:00 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$345,261	$320,678	$24,583
Energy Demand Charges	$107,776	$97,940	$9,837
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
Subtotal (for Future Cost Items)	$453,037	$394,267	$58,770
Total PV Life-Cycle Cost	$453,037	$447,934	$5,103

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$34,420
- Increased Total Investment	$29,316

Net Savings $5,103

Savings-to-Investment Ratio (SIR)

SIR = 1.17

Adjusted Internal Rate of Return

AIRR = 3.66%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 25

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	237,001.0 kWh	215,725.0 kWh	21,276.0 kWh	531,885.4 kWh
Natural Gas	3,590.0 Therm	3,731.0 Therm	-141.0 Therm	-3,524.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	808.7 MBtu	736.1 MBtu	72.6 MBtu	1,814.9 MBtu
Natural Gas	359.0 MBtu	373.1 MBtu	-14.1 MBtu	-352.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO2	184,365.28 kg	167,814.48 kg	16,550.80 kg	413,758.63 kg
SO2	459.04 kg	417.83 kg	41.21 kg	1,030.18 kg
NOx	384.81 kg	350.26 kg	34.54 kg	863.59 kg
Natural Gas				
CO2	18,961.57 kg	19,706.30 kg	-744.73 kg	-18,617.75 kg
SO2	153.03 kg	159.04 kg	-6.01 kg	-150.25 kg
NOx	15.91 kg	23.23 kg	-7.32 kg	-182.92 kg
Total:				
CO2	203,326.85 kg	187,520.79 kg	15,806.07 kg	395,140.88 kg
SO2	612.06 kg	576.86 kg	35.20 kg	879.93 kg
NOx	400.71 kg	373.49 kg	27.23 kg	680.67 kg

Office Highest Heating Savings – Otter Tail Power

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office\office best heating scenario.xml
Date of Study:	Wed Jan 22 13:41:23 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$334,012	$310,439	$23,573
Energy Demand Charges	$54,633	$50,181	$4,452
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
Subtotal (for Future Cost Items)	$388,645	$336,269	$52,376
Total PV Life-Cycle Cost	$388,645	$389,936	-$1,291

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$28,025
- Increased Total Investment	$29,316

Net Savings -$1,291

Savings-to-Investment Ratio (SIR)

SIR = 0.96

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 2.81%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	237,001.0 kWh	215,725.0 kWh	21,276.0 kWh	531,885.4 kWh
Natural Gas	3,590.0 Therm	3,731.0 Therm	-141.0 Therm	-3,524.9 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	808.7 MBtu	736.1 MBtu	72.6 MBtu	1,814.9 MBtu
Natural Gas	359.0 MBtu	373.1 MBtu	-14.1 MBtu	-352.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO_2	184,365.28 kg	167,814.48 kg	16,550.80 kg	413,758.63 kg
SO_2	459.04 kg	417.83 kg	41.21 kg	1,030.18 kg
NOx	384.81 kg	350.26 kg	34.54 kg	863.59 kg
Natural Gas				
CO_2	18,961.57 kg	19,706.30 kg	-744.73 kg	-18,617.75 kg
SO_2	153.03 kg	159.04 kg	-6.01 kg	-150.25 kg
NOx	15.91 kg	23.23 kg	-7.32 kg	-182.92 kg
Total:				
CO_2	203,326.85 kg	187,520.79 kg	15,806.07 kg	395,140.88 kg
SO_2	612.06 kg	576.86 kg	35.20 kg	879.93 kg
NOx	400.71 kg	373.49 kg	27.23 kg	680.67 kg

Office Highest Heating Savings – Xcel Energy

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing office

Alternative: Office - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\office\office best heating scenario.xml
Date of Study:	Wed Jan 22 13:34:56 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$53,667	-$53,667
Future Costs:			
Energy Consumption Costs	$181,956	$172,033	$9,923
Energy Demand Charges	$203,833	$186,664	$17,169
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$24,351	$24,351
	------------	------------	------------
Subtotal (for Future Cost Items)	$385,790	$334,347	$51,442
	------------	------------	------------
Total PV Life-Cycle Cost	$385,790	$388,014	-$2,225

