Analysis of Greenhouse Gas Emissions Reductions Using Functional Storage Options in California

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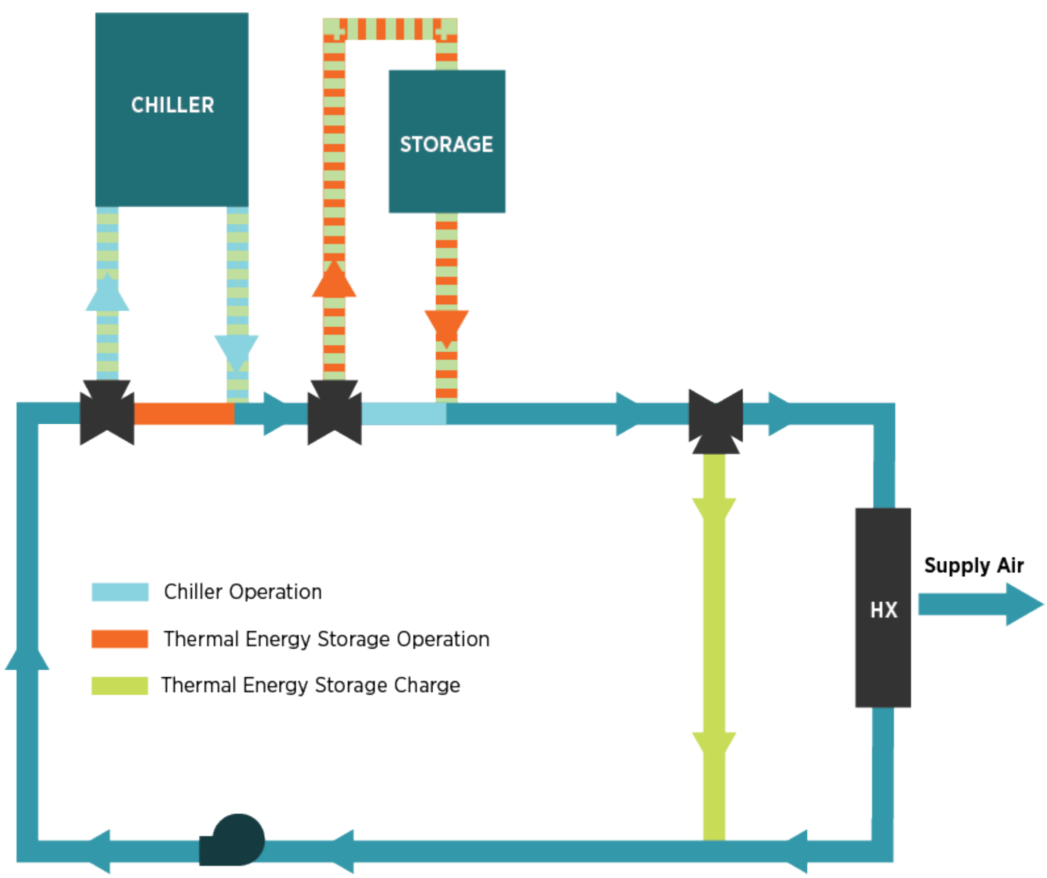
EXECUTIVE SUMMARY

This research investigates the potential impact thermal energy storage systems can have on greenhouse gas (GHG) emissions by shifting the electric load associated with vapor-compression systems from peak to off-peak hours. Annual whole building energy simulations were used to model the electric load of commercial heating, ventilation and air conditioning (HVAC) systems with and without thermal energy storage capabilities in a four-story office building in three different California cities. Historical weather data for Sacramento, Burbank and Riverside from the 2018 calendar year was used to model ambient conditions at each site. A high-resolution, utility-specific dataset of historical marginal emission rates of carbon dioxide (CO_2) resulting from electricity generation and distribution was used to estimate the indirect emissions from the operation of the simulated HVAC system. Simulation results show that thermal energy storage systems were effective at reducing GHG emissions by shifting the HVAC electric load from peak to off-peak hours. The simulated thermal energy storage system reduced annual emissions by as much as 21.3 kilograms of CO_2 per kilowatt-hour of connected curtailment capacity. When compared to the CO_2 emissions from the baseline building simulation, buildings simulated with thermal energy storage systems had reduced annual CO_2 emissions from HVAC electric demand by as much as 8% in Sacramento, 12% in Burbank and 11% in Riverside.



INTRODUCTION

This research investigates the potential impact thermal energy storage (TES) systems can have on greenhouse gas (GHG) emissions by shifting the electric load associated with vapor-compression systems from peak to off-peak hours. Annual whole building energy simulations were used to model the electric load of commercial heating, ventilation and air conditioning (HVAC) systems with and without thermal energy storage capabilities in a four-story office building in three different California cities. Historical weather data for Sacramento, Burbank and Riverside from the 2018 calendar year was used to model ambient conditions at each site. A high-resolution, utility-specific dataset of historical marginal emission rates of carbon dioxide resulting from electricity generation and distribution was used to estimate the indirect emissions from the operation of the simulated HVAC system.

When TES is deployed to offset a cooling load, the grid impact is the difference between the electric demand that would have been required by the primary cooling system to meet the offset load and the electricity demand associated with operating the TES system. Since most building cooling systems use vapor-compression cycles, the reduced electric demand achieved by TES systems is attributed to de-energizing the compressor and condenser fan or cooling tower in the vapor-compression cycle. The system efficiency of vapor-compression equipment decreases as outdoor air temperature increases resulting in an elevated electrical demand to meet a given thermal load at hotter ambient air temperatures. Thus, as the outdoor air temperature increases, the value of stored thermal energy increases.

Utilities, system operators, and regulators are charged with maintaining the reliability and stability of electricity distribution grids. To satisfy this obligation, they maintain adequate reserve margins such that involuntary load shedding resulting from inadequate electricity supply should only occur once in ten years. This need is primarily met by having sufficient power capacity to meet the chosen reserve margin, although the capacity assets must also have an appreciable level of available energy to maintain output for a reasonable amount of time. To meet their reserve margins, some utilities pay to offset the cost of TES systems by providing incentives. An example of this would be Permanent Load Shift (PLS) programs. These programs, primarily focused on resources as capacity, pay based upon peak load impacts.

BACKGROUND

The majority of building cooling technologies use electricity to drive a vapor-compression cycle that absorbs heat from inside the building and rejects it to outdoor air. Although at one time air conditioning was considered a luxury, the market penetration of modern air conditioners has nearly reached saturation in many parts of the world, including the USA, Japan, and urban China (Santamouris, 2016).

Changes in electricity demand from air conditioning in a given region are driven by economic development, population growth, and global climate change. In developing regions, the market penetration of air conditioners is rapidly increasing; 38 of the 50 largest metropolitan areas are in developing countries with warmer than average climates (Sivak, 2009). If the cooling strategies used in the USA were deployed in India, the cooling load from metropolitan Mumbai alone would be 24% of the cooling load of the entire USA (Sivak, 2009). By 2050, the annual global cooling demand is predicted to increase by 750% in commercial buildings and 275% in residential buildings (Santamouris, 2016).

Compared to other electric loads, increased cooling demand has a disproportionate impact on peak demand since it is driven by ambient temperature and is therefore coincident with electricity grid peak. Also, an increase in outdoor air temperature not only increases the cooling load of a building, but also decreases the efficiency of the vapor-compression cycle. Thus, technologies that can reduce the use of air conditioners during peak periods are vital to curbing the compound effect that peak outdoor air temperatures have on the electric grid.

Another trend that is having a large impact on the electric grid and energy management is the increased use of renewable energy. Harvested sources of renewable energy, including hydro-electric, geothermal power, geothermal heat, solar photovoltaics, solar thermal, tidal power, and wind, are steadily increasing in market penetration across the globe. From the year 2000 to 2013, the amount of renewable energy per capita has increased globally from 1.73 W to 75.38 W, more than a 40X increase (Sørensen, 2017).

The supply of renewable energy from solar and wind are intermittent and do not follow the demand for electricity. Although hydroelectric and geothermal power can be controlled more easily than solar and wind, these sources of renewable energy are geographically restricted to certain regions. Electric grids with a large amount of connected solar and wind experience daily periods of over and under generation that must be reconciled by utility grid operators to maintain grid stability and avoid involuntary load shedding. Electric grids are especially stressed by rapid shifts between periods of abundant renewable energy and low electric demand, and periods of scarce renewable energy and high electric demand, the risk of which increases as the amount of connected renewable energy increases.

TES is a technology that can alleviate the stress placed on the electric grid by buildings. Conventional TES systems use the vapor-compression cycle to cool a thermal mass, such as stratified chilled water, or cause a phase change in a material such as ice, wax or salt. The thermal energy stored in the cooled material can then be used at a later time to cool the building. TES decouples the demand for cooling and the demand for electricity necessary to meet that cooling demand. Using TES, the electric demand from cooling can be shifted to off-peak hours. Additionally, at times when there is a large amount of solar or wind energy available on the grid but the cooling demand is low, TES systems can be used to absorb excess grid capacity, allowing the utility grid operators to avoid costly abatement.

An alternative to TES is electrochemical energy storage (batteries). Although individual electrochemical battery cells have a very high energy density, when they are assembled into a battery pack they require a container, air gaps, cooling system, battery management system, and an inverter. A battery pack built into a 40-foot shipping container typically has a capacity of up to 1 MWh resulting in an energy density by volume of approximately 50 kJ/L. Similarly, ice storage tanks require insulation and a glycol loop resulting in an energy density by volume for the TES system of approximately 200 kJ/L. Thermal energy, however, is not equivalent to electric energy; if the energy stored in a 1 MWh battery pack were used to power a chiller with a coefficient of performance of 3.3 it would produce 3.3 MWh of cooling giving it a thermal energy density of 165 kJ/L. Though ice storage tanks can store approximately 20% more thermal energy per volume than a large battery pack powering a chiller, a cylindrical ice storage tank will have a larger footprint than a rectangular battery pack of the same volume.

