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Thermal Energy Storage for Electricity Peak-demand Mitigation: A Solution in Developing and Developed World Alike

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Abstract

In much of the developed world, air-conditioning in buildings is the dominant driver of summer peak electricity demand. In the developing world a steadily increasing utilization of air-conditioning places additional strain on already-congested grids. This common thread represents a large and growing threat to the reliable delivery of electricity around the world, requiring capital-intensive expansion of capacity and draining available investment resources. Thermal energy storage (TES), in the form of ice or chilled water, may be one of the few technologies currently capable of mitigating this problem cost effectively and at scale. The installation of TES capacity allows a building to meet its on-peak air conditioning load without interruption using electricity purchased off-peak and operating with improved thermodynamic efficiency. In this way, TES has the potential to fundamentally alter consumption dynamics and reduce impacts of air conditioning. This investigation presents a simulation study of a large office building in four distinct geographical contexts: Miami, Lisbon, Shanghai, and Mumbai. The optimization tool DER-CAM (Distributed Energy Resources Customer Adoption Model) is applied to optimally size TES systems for each location. Summer load profiles are investigated to assess the effectiveness and consistency in reducing peak electricity demand. Additionally, annual energy requirements are used to determine system cost feasibility, payback periods and customer savings under local utility tariffs.

Introduction

The growing threat of cooling demand

In much of the world, energy consumption in buildings is rising quickly, representing over 30% of the total source energy consumption [IEA, 2011]. In developed economies, a substantial components of this consumption is air-conditioning, which dominates summer peak electricity consumption. Cooling loads represent a unique threat to electricity reliability, given that they are met almost exclusively with electricity and cooling peaks within buildings tend to coincide with peak conditions on the grid. This threat also creates an opportunity for alternative cooling technologies to reduce cost and mitigate peak conditions. In the developing world, economic growth creates demand for new building construction along with the energy to cool it. This is particularly true in countries such as China, India and Brazil [WBCSD 2008], where steadily increasing utilization of air-conditioning places additional strains on already-congested under development grids.

As of 2009, in the 50 largest metropolitan areas of the world, 76% of the potential cooling energy demand comes from developing countries [Sivak 2009]. Given the largely immature market for cooling in these countries, cooling represents a significant source of future energy demand growth [IEA, 2011]. As per capita incomes in these developing countries increase, so too will the frequency of air conditioning [WBCSD 2008]. Although a mature market in most developed economies, air conditioning in buildings is still growing in most developing nations. In 2011, 55% of new air-conditioning units were sold in the Asia Pacific region. In both India and China, air-conditioning sales are growing 20% every year [Rosenthal and Lehren, 2012]. Between now and 2030, over half of new building construction is expected to take place in China and India. In that time, commercial energy consumptions in these countries is expected to double [WBCSD 2008]. This trend could potentially create serious summer shortfalls in both India and China without commensurate investment in generation and distribution capacity.

Alleviating the peak conditions created by cooling demand requires capital-intensive expansion of generation, transmission and distribution infrastructure that may only be utilized during the brief annual peaks. This inefficient allocation of resources draws capital away from alternative uses, which may be used to reduce costs, improve reliability or decarbonize the existing electricity grid.

Thus, there is clearly a need to explore alternatives to technologies for meeting cooling demand applicable to both developed and developing countries. Thermal energy storage (TES) for cooling is a simple technology, but one that may be well positioned to address these issues in both contexts. TES has been used effectively to compliment thermal energy systems in a wide number of industrial and commercial applications [Dincer, Saito, 2002]. There exist a number of different TES technologies, including chilled water, ice and other phase change material. This investigation considers chilled water systems exclusively. By charging off-peak and discharging on-peak, TES allows for the dynamic time shifting between cooling load supply and demand. The myriad benefits, both to customer and utility, of this time-shifting is the focus of this investigation

The investigation presented in this paper consists of a simulation study of a large office building in cities of four distinct geographical contexts: Miami, Lisbon, Shanghai and Mumbai. The first two are intended to represent the developed world, while the latter two represent the developing world. The city of Shanghai is itself quite developed, however, it is representative, in terms of climate and electricity tariff, of a region where growth in demand is likely to be high.

Drivers of TES feasibility

A report by PG&E on TES strategies for commercial buildings has identified a number of feasibility criteria for the deployment of TES systems [PG&E 1997] which remain relevant today. Of these criteria, the theoretical applicability of TES depends heavily on the two listed below. Reference cities have been selected such that they exhibit one or both of these conditions.