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$27,092
- Increased Total Investment	$29,316

Net Savings -$2,225

Savings-to-Investment Ratio (SIR)

SIR = 0.92

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 2.68%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	237,001.0 kWh	215,725.0 kWh	21,276.0 kWh	531,885.4 kWh
Natural Gas	3,590.0 Therm	3,731.0 Therm	-141.0 Therm	-3,524.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	808.7 MBtu	736.1 MBtu	72.6 MBtu	1,814.9 MBtu
Natural Gas	359.0 MBtu	373.1 MBtu	-14.1 MBtu	-352.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO_2	184,365.28 kg	167,814.48 kg	16,550.80 kg	413,758.63 kg
SO_2	459.04 kg	417.83 kg	41.21 kg	1,030.18 kg
NO_x	384.81 kg	350.26 kg	34.54 kg	863.59 kg
Natural Gas				
CO_2	18,961.57 kg	19,706.30 kg	-744.73 kg	-18,617.75 kg
SO_2	153.03 kg	159.04 kg	-6.01 kg	-150.25 kg
NO_x	15.91 kg	23.23 kg	-7.32 kg	-182.92 kg
Total:				
CO_2	203,326.85 kg	187,520.79 kg	15,806.07 kg	395,140.88 kg
SO_2	612.06 kg	576.86 kg	35.20 kg	879.93 kg
NO_x	400.71 kg	373.49 kg	27.23 kg	680.67 kg

School Highest Cooling Savings – MN Average Rates

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best cooling scenario.xml
Date of Study:	Mon Jan 20 12:43:09 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$187,851	$181,239	$6,611
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
	------------	------------	------------
Subtotal (for Future Cost Items)	$187,851	$174,409	$13,441
	------------	------------	------------
Total PV Life-Cycle Cost	$187,851	$189,462	-$1,612

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$6,611
- Increased Total Investment	$8,223

Net Savings -$1,612

Savings-to-Investment Ratio (SIR)

SIR = 0.80

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 2.11%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	96,160.0 kWh	93,752.0 kWh	2,408.0 kWh	60,198.4 kWh
Natural Gas	1,485.0 Therm	1,310.0 Therm	175.0 Therm	4,374.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	328.1 MBtu	319.9 MBtu	8.2 MBtu	205.4 MBtu
Natural Gas	148.5 MBtu	131.0 MBtu	17.5 MBtu	437.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO_2	74,803.76 kg	72,930.55 kg	1,873.21 kg	46,828.86 kg
SO_2	186.25 kg	181.58 kg	4.66 kg	116.60 kg
NO_x	156.13 kg	152.22 kg	3.91 kg	97.74 kg
Natural Gas				
CO_2	7,843.44 kg	6,919.13 kg	924.31 kg	23,107.13 kg
SO_2	63.30 kg	55.84 kg	7.46 kg	186.48 kg
NO_x	6.58 kg	8.15 kg	-1.57 kg	-39.35 kg
Total:				
CO_2	82,647.19 kg	79,849.68 kg	2,797.52 kg	69,935.99 kg
SO_2	249.55 kg	237.42 kg	12.12 kg	303.08 kg

School Highest Cooling Savings – Reduced PCM (MN Average)

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best cooling scenario.xml
Date of Study:	Thu Jan 30 19:31:04 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$6,774	-$6,774
Future Costs:			
Energy Consumption Costs	$187,851	$182,561	$5,290
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$3,074	$3,074
	------------	------------	------------
Subtotal (for Future Cost Items)	$187,851	$179,487	$8,364
	------------	------------	------------
Total PV Life-Cycle Cost	$187,851	$186,261	$1,590

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$5,290
- Increased Total Investment	$3,700

Increased Total Investment	[illegible]

Net Savings	$1,590

Savings-to-Investment Ratio (SIR)