The charge-discharge process of all energy storage systems is less than 100% efficient. Modern TES systems have round-trip thermal efficiencies between 97.5% and 99% (Nyamdash, Denny, & O'Malley, 2010). The inefficiency of the charge-discharge process usually means that the use of energy storage for peak shifting consumes electricity. This is not always the case for TES systems due to the temperature dependency of the vapor-compression cycle efficiency. Depending on the ambient temperatures, the energy lost to the charge-discharge process can be less than the electric energy saved by charging the TES system during off-peak hours instead of using the vapor-compression cycle during peak hours to directly meet the cooling load, resulting in a reduced net electricity consumption (Deetjen, Reimers, & Webber, 2018).

Although TES cannot be efficiently used for electric round trip storage (grid to storage back to grid) it directly addresses the cooling load, which is often the largest contributor to the peak demand of buildings. Additionally, when compared to batteries, TES is significantly cheaper, is built with abundant recyclable materials, is not prone to cycling-induced degradation, and has a long usable lifetime (Alva, Lin, & Fang, 2018).

Electricity Generation

Utility operators manage a diverse portfolio of generation sources that varies from state to state and between utility territories. These generation sources usually include some combination of nuclear, coal, natural gas, solar, hydro, wind, geothermal, biomass and biogas. Additionally, electricity can be imported from out of state or generation can be shifted from peak to off-peak hours using batteries. These generation facilities differ from each other in cost, responsiveness, availability, reliability and emissions. As such, some are better suited for serving a constant baseload, while some excel at responding to rapid fluctuations in a dynamic load profile and others minimize the environmental impact of electricity generation. The generation sources that were used to meet the electric demand of California utility customers throughout the day on August 10, 2018 are shown in Figure 1.

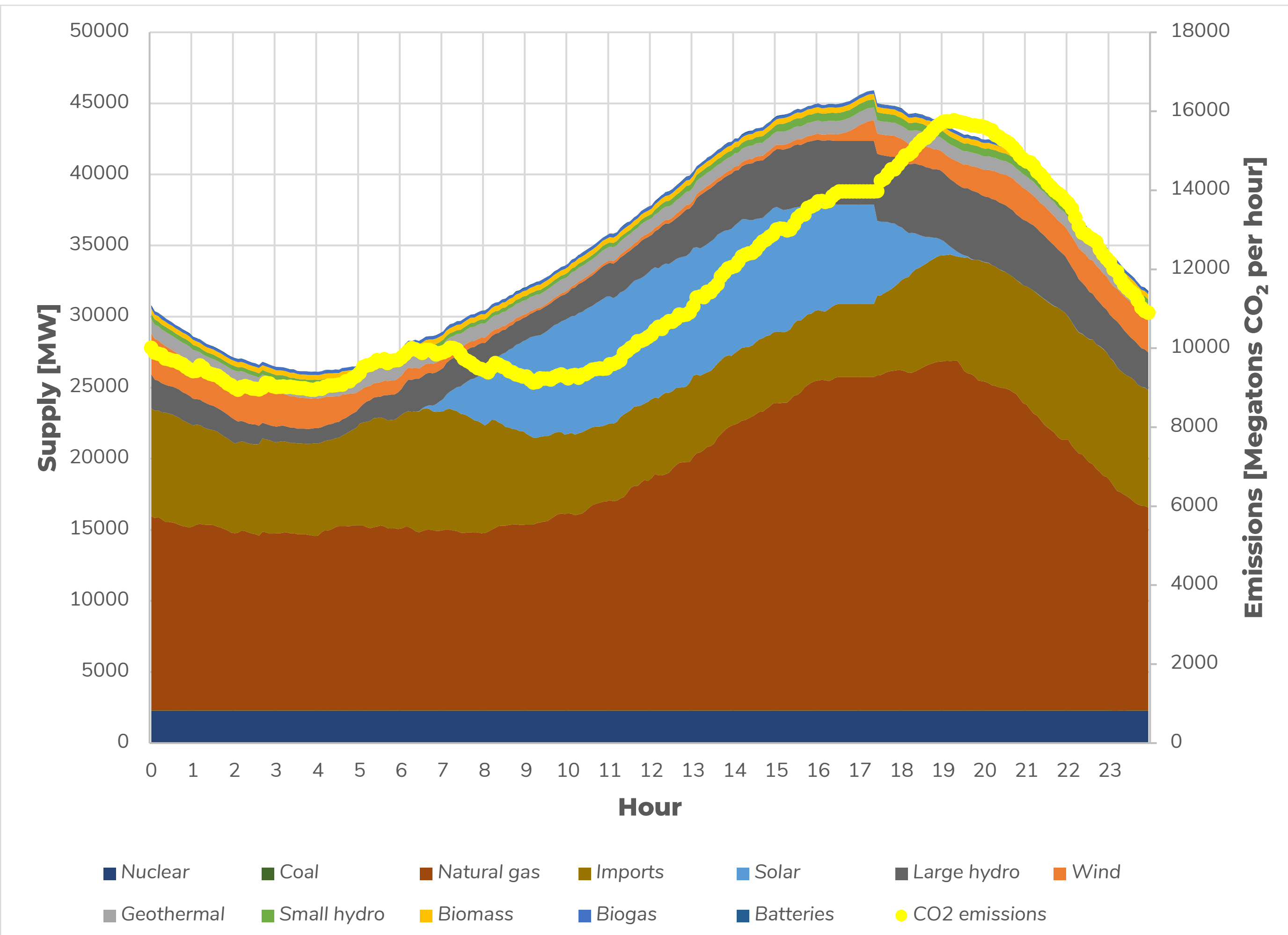


Figure 1 – Electricity generation and associated CO_2 emissions in California on August 10, 2018

Although small, nuclear power contributes to the constant baseload. Natural gas power plants are the largest generation source and supply the largest portion of the baseload as well as meeting the largest portion of the peak demand at 17:00. Electricity is being imported at all hours of the day; however it does ramp down as solar comes online between 7:00 and 19:00. Wind generation has the opposite profile as solar, contributing a significant amount of generation at night until the late morning and again in the early evening through the night. Electricity generation from hydro is ramped up to meet the peak demand. The peak in CO_2 emissions occurs between 19:00 and 20:00, around that same time solar generation goes offline, electricity imports peak and generation from natural gas peaks.

Marginal Emissions

The annual average carbon intensity (tons of CO_2 emissions per GWh of electricity generation) of electric grids varies across the USA from 133 tons/GWh in Washington to 298 tons/GWh in West Virginia with a United States Average of 202 tons/GWh (Energy Information Association). The annual average carbon intensity for the California electric grids is 194 tons/GWh. However, when considering the GHG emissions from increasing the load on an electric grid (such as through widespread adoption of electrification) it is important to consider the marginal emissions rate.

Utility grid operators respond to fluctuations in load on the electric grid by increasing or decreasing the amount of power that is purchased from various generation sources. These generation sources that operate on the margin are usually the most expensive and highest emitting power generators in the portfolio and contribute to the marginal emissions rate. As a result, the marginal emissions rate is almost always higher than the average carbon intensity of an electric grid. For example, although the state of Washington has one of the cleanest power generation portfolios in the USA, The Bonneville Power Administration has many coal powerplants that operate on its margin contributing to an average marginal emissions rate of approximately 920 tons/GWh (WattTime). In 2018, the average marginal emissions rate for the Pacific Gas and Electric Company in California was approximately 300 tons/GWh (WattTime). The average daily marginal CO_2 emissions profile for each month of 2018 are shown in Figure 2, Figure 3 and Figure 4 for the Sacramento, Riverside and Burbank areas respectively.

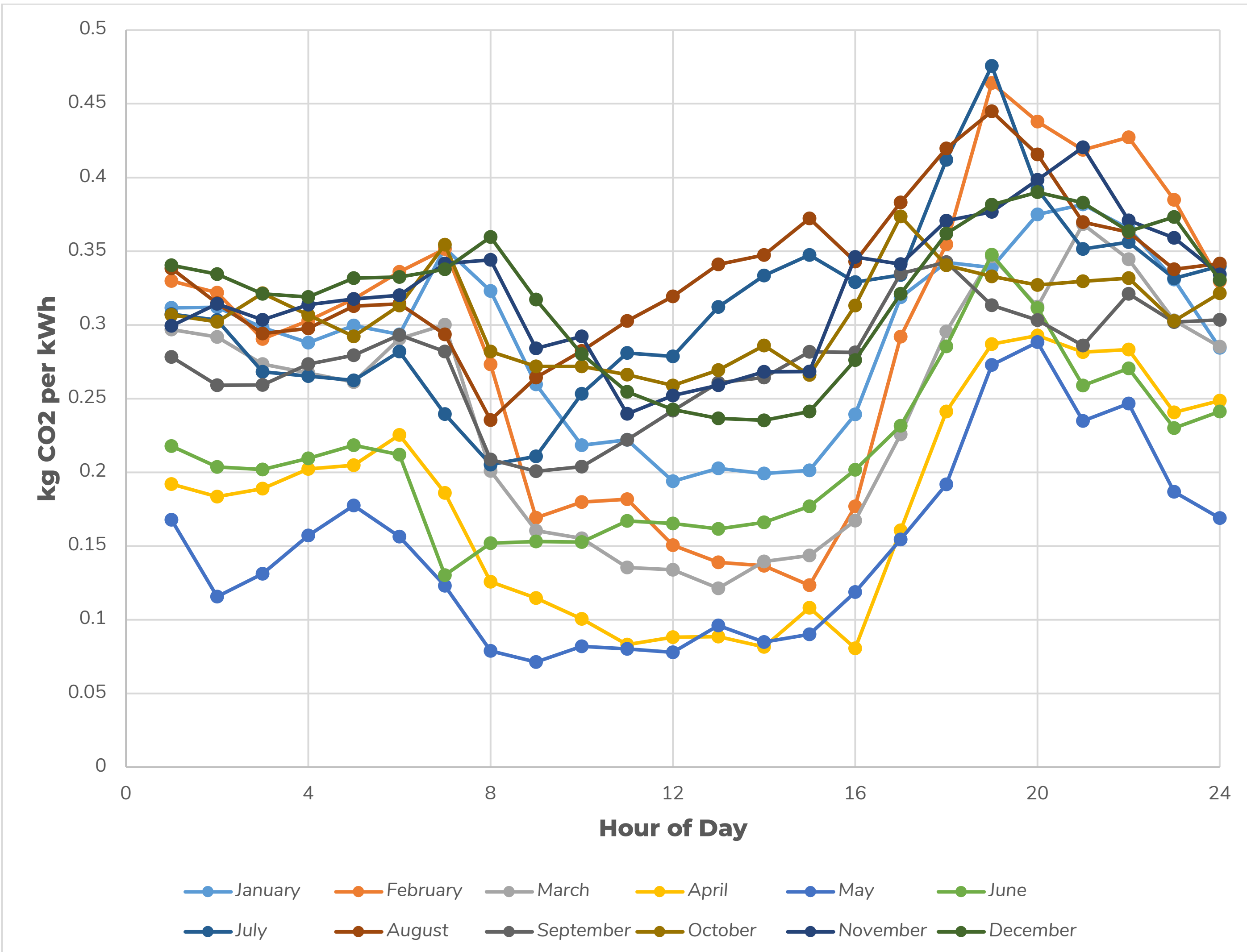


Figure 2 – Average daily marginal CO_2 emissions profile for each month of 2018 in the Sacramento area