- The maximum cooling load of the facility is significantly higher than the average load.
- The electric utility rate structure includes high demand charges

Climate

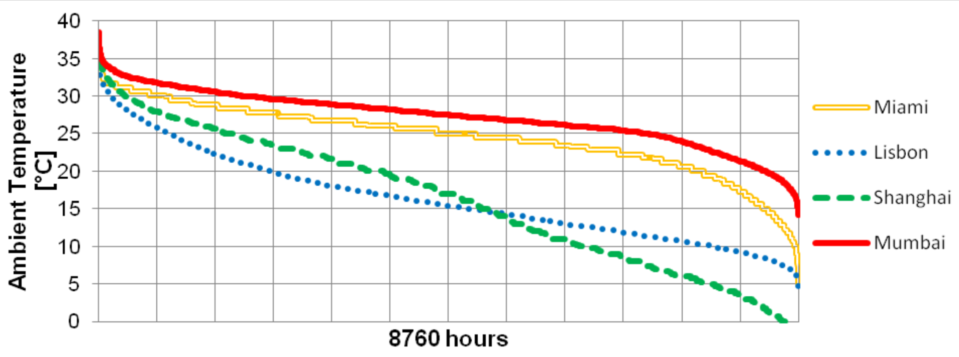

Figure 1. Temperature duration curves for reference cities.

The principle driver of cooling demand is intuitively climate, particularly summer high temperatures and humidity. Economic conditions such as income will often dictate how much of this thermal demand is actually met with air conditioning [Sailor 2003]. A large office building represents a setting where thermal demands are likely to be met. In an office building, where non-thermal loads tend to peak during the middle of the day, high daytime temperatures will drive total electricity demand significantly above average loads. The four reference cities selected each exhibit a cooling season of sufficient duration and magnitude to merit the consideration of TES. Temperature duration curves, which indicate the typical hourly average temperature in descending order, are shown in Figure 1. Table 1 provides additional metrics to describe the cooling season. Of these cities, Mumbai clearly has the most substantial cooling period, with the highest typical maximum temperature and the most cooling degree days (CDD). CDD is a simple metric which accounts annually for the duration and intensity of external temperatures. Shanghai and Lisbon exhibit the next highest maximum temperatures, however their CDD totals are lower than that of Miami, indicating that while its maximum temperature may be lower, the cooling season in Miami is more prolonged. While the metric presented here describe only temperature differences, humidity control is also taken into account for building thermal loads.

Table 1. Climate details for reference cities. Cooling degree days (CDD) reflect both the magnitude and duration of the cooling season. Values are determined from typical meteorological year (TMY3) data for each location.

	Miami	Lisbon	Shanghai	Mumbai
Tmax [°C]	35.6	36	38	38.5
CDD [°C-day]	2494	617	1063	3355

Tariff

The costs associated with meeting the cooling demand with an electric chiller will be determined by the local electricity tariff. As previous DER-CAM investigations have shown, the tariff structure and in particular the rates imposed on power demands have a strong influence on the optimal behavior and configuration of DER installations [Stadler 2009, 2010]. Tariffs with high on-peak energy rates and on-peak demand charges create opportunities for economic savings from load shifting. Figure 2 shows the tariff structure for summer periods in each reference city. Each tariff has three basic components: an energy rate which may vary by time of use (TOU), incurred for each kWh consumed, TOU power rates, which are incurred on the highest power demand in each TOU period, and non-coincident demand charge (NCDC), which is incurred on the maximum monthly power demand, regardless of period. The impact of these particular tariff structures on the optimization results will be examined in subsequence sections. Tariff data has been collected from Florida Power and Light, Energias de Portugal, State Grid Shanghai and Brihan Mumbai Electric Supply & Transport.