SIR = 1.43

Adjusted Internal Rate of Return

AIRR = 4.48%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 23

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	96,160.0 kWh	94,233.0 kWh	1,927.0 kWh	48,173.7 kWh
Natural Gas	1,485.0 Therm	1,345.0 Therm	140.0 Therm	3,499.9 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	328.1 MBtu	321.5 MBtu	6.6 MBtu	164.4 MBtu
Natural Gas	148.5 MBtu	134.5 MBtu	14.0 MBtu	350.0 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO_2	74,803.76 kg	73,304.73 kg	1,499.03 kg	37,474.75 kg
SO_2	186.25 kg	182.52 kg	3.73 kg	93.31 kg
NO_x	156.13 kg	153.00 kg	3.13 kg	78.22 kg
Natural Gas				
CO_2	7,843.44 kg	7,103.99 kg	739.45 kg	18,485.71 kg
SO_2	63.30 kg	57.33 kg	5.97 kg	149.19 kg
NO_x	6.58 kg	8.37 kg	-1.79 kg	-44.80 kg
Total:				
CO_2	82,647.19 kg	80,408.71 kg	2,238.48 kg	55,960.46 kg
SO_2	249.55 kg	239.85 kg	9.70 kg	242.49 kg
NO_x	162.71 kg	161.37 kg	1.34 kg	33.42 kg

School Highest Cooling Savings – Connexus Energy

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best cooling scenario.xml
Date of Study:	Mon Jan 20 12:44:29 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$125,527	$120,476	$5,051
Energy Demand Charges	$99,953	$95,452	$4,501
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
	------------	------------	------------
Subtotal (for Future Cost Items)	$225,479	$209,098	$16,382
	------------	------------	------------
Total PV Life-Cycle Cost	$225,479	$224,151	$1,329

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$9,552
- Increased Total Investment	$8,223

Net Savings $1,329

Savings-to-Investment Ratio (SIR)

SIR = 1.16

Adjusted Internal Rate of Return

AIRR = 3.62%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 25

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	96,160.0 kWh	93,752.0 kWh	2,408.0 kWh	60,198.4 kWh
Natural Gas	1,485.0 Therm	1,310.0 Therm	175.0 Therm	4,374.9 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	328.1 MBtu	319.9 MBtu	8.2 MBtu	205.4 MBtu
Natural Gas	148.5 MBtu	131.0 MBtu	17.5 MBtu	437.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO_2	74,803.76 kg	72,930.55 kg	1,873.21 kg	46,828.86 kg
SO_2	186.25 kg	181.58 kg	4.66 kg	116.60 kg
NO_x	156.13 kg	152.22 kg	3.91 kg	97.74 kg
Natural Gas				
CO_2	7,843.44 kg	6,919.13 kg	924.31 kg	23,107.13 kg
SO_2	63.30 kg	55.84 kg	7.46 kg	186.48 kg
NO_x	6.58 kg	8.15 kg	-1.57 kg	-39.35 kg
Total:				
CO_2	82,647.19 kg	79,849.68 kg	2,797.52 kg	69,935.99 kg
SO_2	249.55 kg	237.42 kg	12.12 kg	303.08 kg
NO_x	162.71 kg	160.37 kg	2.34 kg	58.39 kg

School Highest Cooling Savings – Dakota Electric

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best cooling scenario.xml
Date of Study:	Mon Jan 20 12:52:45 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$142,477	$136,940	$5,536
Energy Demand Charges	$84,159	$80,247	$3,912
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
	------------	------------	------------
Subtotal (for Future Cost Items)	$226,635	$210,357	$16,278
	------------	------------	------------
Total PV Life-Cycle Cost	$226,635	$225,410	$1,225

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$9,448
- Increased Total Investment	$8,223

Net Savings $1,225

Savings-to-Investment Ratio (SIR)

