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Optimal Deployment of Thermal Energy Storage under Diverse Economic and

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Optimal Deployment of Thermal Energy Storage under Diverse Economic and Climate Conditions

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Keywords:

Thermal energy storage; chilled water storage; cooling; optimization;
distributed energy resources; net present value

Highlights:

- We simulated chilled water thermal energy storage (TES) under diverse conditions.
- TES systems reduced annual electricity cost by 5% to 15% across four locations.
- TES systems also reduced peak electricity demand by 13% to 30% across locations.
- Optimally sized TES systems were compared to simple, heuristically sized systems.
- Optimization is critical to TES sizing when tariff and load drivers less present.

Abstract

This paper presents an investigation of the economic benefit of thermal energy storage (TES) for cooling, across a range of economic and climate conditions. Chilled water TES systems are simulated for a large office building in four distinct locations, Miami in the U.S.; Lisbon, Portugal; Shanghai, China; and Mumbai, India. Optimal system size and operating schedules are determined using the optimization model DER-CAM, such that total cost, including electricity and amortized capital costs are minimized. The economic impacts of each optimized

TES system is then compared to systems sized using a simple heuristic method, which bases system size as fraction (50% and 100%) of total on-peak summer cooling loads.

Results indicate that TES systems of all sizes can be effective in reducing annual electricity costs (5%-15%) and peak electricity consumption (13%-33%). The investigation also identifies a number of criteria which drive TES investment, including low capital costs, electricity tariffs with high power demand charges and prolonged cooling seasons. In locations where these drivers clearly exist, the heuristically sized systems capture much of the value of optimally sized systems; between 60% and 100% in terms of net present value. However, in instances where these drivers are less pronounced, the heuristic tends to oversize systems, and optimization becomes crucial to ensure economically beneficial deployment of TES, increasing the net present value of heuristically sized systems by as much as 10 times in some instances.

1. Introduction

In much of the developed world, air-conditioning in buildings is the dominant driver of summer peak electricity demand [1]. 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 trend is likely to continue as global average temperatures increase [2]. In the developing world a steadily increasing utilization of air-conditioning places additional strain on already-congested grids [3]. By one estimate, building air conditioning currently accounts for as much as 40% Mumbai's summer electricity consumption [4]. According to a 2009 study of the 50 largest metropolitan areas, 76% of the potential cooling energy demand comes from developing countries [5]. Given the largely immature market for cooling in these countries, cooling represents a significant source of future energy demand growth [6]. As per capita incomes in these developing countries increase, so too will the frequency of air conditioning [3, 7]. Between now and 2030, over half of new building construction is expected to take place in China and India. In that time, commercial energy demand in these countries is expected to double [3], potentially requiring capital-intensive expansion of generation, transmission and distribution infrastructure that may only be utilized during brief summer 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 [2].

Thus, there is clearly a need to explore alternative technologies for meeting cooling demand while reducing peak loads, applicable to diverse conditions of both developed and developing countries. Thermal energy storage (TES) in the form of chilled water or ice storage is a simple technology, but one that may be well

positioned to address these issues in both contexts. TES has been used effectively to complement thermal energy systems in a wide number of industrial and commercial applications [8-12]. By charging TES during off-peak hours then discharging to meet on-peak loads, TES allows for the dynamic time shifting between cooling load supply and demand and provides a myriad of benefits to both customer and utility, including cost and peak load reductions and demand-side flexibility.

Many previous studies have demonstrated the economic and efficiency benefits of TES deployment, including reducing peak electricity load by up to 23% in an office building in Saudi Arabia [13], shifting 35% of cooling load off-peak at a large office complex in Texas [14], producing annual electricity cost savings of \$3.4 per MWh of installed TES capacity at a California university [15], \$6.36 per MWh at a Florida university [16], and \$5.35 per MWh at a large medical facility in Pennsylvania [17]. Few of these studies and examples have focused on how cost and use patterns influence system sizing decisions, and subsequently the economics of TES deployment. Determining the appropriate size of an individual TES system is a complicated problem, which must take into account a number of economic and technical factors, including climate, load, tariffs and capital costs. 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, taking into account local weather, loads and electricity tariffs. Capital costs are varied to understand the sensitivity of system cost on deployment size. Costs and benefits of optimized TES systems are compared to systems sized using a simpler, heuristic strategy, in order to demonstrate the value of detailed investment analysis and optimization. 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, net present value of investment and annual customer savings.

2. Background

2.1. Thermal Energy Storage

There exist a number of types of TES technologies for diurnal use: sensible (e.g. chilled water), where the storage medium changes temperature but does not undergo any phase change, and latent (e.g. ice and other phase change material [18]) where the medium exploits latent heat for additional storage capacity [9]. Given the high latent heat of fusion of water, ice storage has much higher energy density than chilled water storage. However, in order to charge, ice storage requires temperatures below the operating range of conventional

chillers, creating added complexity for system integration [8,9]. Chilled water TES systems are simpler to integrate with conventional chiller systems, because they operate within the temperature ranges of standard chiller systems (3.3–5.5 °C) [8]. The lower energy density means that chilled water systems require larger storage tanks. In general considering system integration costs, chilled water TES systems are most economical for systems larger than 7000 kWh [8]. Given the high cooling loads of the large office building investigated here, only chilled water TES systems are considered here. A simplified system diagram of TES integration is given in Figure 1. When charging, warm water is taken from the top of the stratified thermal storage tank and cooled via a heat exchanger with the chiller loop. This chilled water is then deposited in the bottom of the stratified tank. When discharging, chilled water is taken from the bottom of the tank and directed to meet the cooling load. The existing chiller can be used to charged storage or to meet building cooling loads directly.