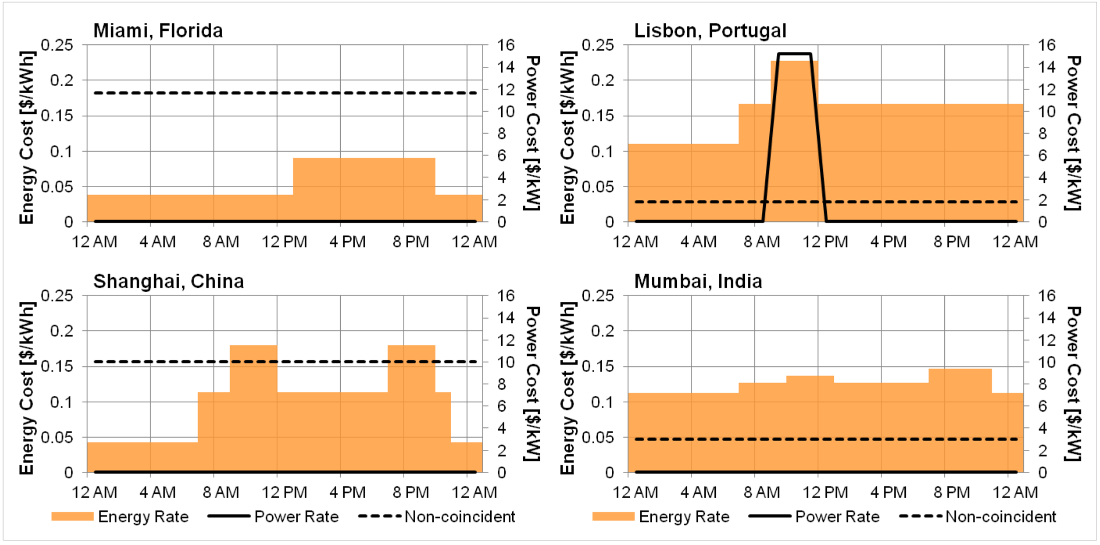

Figure 2. ***Summer weekday tariff profiles.*** *Energy rates are incurred per kWh purchased in each period. Power rates are incurred for maximum power demand within that demand period each month. Non-coincident demand charge is applied to absolute monthly maximum regardless of which demand period it occurs in. Note: axis are scaled the same among figures for comparison.*

DER-CAM Optimization

The Distributed Energy Resources Customer Adoption Model (DER-CAM) is an optimization tool built to inform decisions of distributed energy resources (DER) planning and operation. It is able to determine cost or carbon minimal solutions that satisfy end-use demands under local economic and climate conditions. DER-CAM has been developed over the past decade by researchers at Lawrence Berkeley National Laboratory and has already been applied to a number of diverse projects [Stadler et al., 2010, 2009]. The mixed integer linear program (MILP) is written in the text-based optimization language GAMS DER-CAM, however a web-based graphical user interface has been developed for DER-CAM and is freely available [Web-Opt, 2013]. DER-CAM is technology neutral, meaning it selects the optimal combination DER technologies, as defined by the user, in order to minimize its objective. In most cases, DER-CAM selects from a diverse menu of technologies, however in this investigation, DER-CAM will be used exclusively to size the TES system. It may be that this investigation misses important synergies between different DER technologies (for instance solar thermal and absorption cooling) and fails to reach a true optimum. A more detailed DER-CAM analysis would be required to determine how other DER technologies may compliment or compete with TES.

Methodology

EnergyPlus simulation

Simulations have been conducted using EnergyPlus 7.0 for a large commercial office building reference file created by the Commercial Building Initiative at U.S. Department of Energy. The 46,000 m^2 office exhibits an approximately 1.1 MW peak electrical demand for non-thermal loads. Given the diverse international scope of this investigation, the building envelope performance characteristics have been varied to encompass the various national building efficiency standards. In reviewing these building standards, it was found that the developing world cities have quite rigorous prescriptive requirements, however very little data is available on standards enforcement. Consequently, two generic building envelopes have been constructed to capture the difference in performance between developed and developing world contexts. Details are presented in Table 2. While the medium efficiency building may underestimate the performance of many standard-compliant buildings in Shanghai and Mumbai, it illustrates the influence of building shell on TES adoption trends.

Table 2. Building envelope performance levels

Building Envelope	Reference City	U-factor Walls [W/m^2-K]	U-factor Roof [W/m^2-K]	U-factor Window [W/m^2-K]	SHGC - Window [--]
High Efficiency	Miami, Lisbon	0.7	0.3	3.0	0.25
Medium Efficiency	Shanghai, Mumbai	2.0	0.6	6.0	0.50

Modeling TES in DER-CAM

Hourly end-use loads from EnergyPlus are used to generate typical load profiles for weekdays, weekends and high demand, peak days for each month. These profiles are the basis on which DER-CAM optimizes the capacity of TES at each location, taking into account local conditions, including the electricity tariff and ambient temperature. The optimization results will also depend on the cost to install TES. To determine this cost, a review of TES projects constructed in the United States over the past 15 years has been conducted. While there are many such examples, few have readily available date on both the technical details, such as capacity and the capital cost of installation. A cost curve developed from sufficiently documented projects is given in Figure 3. Investment costs have been adjusted for inflation to 2013 values. From this analysis, it is determined that TES exhibits a variable cost of $31.80 (€24.46) per kWh capacity. Note this estimate is intended to reflect TES cost as part of new building construction, and neglects other factors such as system integration and available space, which may also constrain capacity. In addition to materials, investment costs include costs for labor, which are likely to vary significantly between locations. Project data was not sufficiently detailed to make this characterization, and it was therefore neglected. Operations and maintenance costs are assumed to be low relative to investment costs and are also neglected.