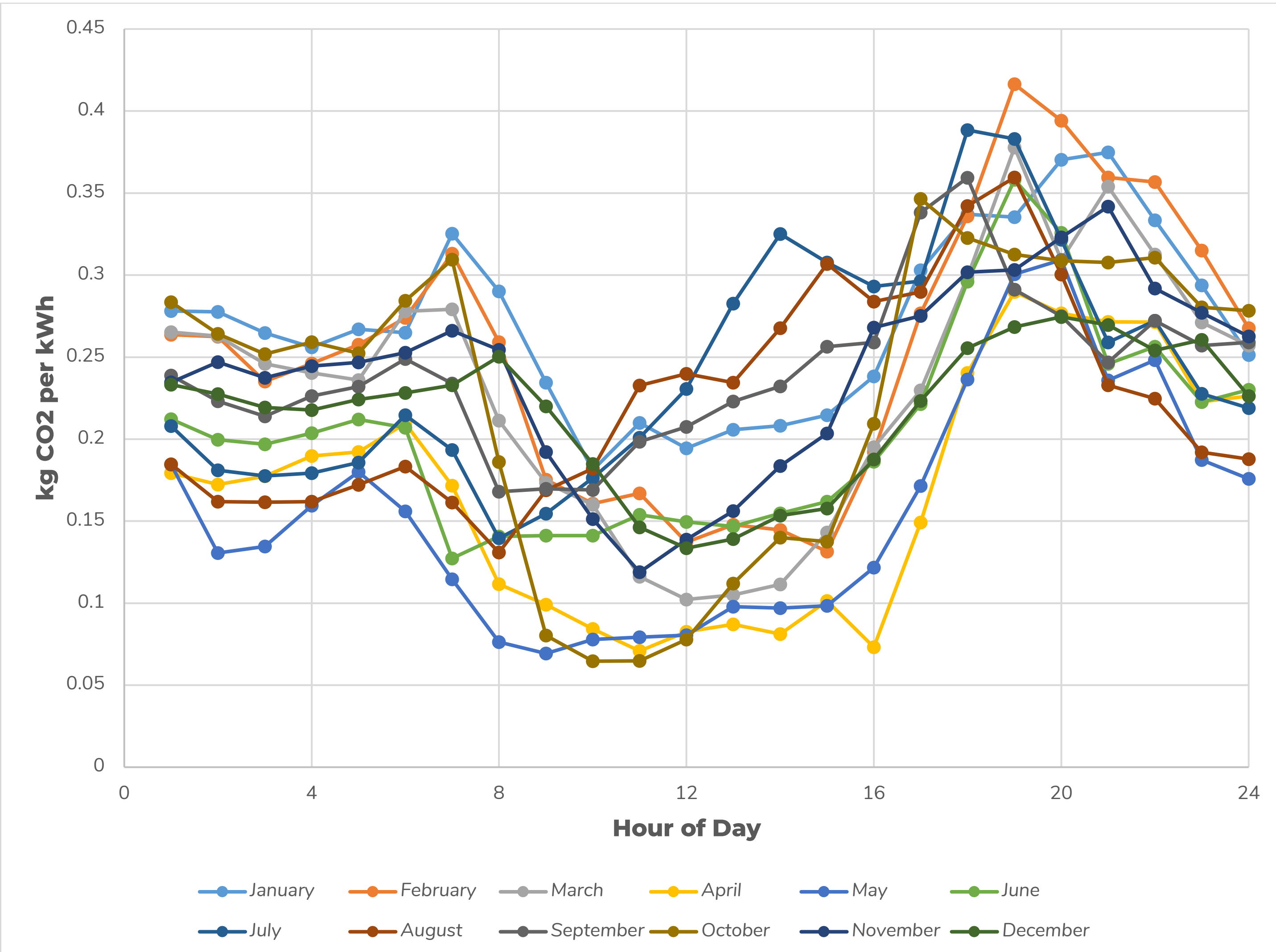


Figure 1 - Average daily marginal CO_2 emissions profile for each month of 2018 in the Riverside area

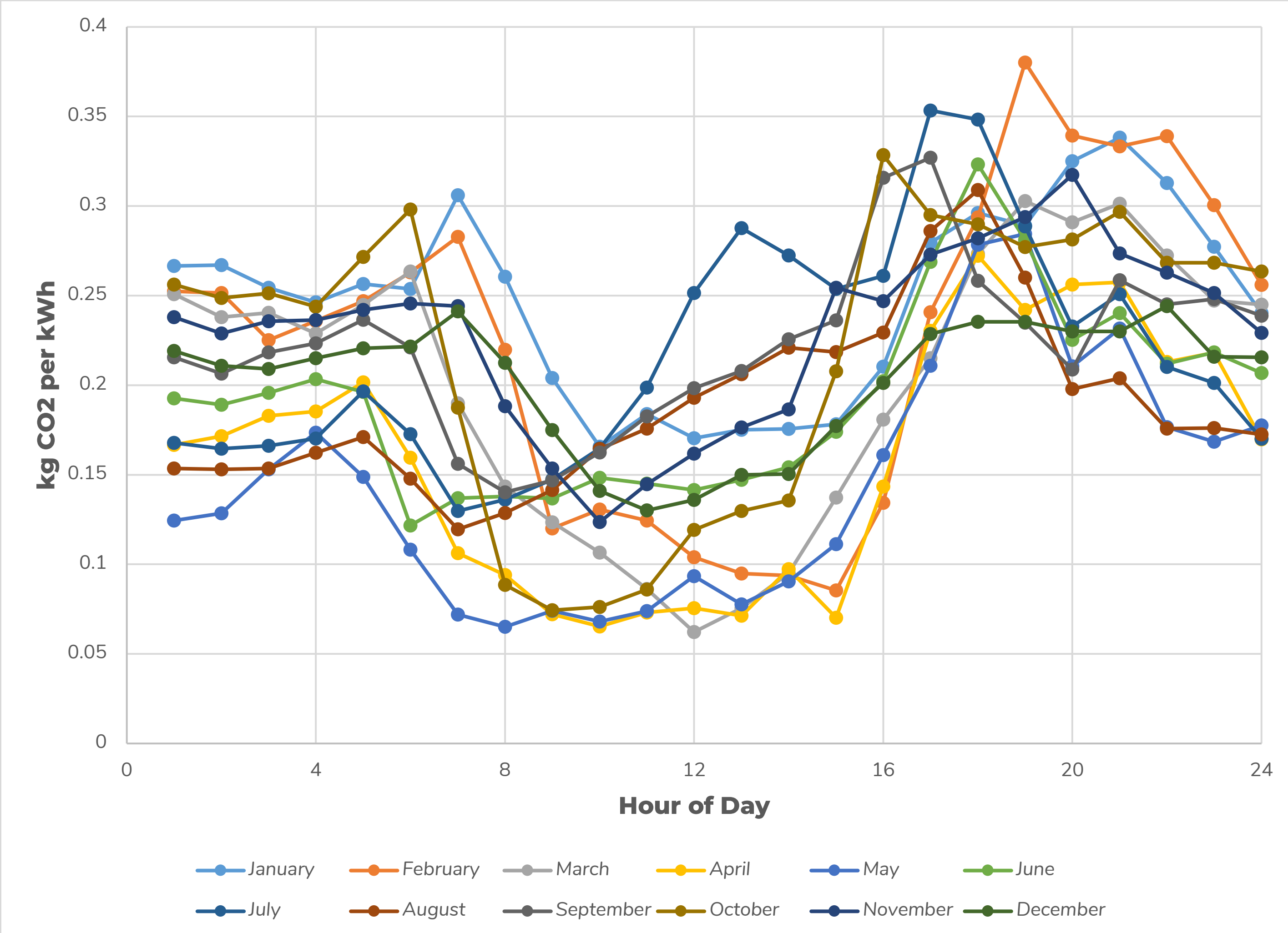


Figure 4 – Average daily marginal CO_2 emissions profile for each month of 2018 in the Burbank area

Although there is significant variation from month to month, every profile has a peak between 17:00 and 21:00 and a low period for some hours between 7:00 and 16:00. The night hours, between 24:00 and 6:00, have steady mid-level marginal emissions rates for the month. When the months of the year are grouped into the colder months, October through May, and the hotter months, June through September, clearer trends can be seen in the average daily CO_2 emissions profile. The average daily marginal CO_2 emissions profile, weighted by the monthly energy consumption (kWh) of the cooling system, for winter and summer of 2018 are shown in Figure 5, Figure 6 and Figure 7 for the Sacramento, Riverside and Burbank areas respectively.