SIR = 1.15

Adjusted Internal Rate of Return

AIRR = 3.57%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 25

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	96,160.0 kWh	93,752.0 kWh	2,408.0 kWh	60,198.4 kWh
Natural Gas	1,485.0 Therm	1,310.0 Therm	175.0 Therm	4,374.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	328.1 MBtu	319.9 MBtu	8.2 MBtu	205.4 MBtu
Natural Gas	148.5 MBtu	131.0 MBtu	17.5 MBtu	437.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO2	74,803.76 kg	72,930.55 kg	1,873.21 kg	46,828.86 kg
SO2	186.25 kg	181.58 kg	4.66 kg	116.60 kg
NOx	156.13 kg	152.22 kg	3.91 kg	97.74 kg
Natural Gas				
CO2	7,843.44 kg	6,919.13 kg	924.31 kg	23,107.13 kg
SO2	63.30 kg	55.84 kg	7.46 kg	186.48 kg
NOx	6.58 kg	8.15 kg	-1.57 kg	-39.35 kg
Total:				
CO2	82,647.19 kg	79,849.68 kg	2,797.52 kg	69,935.99 kg
SO2	249.55 kg	237.42 kg	12.12 kg	303.08 kg
NOx	162.71 kg	160.37 kg	2.34 kg	58.39 kg

School Highest Cooling Savings – Minnesota Power

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best cooling scenario.xml
Date of Study:	Mon Jan 20 12:51:38 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$140,478	$135,053	$5,425
Energy Demand Charges	$54,354	$51,932	$2,422
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
Subtotal (for Future Cost Items)	$194,833	$180,155	$14,677
Total PV Life-Cycle Cost	$194,833	$195,208	-$376

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$7,847
- Increased Total Investment	$8,223

Net Savings -$376

Savings-to-Investment Ratio (SIR)

SIR = 0.95

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 2.81%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	96,160.0 kWh	93,752.0 kWh	2,408.0 kWh	60,198.4 kWh
Natural Gas	1,485.0 Therm	1,310.0 Therm	175.0 Therm	4,374.9 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	328.1 MBtu	319.9 MBtu	8.2 MBtu	205.4 MBtu
Natural Gas	148.5 MBtu	131.0 MBtu	17.5 MBtu	437.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO2	74,803.76 kg	72,930.55 kg	1,873.21 kg	46,828.86 kg
SO2	186.25 kg	181.58 kg	4.66 kg	116.60 kg
NOx	156.13 kg	152.22 kg	3.91 kg	97.74 kg
Natural Gas				
CO2	7,843.44 kg	6,919.13 kg	924.31 kg	23,107.13 kg
SO2	63.30 kg	55.84 kg	7.46 kg	186.48 kg
NOx	6.58 kg	8.15 kg	-1.57 kg	-39.35 kg
Total:				
CO2	82,647.19 kg	79,849.68 kg	2,797.52 kg	69,935.99 kg
SO2	249.55 kg	237.42 kg	12.12 kg	303.08 kg
NOx	162.71 kg	160.37 kg	2.34 kg	58.39 kg

School Highest Cooling Savings – Otter Tail Power

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best cooling scenario.xml
Date of Study:	Mon Jan 20 12:54:48 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$135,914	$130,603	$5,311
Energy Demand Charges	$27,202	$25,958	$1,244
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
	------------	------------	------------
Subtotal (for Future Cost Items)	$163,116	$149,731	$13,385
	------------	------------	------------
Total PV Life-Cycle Cost	$163,116	$164,784	-$1,668

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$6,555
- Increased Total Investment	$8,223

Net Savings -$1,668

Savings-to-Investment Ratio (SIR)