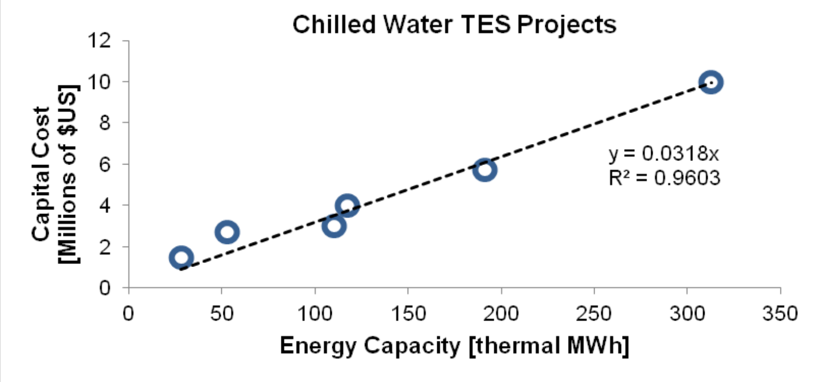

Figure 3. Cost curve of TES projects. *Cost curve is developed from public data on recent U.S. TES projects.*

Within DER-CAM, TES is modeled as a thermal battery, with charging and discharging decisions determined by the optimization. Thermal losses are assumed to be low at .1% per hour. A charging efficiency of 95% is used to approximate losses due to pumping chilled water in and out of the storage tanks. The maximum charging and discharging rates are assumed to 25% per hour, meaning full charging or discharging requires at least 4 hours.

It is also assumed that the performance of the chiller will vary in response to changing conditions, particularly ambient temperature. Thermodynamically, it becomes more difficult for the chiller to reject heat as the ambient temperature increases. Derived from the detailed EnergyPlus outputs, a 1.5% penalty is imposed on the chiller coefficient of performance (COP) for every °C. The reference COP is 2.5 at a temperature of 35°C. Consequently, the chiller tends to operate more efficiently during cooler night time hours.

Results

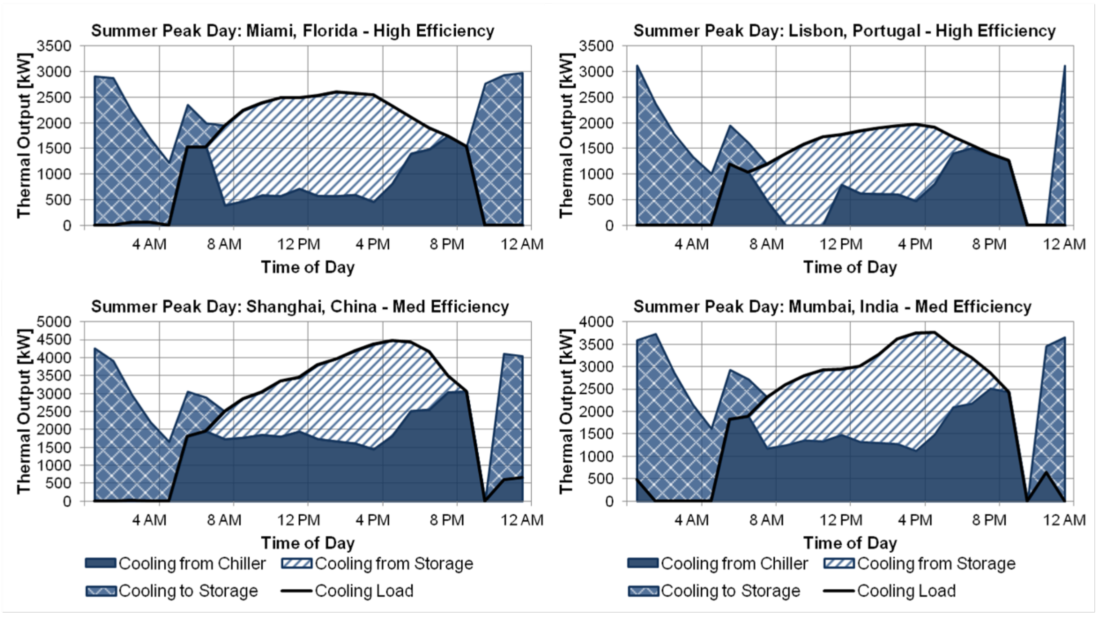

Figure 4. Summer peak cooling load profiles. *The above shows the optimal capacity of TES being dispatched to meet summer peak cooling demand.*