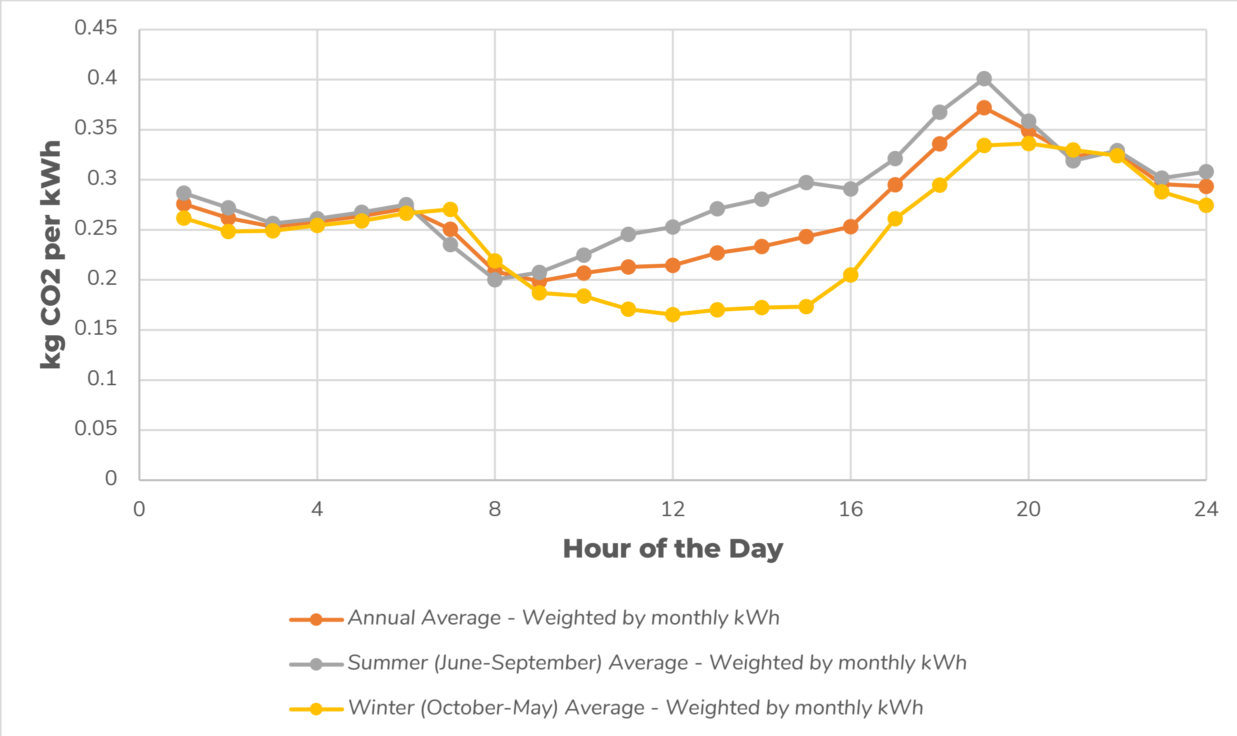


Figure 5 - Average daily marginal CO_2 emissions profile, weighted by the monthly energy consumption (kWh) of the cooling system, for winter and summer of 2018 in the Sacramento area

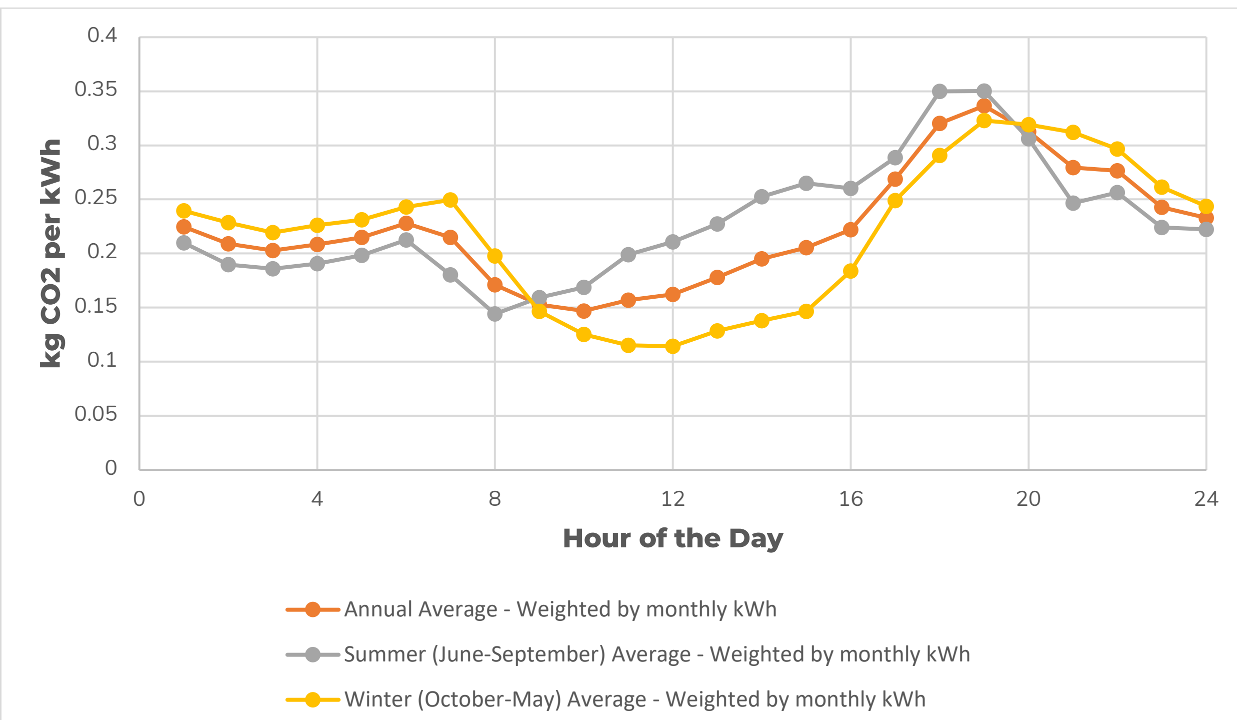


Figure 6 - average daily marginal CO_2 emissions profile, weighted by the monthly energy consumption (kWh) of the cooling system, for winter and summer of 2018 in the Riverside area

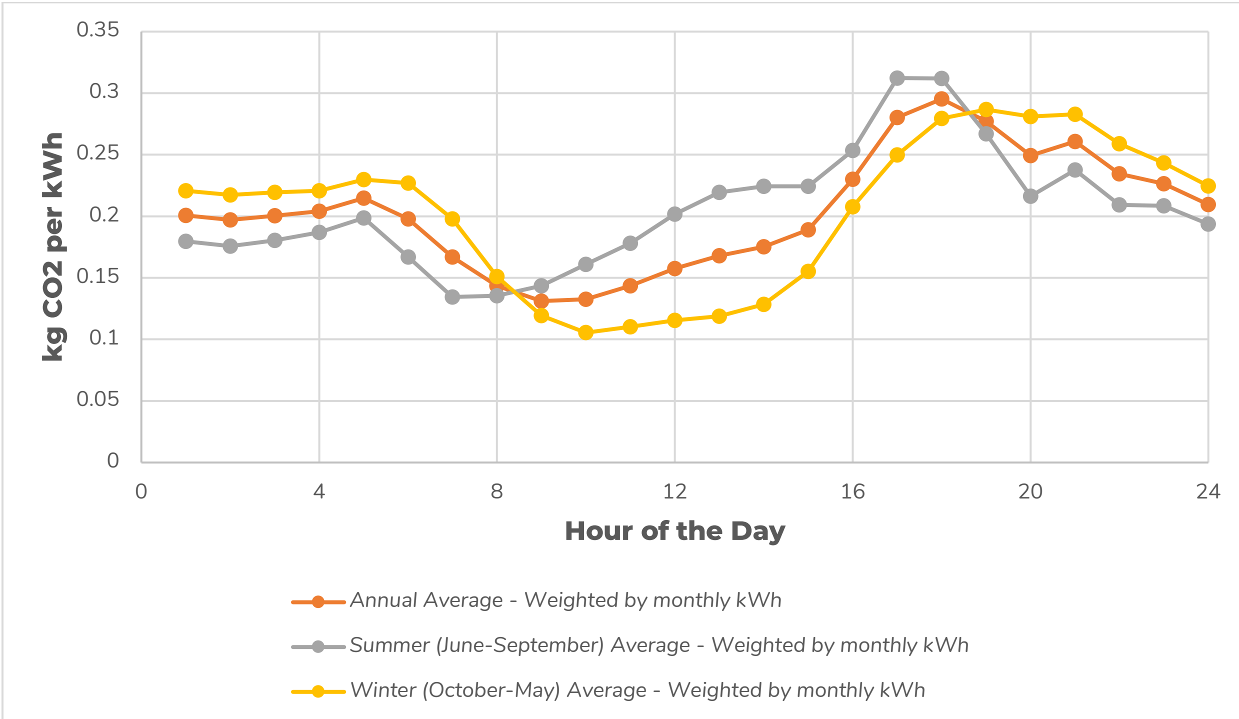


Figure 7 - average daily marginal CO_2 emissions profile, weighted by the monthly energy consumption (kWh) of the cooling system, for winter and summer of 2018 in the Burbank area

Figure 5, Figure 6 and Figure 7 show consistent trends in the seasonal variation of the average daily marginal CO_2 emissions profile. For the summer months, there is a peak between 17:00 and 19:00 followed by a sharp decline. After the decline following the evening peak, the daily emissions profile has a small bump between 21:00 and 22:00 before leveling out for a consistent mid-level overnight. There is a morning peak at 6:00 followed by a sharp decline until the daily minimum around 8:00. After the minimum, the daily emissions profile gradually rises throughout the morning and afternoon until about 16:00 when it abruptly rises back into the evening peak.

For the winter months, the peak occurs around 19:00 and is sustained for several hours, gradually falling off throughout the evening. The daily emissions profile levels out around 24:00 and gradually rises to a morning peak between 6:00 and 7:00. The morning peak is followed by sharp decline into a relatively flat, low period between 9:00 and 15:00 after which the profile rises steadily back into the evening peak.

For all locations, the winter peak is smaller than the summer peak. During the day, between 9:00 and 15:00, the winter daily average marginal emissions profile remains below the annual average for that period while the summer profile remains above the annual average. For the Riverside and Burbank areas, the winter profile is above the annual average from evening to morning and the summer profile is conversely below average during that time. For the Sacramento area, the winter and summer profiles are very close to the annual average from evening to morning.

RESEARCH METHODOLOGY

Annual whole-building energy simulations were used to model the electric grid impact of TES systems. TRACE 700 Load Design software was used to simulate an office building in three California climate zones and produce hourly electric loads for the HVAC equipment. TRACE 700 v6.3.4 has completed the BESTEST validation for calculation and comparison with similar analysis programs and is compliant with ANSI/ASHRAE Standard 140–2011 (Bohnert, 2018).