SIR = 0.80

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 2.07%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	96,160.0 kWh	93,752.0 kWh	2,408.0 kWh	60,198.4 kWh
Natural Gas	1,485.0 Therm	1,310.0 Therm	175.0 Therm	4,374.9 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	328.1 MBtu	319.9 MBtu	8.2 MBtu	205.4 MBtu
Natural Gas	148.5 MBtu	131.0 MBtu	17.5 MBtu	437.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO2	74,803.76 kg	72,930.55 kg	1,873.21 kg	46,828.86 kg
SO2	186.25 kg	181.58 kg	4.66 kg	116.60 kg
NOx	156.13 kg	152.22 kg	3.91 kg	97.74 kg
Natural Gas				
CO2	7,843.44 kg	6,919.13 kg	924.31 kg	23,107.13 kg
SO2	63.30 kg	55.84 kg	7.46 kg	186.48 kg
NOx	6.58 kg	8.15 kg	-1.57 kg	-39.35 kg
Total:				
CO2	82,647.19 kg	79,849.68 kg	2,797.52 kg	69,935.99 kg
SO2	249.55 kg	237.42 kg	12.12 kg	303.08 kg
NOx	162.71 kg	160.37 kg	2.34 kg	58.39 kg

School Highest Cooling Savings – Xcel Energy

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM cooling

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best cooling scenario.xml
Date of Study:	Mon Jan 20 12:47:30 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$74,219	$70,454	$3,766
Energy Demand Charges	$102,048	$97,449	$4,599
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
	------------	------------	------------
Subtotal (for Future Cost Items)	$176,267	$161,072	$15,195
	------------	------------	------------
Total PV Life-Cycle Cost	$176,267	$176,125	$142

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$8,365
- Increased Total Investment	$8,223

Net Savings $142

Savings-to-Investment Ratio (SIR)

SIR = 1.02

Adjusted Internal Rate of Return

AIRR = 3.07%

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Simple Payback occurs in year 25

Discounted Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	96,160.0 kWh	93,752.0 kWh	2,408.0 kWh	60,198.4 kWh
Natural Gas	1,485.0 Therm	1,310.0 Therm	175.0 Therm	4,374.9 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	328.1 MBtu	319.9 MBtu	8.2 MBtu	205.4 MBtu
Natural Gas	148.5 MBtu	131.0 MBtu	17.5 MBtu	437.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO2	74,803.76 kg	72,930.55 kg	1,873.21 kg	46,828.86 kg
SO2	186.25 kg	181.58 kg	4.66 kg	116.60 kg
NOx	156.13 kg	152.22 kg	3.91 kg	97.74 kg
Natural Gas				
CO2	7,843.44 kg	6,919.13 kg	924.31 kg	23,107.13 kg
SO2	63.30 kg	55.84 kg	7.46 kg	186.48 kg
NOx	6.58 kg	8.15 kg	-1.57 kg	-39.35 kg
Total:				
CO2	82,647.19 kg	79,849.68 kg	2,797.52 kg	69,935.99 kg
SO2	249.55 kg	237.42 kg	12.12 kg	303.08 kg
NOx	162.71 kg	160.37 kg	2.34 kg	58.39 kg

School Highest Heating Savings – MN Average Rates

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best heating scenario.xml
Date of Study:	Mon Jan 20 13:31:41 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$193,817	$189,814	$4,003
Energy Demand Charges	$0	$0	$0
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
	------------	------------	------------
Subtotal (for Future Cost Items)	$193,817	$182,984	$10,833
	------------	------------	------------
Total PV Life-Cycle Cost	$193,817	$198,037	-$4,220

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$4,003
- Increased Total Investment	$8,223

Net Savings -$4,220

Savings-to-Investment Ratio (SIR)

SIR = 0.49

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 0.08%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	99,852.0 kWh	99,484.0 kWh	368.0 kWh	9,199.7 kWh
Natural Gas	1,452.0 Therm	1,209.0 Therm	243.0 Therm	6,074.8 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	340.7 MBtu	339.5 MBtu	1.3 MBtu	31.4 MBtu
Natural Gas	145.2 MBtu	120.9 MBtu	24.3 MBtu	607.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO_2	77,675.80 kg	77,389.53 kg	286.27 kg	7,156.57 kg
SO_2	193.40 kg	192.69 kg	0.71 kg	17.82 kg
NO_x	162.12 kg	161.53 kg	0.60 kg	14.94 kg
Natural Gas				
CO_2	7,669.14 kg	6,385.67 kg	1,283.47 kg	32,085.91 kg
SO_2	61.89 kg	51.53 kg	10.36 kg	258.94 kg
NO_x	6.43 kg	5.36 kg	1.08 kg	26.92 kg
Total:				
CO_2	85,344.94 kg	83,775.19 kg	1,569.74 kg	39,242.48 kg
SO_2	255.29 kg	244.22 kg	11.07 kg	276.76 kg
NO_x	168.56 kg	166.88 kg	1.67 kg	41.86 kg