A summary of results for each city is presented in Table 3. In each case, DER-CAM has determined the optimal TES installation in order to minimize total cost. From the optimization results, changes to annual electricity consumption, cost and peak demand have each been determined. For each location, overall energy consumption changes only slightly, resulting in small parasitic losses from pumping and small efficiency boosts from night time chiller operation. In every location, however, the deployed TES system realizes a substantial reduction to peak electricity consumption, ranging from 30% to nearly 38%. Results for each reference cities are examined individually in the following sections. Typical summer peak day cooling profiles are given in Figure 4 to illustrate the amount of on-peak cooling demand that can be met with TES. Finally, the impact of TES on monthly electricity costs is examined in Figure 5, which designates savings to energy and power charges separately.

Table 3. Summary of results for TES deployment from DER-CAM.

Reference City	Miami	Lisbon	Shanghai	Mumbai
Installed TES Capacity (MWh)	21.9	14.9	25.5	23.5
Payback Period (years)	5.3	3.7	4.2	8.5
Total Annual Electricity Consumption				
Absolute Δ (MWh)	28.4	-23.5	21.4	-3.1
Relative Δ (%)	0.3%	-0.4%	0.3%	0.0%
Total Annual Electricity Cost				
Absolute Δ ($)	-$132,079	-$129,587	-$191,200	-$88,278
Relative Δ (%)	-18.7%	-9.5%	-17.1%	-6.5%
Peak Electricity Demand				
Absolute Δ (kW)	-797	-615	-1234	-1018
Relative Δ (%)	-37.3%	-30.1%	-37.7%	-36.3%

Miami, Florida

Relative to the other cities here, Florida has low energy rates, both on and off peak, and no TOU demand charges. The difference between on-peak and off-peak energy rates is also quite low. Each of these factors will limit the economic benefit of TES. Miami does, however, have the highest NCDC. It also exhibits the second highest CDD total. This means that the duration of Miami's cooling season is likely many months. In each of these months, the peak-shaving capabilities of TES will reduce costs incurred from the high NCDC. Consequently, the optimal TES installed capacity is 21.9 MWh. This system is able to realize an annual savings of approximately $132, 000 (€101,540), which as Figure 5 indicates for Miami come predominately from power savings. The payback period for this TES system is 5.3 years.

Lisbon, Portugal

Lisbon is the only reference city which includes a TOU power charge for on-peak consumption, which is higher than the NCDC rates in every city. Additionally, Lisbon incurs high energy rates for mid-peak and on-peak periods. Each of these factors would suggest favorable conditions for TES deployment. However, of the cities investigated, Lisbon has the least intense summer cooling period. Its on-peak period also occurs earlier in the day, before cooling loads reach their peak. Consequently, its optimal TES installation is only 14.9 MWh, which is 32% smaller than the Miami installation. Figure 5 indicates that this smaller system is adequate to reduce on-peak chiller output to zero, while also offset electricity purchases in mid-peak periods. This smaller system is able to save a comparable $130, 000 (€100,000) , as a result of the higher overall electricity prices, and requires the lowest observed payback period 0f 3.7 years.

Shanghai, China

Revisiting the temperature duration curves in Figure 1, Shanghai is clearly the only reference city that experiences a cold winter period. This means that the value of TES will be limited to a smaller portion of the year. Conversely, this means that its 1063 CDDs will originate from fewer, more intensely hot days. As a result, there will be large potential for savings during a few summer months, and diminishing savings at other times throughout the year (Figure 5). The overall cooling load in Shanghai is higher than the previous cases, as it was modeled with a less efficient building envelope. The Shanghai tariff has a moderately high NCDC and high on-peak TOU energy rates, however, they do not coincide with the cooling demand peak. More importantly, there is nearly a factor 3 difference between off-peak and mid-peak TOU energy rates, creating a significant opportunity for savings from TES load shifting. Ultimately, it is this, along with the higher cooling load that necessitates a TES installation of 25.5 MWh, the highest of the four cities with a payback period of 4.2 years. This system generates an annual savings of $191, 000 (€146,920), also the highest value of the four cites.