The simulated building is for a four-story rectangular office building that is compliant with 2004 Title 24 codes and standards. The modeled building has 120,000 ft2 of conditioned floor space and the window to wall ratio is 40% on all exterior walls.

A building like the simulated building would likely be cooled by a 2004 Title 24 compliant helical rotary (screw) air-cooled chiller, however this kind of chiller would not perform well when paired with an ice TES system due to the extra lift necessary when making ice. In order to achieve an apples-to-apples comparison between the performance of the building cooling system with and without a TES system, a higher efficiency chiller that would perform well with an ice based TES system was modeled in both scenarios. The simulated chiller had a COP of 3.3 at rated conditions. Under ice-making conditions, the chiller had a COP of 2.5 and its cooling capacity was diminished by 30%.

Each building was simulated using historical weather data for the 2018 calendar year for Burbank, CA (California Climate Zone 9), Riverside, CA (CZ 10) and Sacramento, CA (CZ 12). The geographic region covered by each climate zone is shown in Figure 8. Historical weather data was used instead of typical meteorological year (TMY) weather data because the weather data needed to be paired with data for marginal emissions rates from the electric grid serving the region and such data that corresponds with TMY weather data is not readily available. The annual maximum dry-bulb temperatures and coincident wet-bulb temperatures for each climate zone from the 2018 historical data, as well as from three vintages of TMY data and ten-year maximum dry-bulb temperature and coincident wet-bulb temperature from the ASHRAE Fundamentals Handbook (ASHRAE, 2017), are shown in Table 2.

		2018	TMY3	CZRV2 (Pre-2010)	CZ2010	ASHRAE 10-Year
Burbank	Dry-Bulb [°F]	113	100.4	102.0	106.9	109.0
	Wet-Bulb [°F]	67.1	76.1	77.2	78.6	79.7
Riverside	Dry-Bulb [°F]	116.78	110.1	103.7	109.4	111.0
	Wet-Bulb [°F]	70.34	70.8	72.7	74.0	77.0
Sacramento	Dry-Bulb [°F]	103.82	107.6	103.1	107.8	109.8
	Wet-Bulb [°F]	72.68	76.1	74.6	75.5	78.8

Table 2 – Annual maximum dry-bulb temperatures and coincident wet-bulb temperatures from different sources

The annual maximum dry-bulb temperature in Sacramento in 2018 was consistent with CZ2010 (the most recent TMY weather data). In 2018, the annual maximum dry-bulb temperature was higher than even the ASHRAE 10-year maximum in both Burbank and Riverside. This indicates that either 1) 2018 was a particularly hot year in those regions, 2) the climates in those regions have gotten warmer since the TMY and ASHRAE predictions were made or 3) some combination of both 1) and 2).

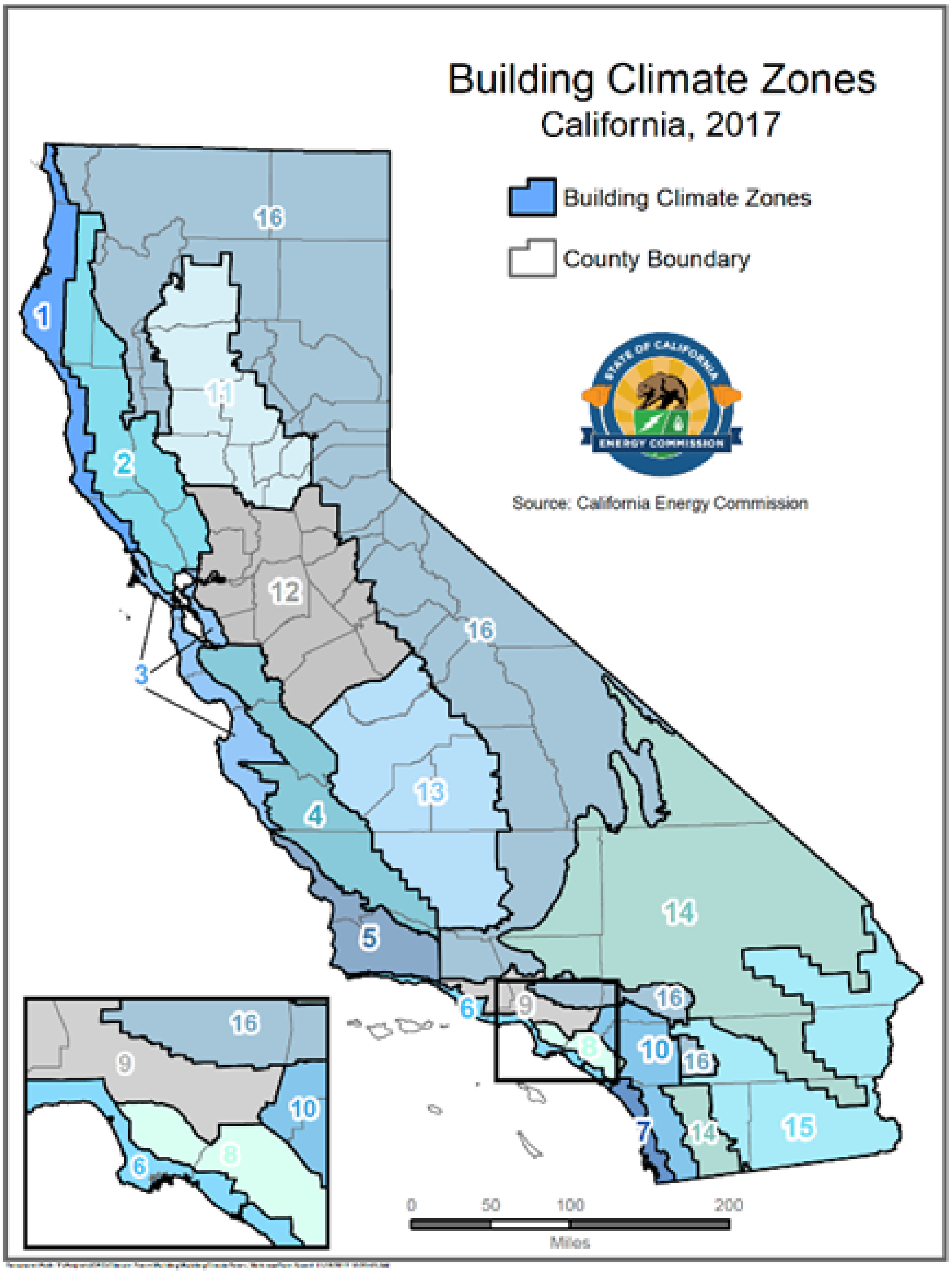


Figure 8 – California Climate Zones

THERMAL ENERGY STORAGE

In each simulation, the TES system was configured to discharge between 16:00 and 21:00. This strategy aligns the discharge cycle with the peak in both electric demand and the marginal CO_2 emissions rate. The ice TES system was simulated with three different charging strategies.

> **Night charging:** The first strategy charges the TES system between 24:00 and 4:00. This strategy aligns the charging cycle with the utility off-peak hours and the lowest building electric demand. The night charging strategy reduces cost by charging during off-peak hours, when the electricity is cheapest based on time of use utility rate structures, and ensures that charging the TES system does not incur increased demand charges by charging when the building electric demand is lowest.
>
> **Morning charging:** The second strategy charges the TES system between 5:00 and 9:00 in the summer months (June through September) and between 9:00 and 13:00 in the winter months (October through May). This strategy aligns the charging cycle with the hours of the day when the marginal CO_2 emissions rates are lowest as observed in Figure 5, Figure 6 and Figure 7. This strategy minimizes CO_2 emissions.
>
> **Smart Morning Charging:** The third charging strategy is the same as the morning charging strategy except that it only operates the TES system on days when charging and discharging the TES system would result in a net reduction in CO_2 emissions.

The capacity of the ice TES system was sized such that it could meet the entire cooling demand of the building during its discharge cycle every day of the year.

RESULTS

When compared to chilling water to supply water coils for on-demand cooling of the building, an efficiency penalty is imposed on the chiller during the TES charge cycle due to the extra lift necessary to make ice. However, the chiller gets an efficiency boost by charging at night or in the morning when the ambient temperatures are lower than daytime temperatures. As a result, depending on the daytime and nighttime ambient temperatures, more specifically the magnitude of the swing between the two, a TES system can result in an increase or a decrease in total system energy use. The percent difference in electricity consumption of the cooling system with and without a TES system is shown in Figure 9, Figure 11 and Figure 13 for the Sacramento, Burbank and Riverside areas respectively.

The marginal emissions rates for the relevant utility territory was applied to the electric demand of the cooling system for the four-story office building in each simulated location to determine the indirect CO_2 emissions of the cooling system with and without TES. The percent reduction in indirect CO_2 emissions for each month of the year as well as the annual average is shown in Figure 10, Figure 12 and Figure 14.