School Highest Heating Savings – Connexus Energy

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best heating scenario.xml
Date of Study:	Mon Jan 20 13:39:57 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$129,100	$125,336	$3,765
Energy Demand Charges	$101,982	$98,496	$3,486
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
	------------	------------	------------
Subtotal (for Future Cost Items)	$231,083	$217,002	$14,081
	------------	------------	------------
Total PV Life-Cycle Cost	$231,083	$232,055	-$972

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$7,251
- Increased Total Investment	$8,223

Net Savings -$972

Savings-to-Investment Ratio (SIR)

SIR = 0.88

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 2.48%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	99,852.0 kWh	99,484.0 kWh	368.0 kWh	9,199.7 kWh
Natural Gas	1,452.0 Therm	1,209.0 Therm	243.0 Therm	6,074.8 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	340.7 MBtu	339.5 MBtu	1.3 MBtu	31.4 MBtu
Natural Gas	145.2 MBtu	120.9 MBtu	24.3 MBtu	607.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO2	77,675.80 kg	77,389.53 kg	286.27 kg	7,156.57 kg
SO2	193.40 kg	192.69 kg	0.71 kg	17.82 kg
NOx	162.12 kg	161.53 kg	0.60 kg	14.94 kg
Natural Gas				
CO2	7,669.14 kg	6,385.67 kg	1,283.47 kg	32,085.91 kg
SO2	61.89 kg	51.53 kg	10.36 kg	258.94 kg
NOx	6.43 kg	5.36 kg	1.08 kg	26.92 kg
Total:				
CO2	85,344.94 kg	83,775.19 kg	1,569.74 kg	39,242.48 kg
SO2	255.29 kg	244.22 kg	11.07 kg	276.76 kg
NOx	168.56 kg	166.88 kg	1.67 kg	41.86 kg

School Highest Heating Savings – Dakota Electric

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best heating scenario.xml
Date of Study:	Mon Jan 20 13:38:16 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$146,620	$142,595	$4,025
Energy Demand Charges	$85,926	$82,931	$2,995
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
	------------	------------	------------
Subtotal (for Future Cost Items)	$232,546	$218,696	$13,850
	------------	------------	------------
Total PV Life-Cycle Cost	$232,546	$233,749	-$1,203

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$7,020
- Increased Total Investment	$8,223

Net Savings -$1,203

Savings-to-Investment Ratio (SIR)

SIR = 0.85

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 2.35%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	99,852.0 kWh	99,484.0 kWh	368.0 kWh	9,199.7 kWh
Natural Gas	1,452.0 Therm	1,209.0 Therm	243.0 Therm	6,074.8 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	340.7 MBtu	339.5 MBtu	1.3 MBtu	31.4 MBtu
Natural Gas	145.2 MBtu	120.9 MBtu	24.3 MBtu	607.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO2	77,675.80 kg	77,389.53 kg	286.27 kg	7,156.57 kg
SO2	193.40 kg	192.69 kg	0.71 kg	17.82 kg
NOx	162.12 kg	161.53 kg	0.60 kg	14.94 kg
Natural Gas				
CO2	7,669.14 kg	6,385.67 kg	1,283.47 kg	32,085.91 kg
SO2	61.89 kg	51.53 kg	10.36 kg	258.94 kg
NOx	6.43 kg	5.36 kg	1.08 kg	26.92 kg
Total:				
CO2	85,344.94 kg	83,775.19 kg	1,569.74 kg	39,242.48 kg
SO2	255.29 kg	244.22 kg	11.07 kg	276.76 kg
NOx	168.56 kg	166.88 kg	1.67 kg	41.86 kg