Mumbai, India

None of the components of the Mumbai tariff are particularly favorable to TES installation. It includes no TOU power rates, the lowest NCDC rate, and TOU energy rates that change only slightly across TOU periods. Mumbai is however consistently hot, meaning that savings from TES, even if they are modest, can be realized throughout the year (Figure 5). Mumbai is also modeled with a medium efficiency building envelope, meaning that its cooling loads will be higher than the developing world case. Even without the strong drivers from the electricity tariff, the optimal installed capacity of TES is determined to be 23.5 MWh, the second highest of the four, but under a relatively high payback period of 8.5 years. Annual savings are a mere $89,000 (€68,460), the lowest observed.

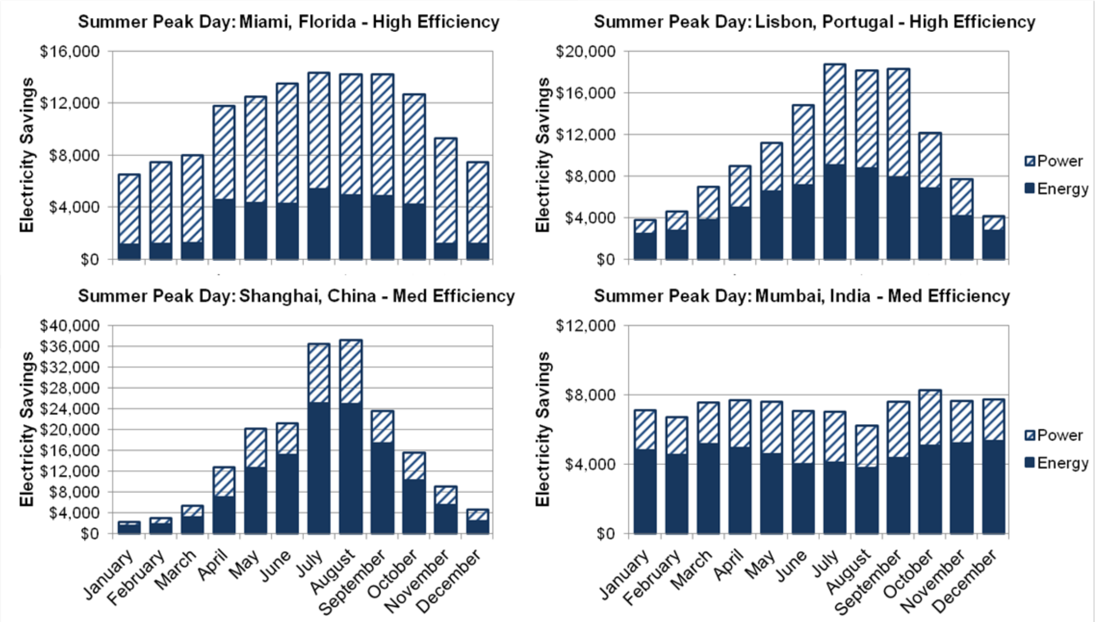

Figure 5. Monthly electricity cost savings. *Savings from monthly electricity are broken down between energy and power charges. Shape and magnitude of savings depend on local tariff structure.*

Conclusion

This investigation has demonstrated the feasibility of TES deployment in both developed and developing world contexts. The most significant drivers of feasibility were identified as high summer temperatures and a tariff comprised of high on-peak rates or a high non-coincident demand charge. These create, respectively, high on-peak electricity demand and strong economic signals to shift or reduce on-peak consumption. While TES installation can address both, these drivers do not need to exist in tandem for TES to be feasible. In the case of Lisbon, an appropriately structured tariff compensates for a relatively mild summer; whereas in Mumbai, a consistently hot climate makes up for a tariff structure that is not particularly favorable to TES deployment. Across locations, the benefits of deployment are also clear. Economically, TES has the ability to generate substantial savings to annual energy costs, ranging from 6.5%-18.7%, often exceeding $130,000 (€100,000). Corresponding payback periods for TES investment are reasonable and range from 3.7-8.5 years. Additionally, the functional link between TES and cooling demand make it uniquely positioned to reduce cooling-driven peak electricity demand. This investigation observed a peak electricity demand reduction ranging from 30% to 38%. While overall energy consumption with TES remains nearly constant, its dynamic load shifting ability make it a promising technology throughout the world. In other building contexts, where similar load profiles and thermal demands exist, energy savings for TES deployment are likely to be comparable.

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Acknowledgements

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