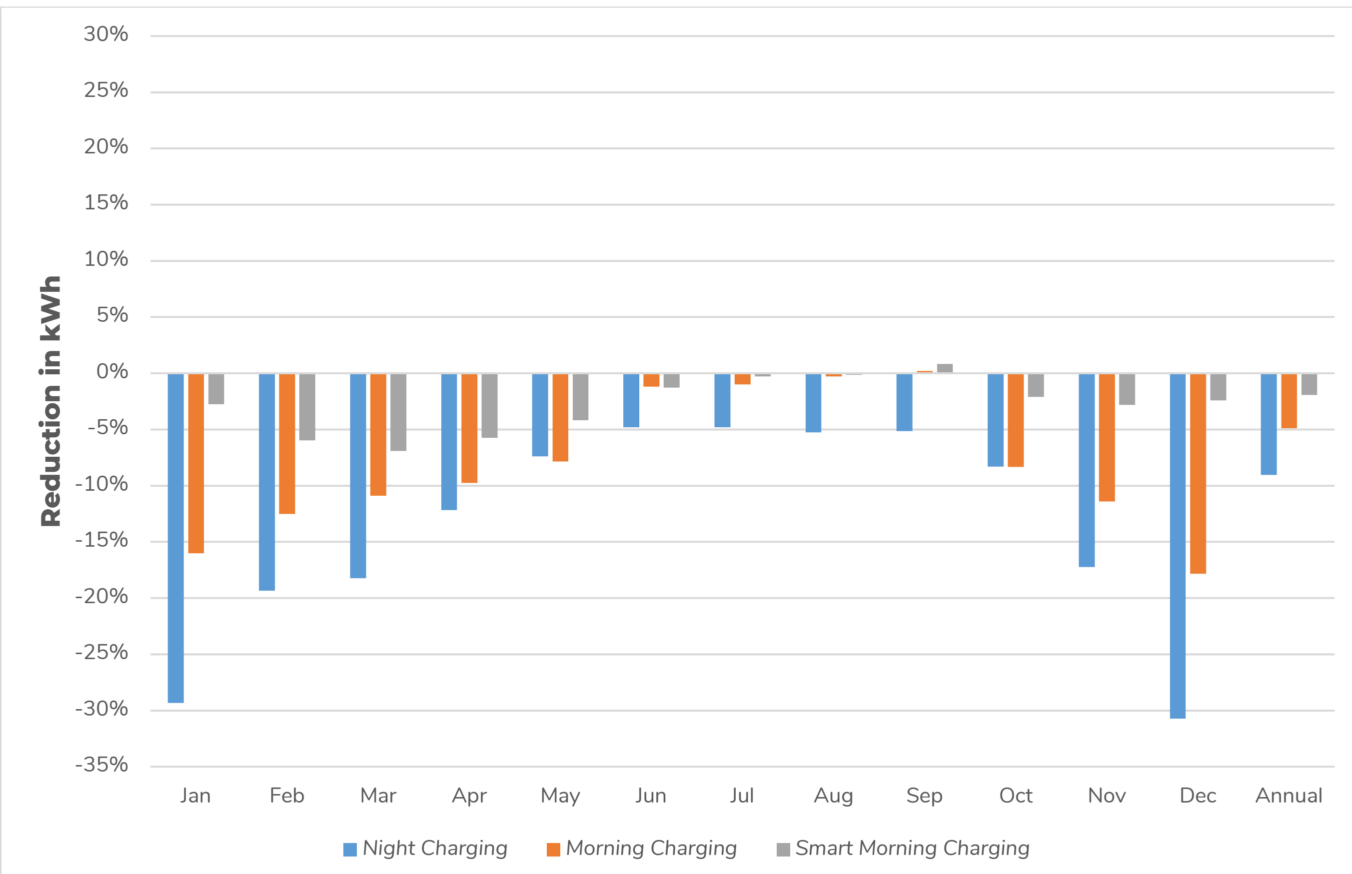


Figure 9 - Percent reduction in electricity consumed by the cooling system in a four-story office building in Sacramento achieved with TES using different charging strategies (note that a negative reduction in kWh indicates an increase in kWh)

In the Sacramento area, the cooling system with TES used more energy than the on-demand cooling system regardless of the charging strategy used. In this climate the daily diurnal is not strong enough to provide a sufficient efficiency boost when charging at night or in the morning to overcome the additional energy necessary to make ice. The daily minimum temperature usually occurs during the morning, as a result, the morning charge cycle consumes less electricity than the night charge cycle.

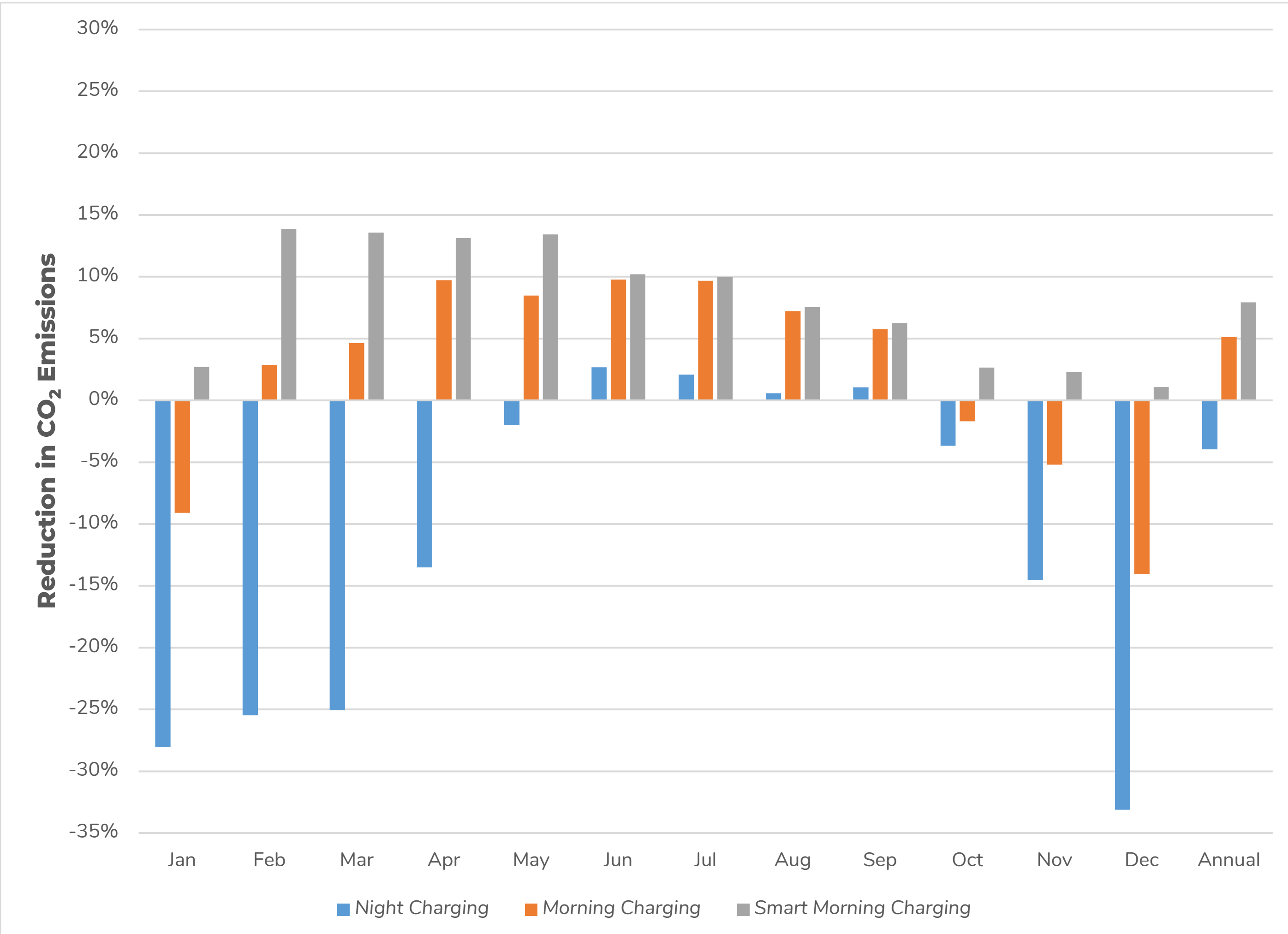


Figure 10 – Percent reduction in indirect CO_2 emissions from the cooling system in a four-story office building in Sacramento achieved with TES using different charging strategies (note that a negative reduction in CO_2 emissions indicates an increase in CO_2 emissions)

The marginal emissions rate is lower at night and in the morning than it is during the discharge cycle in the afternoon. It is therefore possible to use more energy charging the TES system than the baseline system would use for on-demand cooling and still reduce the net indirect CO_2 emissions. For the morning charging strategy and the smart morning charging strategy, the difference in marginal emissions rates between charge and discharge hours result in a net annual decrease in indirect CO_2 emissions of 5% and 8%, respectively. Although the marginal emissions rates during the night charge cycles are also lower than they are during the discharge cycle, the difference is smaller. The smaller difference in marginal emissions rates combined with the increased energy consumption resulted in a net annual increase in indirect CO_2 emissions of 4% when the night charging strategy was used in Sacramento.