School Highest Heating Savings – Minnesota Power

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best heating scenario.xml
Date of Study:	Mon Jan 20 13:35:55 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$144,626	$140,804	$3,822
Energy Demand Charges	$55,451	$53,602	$1,849
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
	------------	------------	------------
Subtotal (for Future Cost Items)	$200,077	$187,576	$12,501
	------------	------------	------------
Total PV Life-Cycle Cost	$200,077	$202,629	-$2,552

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$5,671
- Increased Total Investment	$8,223

Net Savings -$2,552

Savings-to-Investment Ratio (SIR)

SIR = 0.69

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 1.48%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	99,852.0 kWh	99,484.0 kWh	368.0 kWh	9,199.7 kWh
Natural Gas	1,452.0 Therm	1,209.0 Therm	243.0 Therm	6,074.8 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	340.7 MBtu	339.5 MBtu	1.3 MBtu	31.4 MBtu
Natural Gas	145.2 MBtu	120.9 MBtu	24.3 MBtu	607.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO_2	77,675.80 kg	77,389.53 kg	286.27 kg	7,156.57 kg
SO_2	193.40 kg	192.69 kg	0.71 kg	17.82 kg
NO_x	162.12 kg	161.53 kg	0.60 kg	14.94 kg
Natural Gas				
CO_2	7,669.14 kg	6,385.67 kg	1,283.47 kg	32,085.91 kg
SO_2	61.89 kg	51.53 kg	10.36 kg	258.94 kg
NO_x	6.43 kg	5.36 kg	1.08 kg	26.92 kg
Total:				
CO_2	85,344.94 kg	83,775.19 kg	1,569.74 kg	39,242.48 kg
SO_2	255.29 kg	244.22 kg	11.07 kg	276.76 kg
NO_x	168.56 kg	166.88 kg	1.67 kg	41.86 kg

School Highest Heating Savings – Otter Tail Power

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best heating scenario.xml
Date of Study:	Mon Jan 20 13:42:18 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$139,723	$136,082	$3,641
Energy Demand Charges	$27,758	$26,776	$982
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
	------------	------------	------------
Subtotal (for Future Cost Items)	$167,481	$156,028	$11,453
	------------	------------	------------
Total PV Life-Cycle Cost	$167,481	$171,081	-$3,600

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$4,623
- Increased Total Investment	$8,223

Net Savings -$3,600

Savings-to-Investment Ratio (SIR)

SIR = 0.56

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 0.65%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	99,852.0 kWh	99,484.0 kWh	368.0 kWh	9,199.7 kWh
Natural Gas	1,452.0 Therm	1,209.0 Therm	243.0 Therm	6,074.8 Therm

Energy Savings Summary (in MBtu)

Energy	-----Average	Annual	Consumption-----	Life-Cycle
Type	Base Case	Alternative	Savings	Savings
Electricity	340.7 MBtu	339.5 MBtu	1.3 MBtu	31.4 MBtu
Natural Gas	145.2 MBtu	120.9 MBtu	24.3 MBtu	607.5 MBtu

Emissions Reduction Summary

Energy	-----Average	Annual	Emissions-----	Life-Cycle
Type	Base Case	Alternative	Reduction	Reduction
Electricity				
CO_2	77,675.80 kg	77,389.53 kg	286.27 kg	7,156.57 kg
SO_2	193.40 kg	192.69 kg	0.71 kg	17.82 kg
NO_x	162.12 kg	161.53 kg	0.60 kg	14.94 kg
Natural Gas				
CO_2	7,669.14 kg	6,385.67 kg	1,283.47 kg	32,085.91 kg
SO_2	61.89 kg	51.53 kg	10.36 kg	258.94 kg
NO_x	6.43 kg	5.36 kg	1.08 kg	26.92 kg
Total:				
CO_2	85,344.94 kg	83,775.19 kg	1,569.74 kg	39,242.48 kg
SO_2	255.29 kg	244.22 kg	11.07 kg	276.76 kg
NO_x	168.56 kg	166.88 kg	1.67 kg	41.86 kg