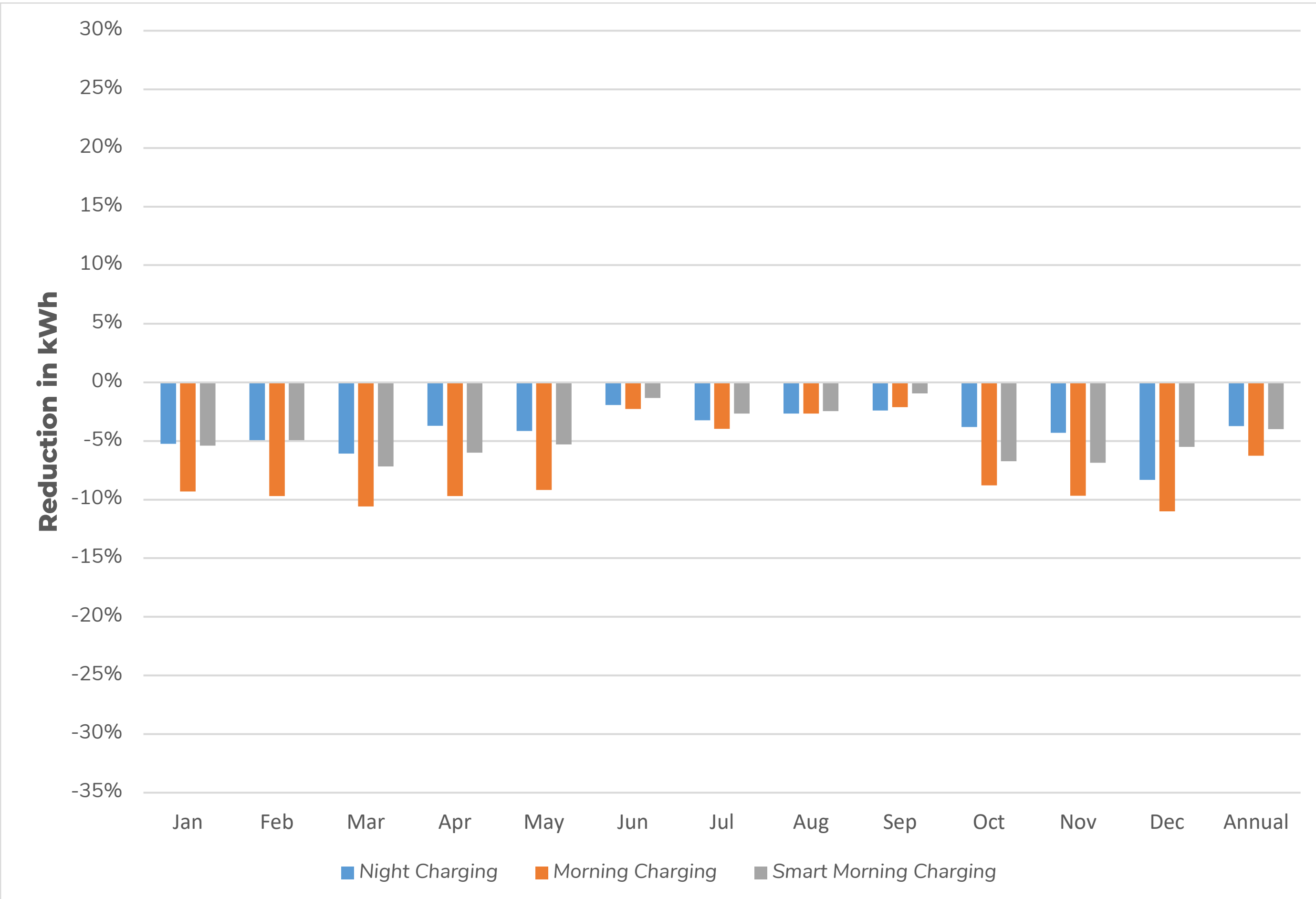


Figure 11 - Percent reduction in electricity consumed by the cooling system in a four-story office building in Riverside achieved with TES using different charging strategies (note that a negative reduction in kWh indicates an increase in kWh)

In the Riverside area the daily minimum temperatures often occurred during the night charge cycle resulting in less energy consumption using the night charging cycle than the morning charging cycle. Although the smart morning charging strategy consumed less energy than the morning charging cycle, it still consumed more energy annually than the night charge cycle. The cooling system with a TES system consumed more energy than the on-demand cooling system by 4% using night charging, 6% using morning charging and 4% using smart morning charging.

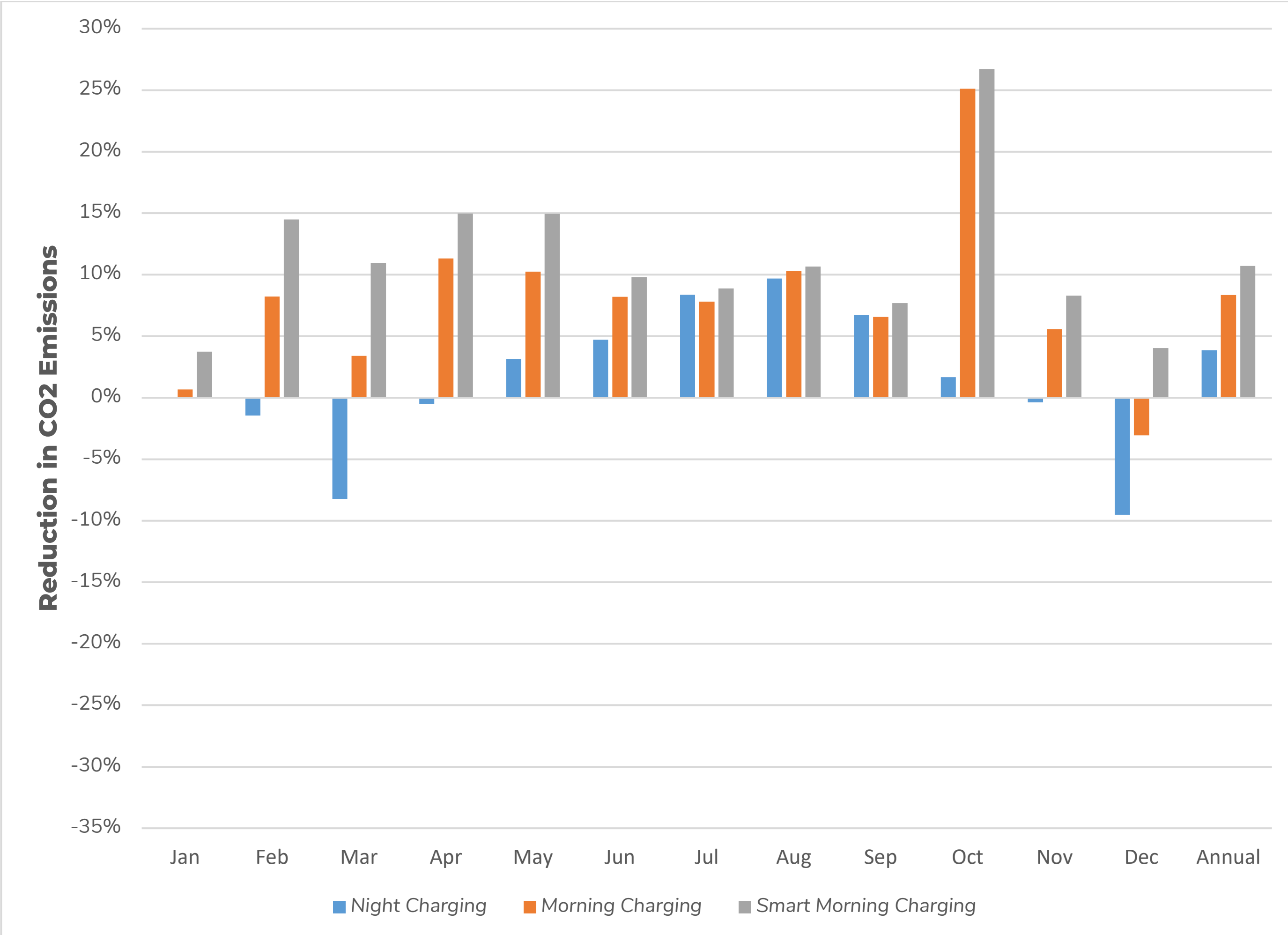


Figure 12 – Percent reduction in indirect CO_2 emissions from the cooling system in a four-story office building in Riverside achieved with TES using different charging strategies (note that a negative reduction in CO_2 emissions indicates an increase in CO_2 emissions)

In the Riverside area, the cooling system with a TES system achieved a net annual decrease in indirect CO_2 emissions of 4% using night charging, 8% using morning charging and 11% using smart morning charging compared to the on-demand cooling system.

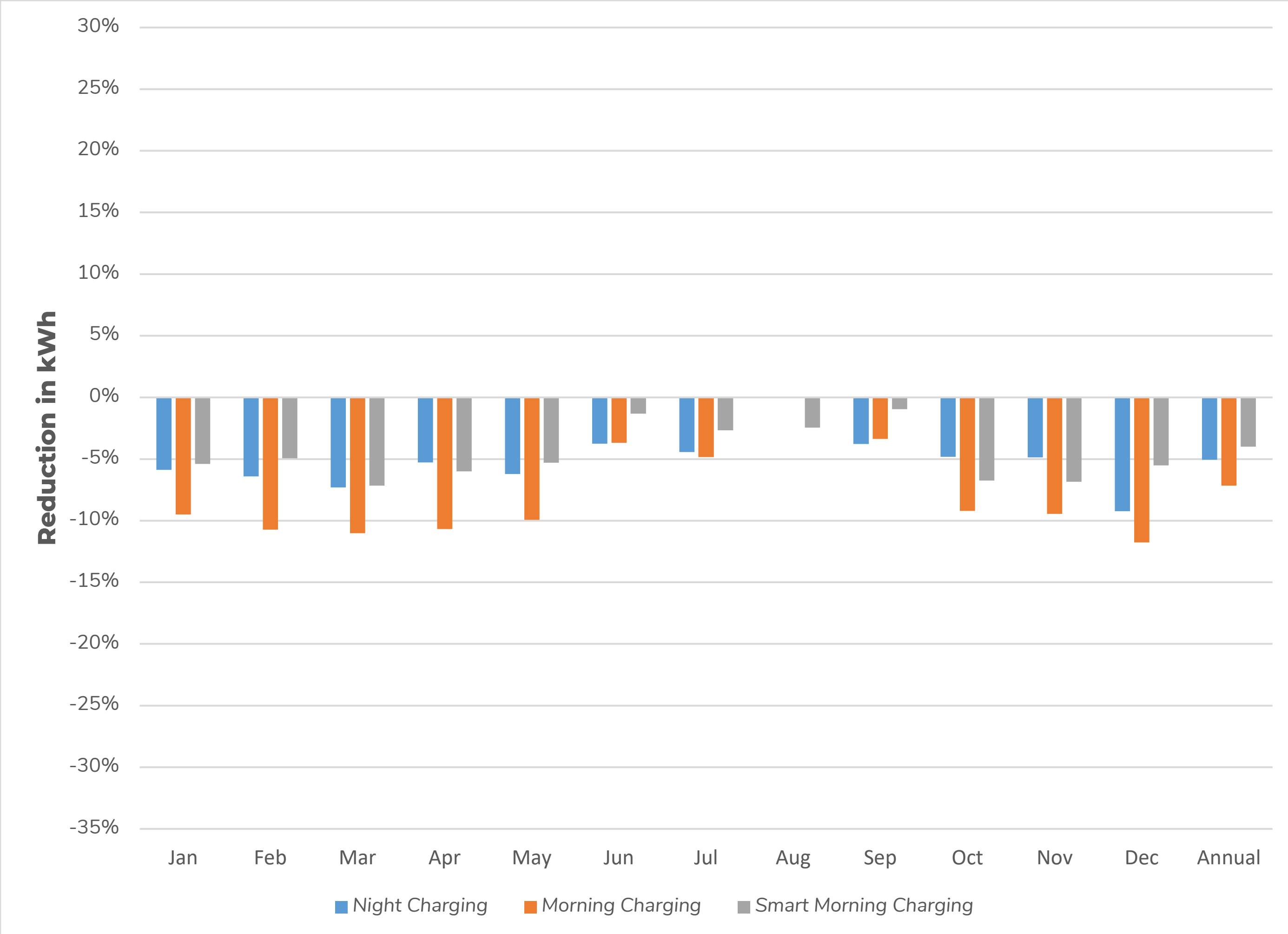


Figure 13 - Percent reduction in indirect electricity consumed by the cooling system in a four-story office building in Burbank achieved with TES using different charging strategies (note that a negative reduction in kWh indicates an increase in kWh)

The cooling system with a TES system performed similarly in the Burbank area as it did in the Riverside area. Like Riverside, the night charging strategy consumed less energy than the morning charging strategy. However, in the Burbank area, the smart morning charging strategy consumed less energy annually than the night charging strategy. The cooling system with a TES system consumed more energy than the on-demand cooling system by 5% using night charging, 7% using morning charging and 4% using smart morning charging.