School Highest Heating Savings – Xcel Energy

NIST BLCC 5.3-19: Comparative Analysis

Consistent with Federal Life Cycle Cost Methodology and Procedures, 10 CFR, Part 436, Subpart A

Base Case: Existing school

Alternative: School - PCM heating

General Information

File Name:	M:\18Proj\180525\500 Technical\503 Calculations\school best heating scenario.xml
Date of Study:	Mon Jan 20 13:32:42 CST 2020
Project Name:	PCM Minnesota
Project Location:	Minnesota
Analysis Type:	FEMP Analysis, Energy Project
Analyst:	MAC
Base Date:	January 1, 2020
Service Date:	January 1, 2020
Study Period:	25 years 0 months(January 1, 2020 through December 31, 2044)
Discount Rate:	3%
Discounting Convention:	End-of-Year

Comparison of Present-Value Costs

PV Life-Cycle Cost

	Base Case	Alternative	Savings from Alternative
Initial Investment Costs:			
Capital Requirements as of Base Date	$0	$15,053	-$15,053
Future Costs:			
Energy Consumption Costs	$75,823	$72,255	$3,568
Energy Demand Charges	$104,110	$100,558	$3,552
Energy Utility Rebates	$0	$0	$0
Water Costs	$0	$0	$0
Recurring and Non-Recurring OM&R Costs	$0	$0	$0
Capital Replacements	$0	$0	$0
Residual Value at End of Study Period	$0	-$6,830	$6,830
	------------	------------	------------
Subtotal (for Future Cost Items)	$179,933	$165,983	$13,950
	------------	------------	------------
Total PV Life-Cycle Cost	$179,933	$181,036	-$1,103

Net Savings from Alternative Compared with Base Case

PV of Non-Investment Savings	$7,120
- Increased Total Investment	$8,223

Net Savings -$1,103

Savings-to-Investment Ratio (SIR)

SIR = 0.87

SIR is lower than 1.0; project alternative is not cost effective.

Adjusted Internal Rate of Return

AIRR = 2.41%

AIRR is lower than your discount rate; project alternative is not cost effective.

Payback Period

Estimated Years to Payback (from beginning of Service Period)

Discounted Payback never reached during study period.

Simple Payback occurs in year 25

Energy Savings Summary

Energy Savings Summary (in stated units)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	99,852.0 kWh	99,484.0 kWh	368.0 kWh	9,199.7 kWh
Natural Gas	1,452.0 Therm	1,209.0 Therm	243.0 Therm	6,074.8 Therm

Energy Savings Summary (in MBtu)

Energy Type	-----Average Base Case	Annual Alternative	Consumption----- Savings	Life-Cycle Savings
Electricity	340.7 MBtu	339.5 MBtu	1.3 MBtu	31.4 MBtu
Natural Gas	145.2 MBtu	120.9 MBtu	24.3 MBtu	607.5 MBtu

Emissions Reduction Summary

Energy Type	-----Average Base Case	Annual Alternative	Emissions----- Reduction	Life-Cycle Reduction
Electricity				
CO_2	77,675.80 kg	77,389.53 kg	286.27 kg	7,156.57 kg
SO_2	193.40 kg	192.69 kg	0.71 kg	17.82 kg
NO_x	162.12 kg	161.53 kg	0.60 kg	14.94 kg
Natural Gas				
CO_2	7,669.14 kg	6,385.67 kg	1,283.47 kg	32,085.91 kg
SO_2	61.89 kg	51.53 kg	10.36 kg	258.94 kg
NO_x	6.43 kg	5.36 kg	1.08 kg	26.92 kg
Total:				
CO_2	85,344.94 kg	83,775.19 kg	1,569.74 kg	39,242.48 kg
SO_2	255.29 kg	244.22 kg	11.07 kg	276.76 kg
NO_x	168.56 kg	166.88 kg	1.67 kg	41.86 kg