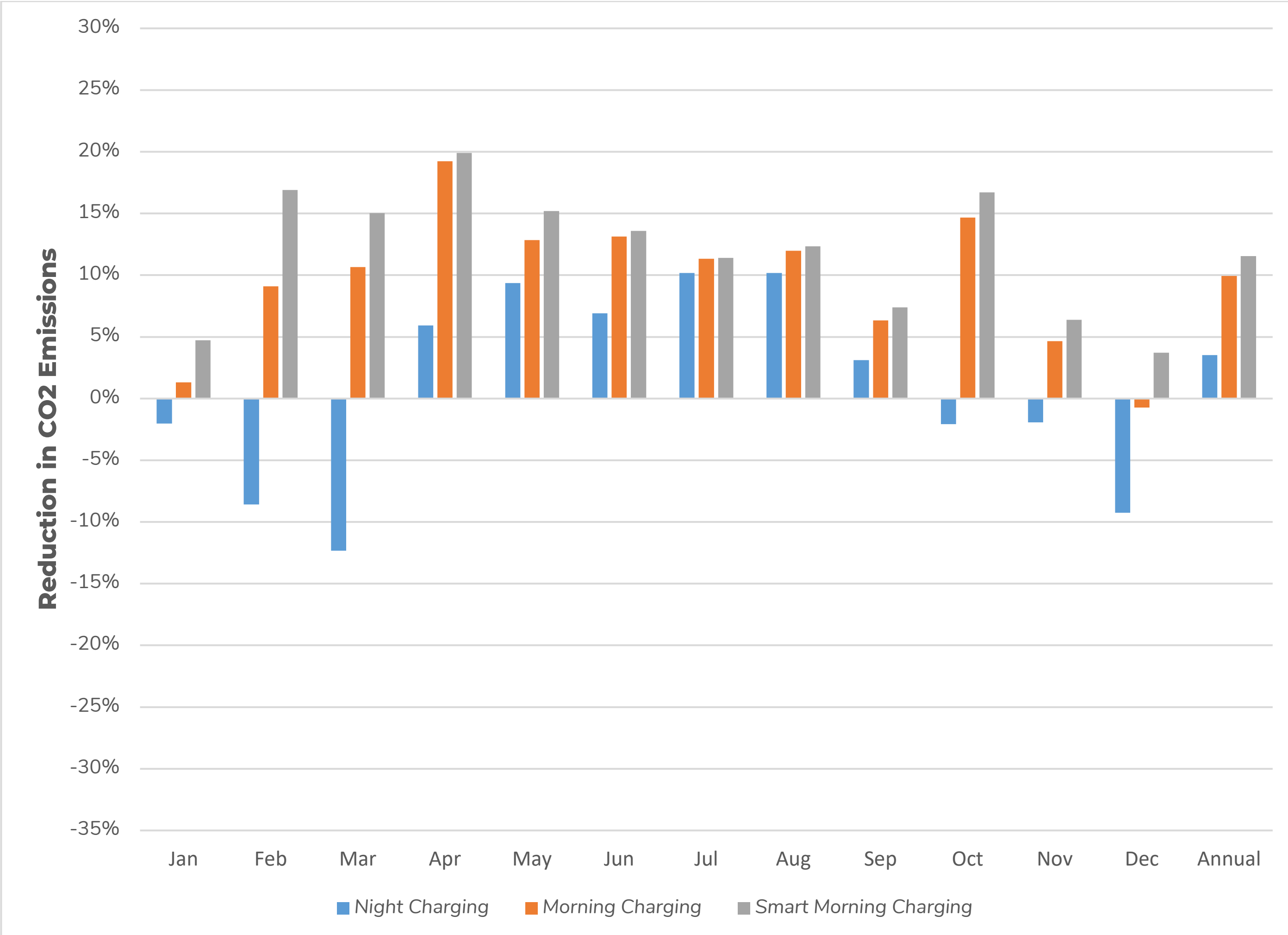


Figure 2 – Percent reduction in indirect CO_2 emissions from the cooling system in a four-story office building in Burbank achieved with TES using different charging strategies note that a negative reduction in CO_2 emissions indicates an increase in CO_2 emissions)

In the Burbank area, the cooling system with a TES system achieved a net annual decrease in indirect CO_2 emissions of 4% using night charging, 10% using morning charging and 12% using smart morning charging compared to the on-demand cooling system.

An important metric used to evaluate the effectiveness of a load shifting technology is the ratio of the annual reduction in CO_2 emissions to the curtailment capacity. Figure 15 shows this ratio calculated from the simulation results for each simulated location and charging strategy.

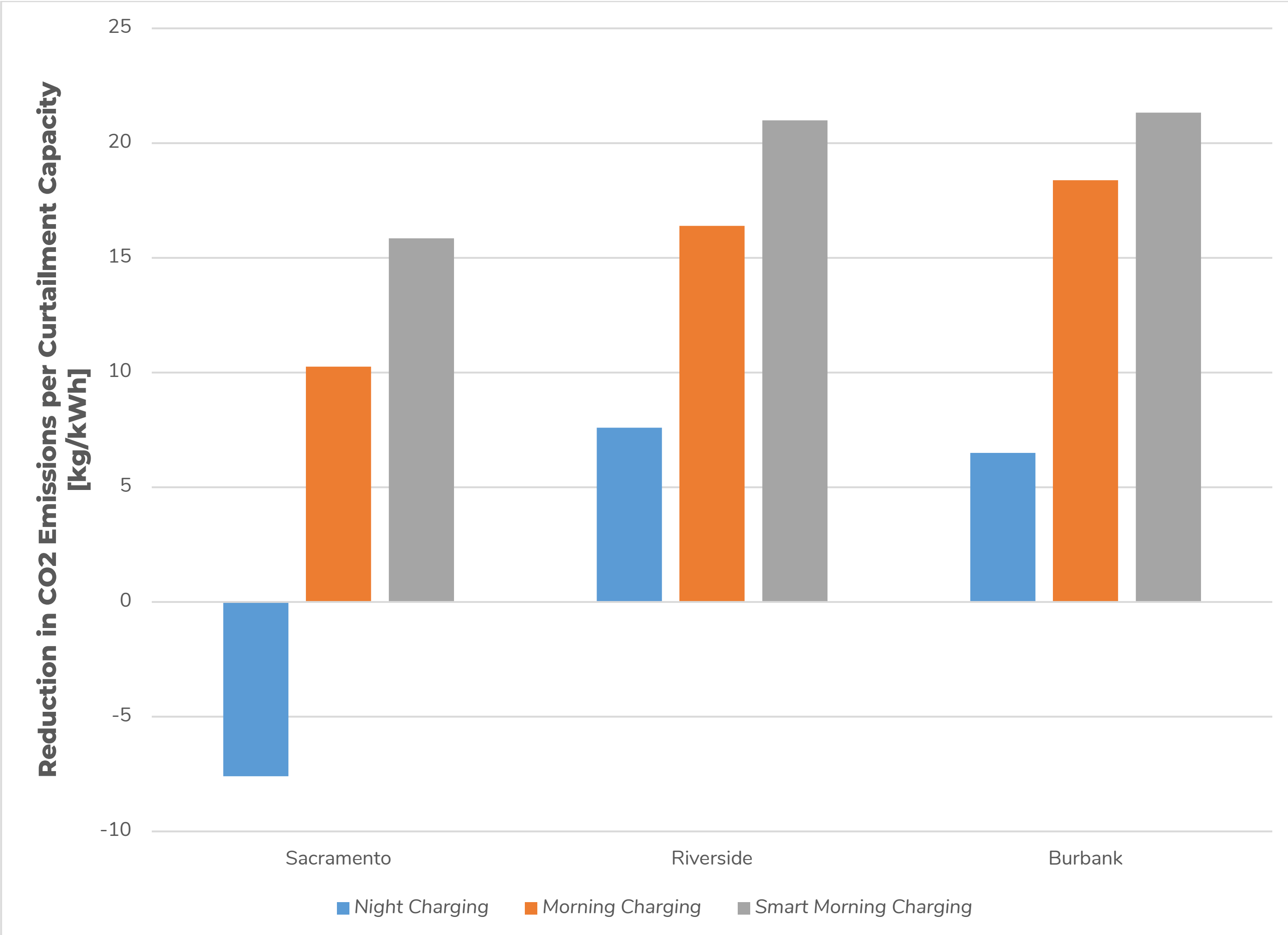


Figure 15 – The ratio of the reduction in CO_2 emissions to the electric curtailment capacity of the TES system using different charging strategies note that a negative reduction in CO2 emissions indicates an increase in CO2 emissions)

Both the morning charging strategy and the smart morning charging strategy showed strong performance in all three locations based on this metric. The night charging strategy was not able to reduce indirect CO_2 emissions in Sacramento but achieved good performance in both Riverside and Burbank.

CONCLUSION

Thermal energy storage systems have the potential to reduce indirect CO_2 emissions from the cooling systems in buildings. As a load shifting technology, TES systems are competitive with, and in many ways outperform, electrochemical energy storage (battery) systems. Development of a TES control strategy for a particular application is complex and must consider the time of use (TOU) utility rate structure, the building energy use profile (to avoid increasing demand charges), the ambient temperature and the marginal emissions rates of the local electricity grid. These factors are not constant, each with its own daily profile, and their impacts on system performance often are not aligned. Although utilities and policymakers have no control over ambient temperature, they can control the TOU rate structure and to some degree, the shape of the marginal emissions profile. To help maximize the environmental and economic benefit that TES systems can provide, energy policy and utility programs could bring the TOU rate structure and marginal emissions rate into alignment with the ambient temperature profile. Additionally, forgiving or de-valuing demand (when calculating demand charges) when marginal emissions are at their daily minimum could help remove economic barriers that are hindering adoption of TES systems.

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