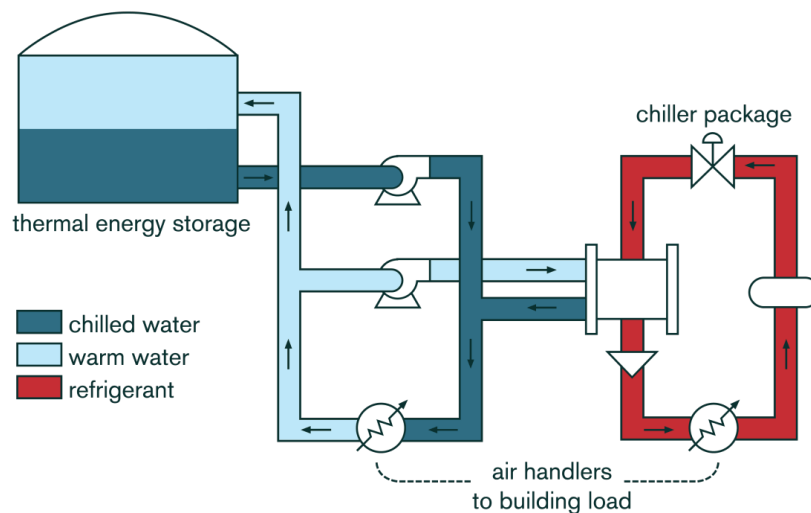


Figure 1. Schematic of chilled water TES integrated with existing chiller system.

2.2. Drivers of TES feasibility

The economics of TES will be influenced by the local conditions. A report by a California utility on TES strategies for commercial buildings has identified a number of feasibility criteria for the deployment of TES systems which remain relevant today [14]. Of these criteria, the theoretical applicability of TES depends heavily on the following: (1) the maximum cooling load of the facility is significantly higher than the average load; and (2) the electric utility rate structure includes high demand charges. For this investigation, cities have been selected such that they exhibit one or both of these conditions.

2.2.1. Climate

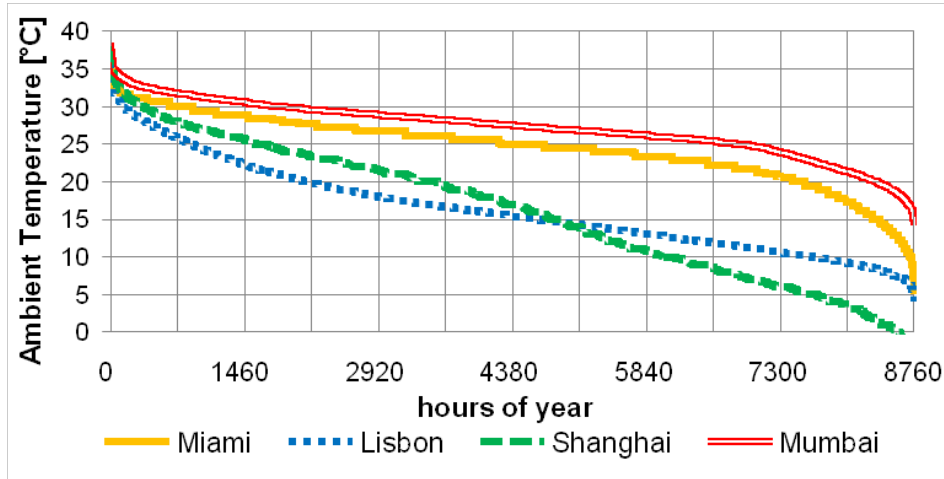


Figure 2. Annual temperature duration curves for reference cities.

Table 1. Climate details for reference cities. Cooling degree days (CDD) reflect both the magnitude and duration of the cooling season. Humidity values account for summer daytime periods only (Jun-Aug, 10am-6pm). Values are determined from typical meteorological year (TMY3) data for each location [20].

	Miami	Lisbon	Shanghai	Mumbai
Maximum Temperature [°C]	35.6	36	38	38.5
CDD [°C days]	2494	617	1063	3355
Average Relative Humidity [%]	66%	47%	70%	79%

The principle driver of cooling demand is intuitively weather, 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 [19]. 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. Based on typical meteorological (TMY3) data [20], each of the four cities appears to 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 2. Table 1 provides additional metrics to describe the cooling season, including summer daytime (June-August, 10am-6pm) average relative humidity and annual cooling degree days (CDD). CDD is a simple metric which accounts annually for the duration and intensity of external temperatures. Equations 1-3 give the formulation of annual CDD based on hourly outdoor temperature and a base temperature, which is 18° for all values present in this paper.

$$CDD = \frac{1}{24} \sum_h \Delta T_h \quad (1)$$

Where:

$$\Delta T_h = T_h - T_{base} \text{ if } T_h > T_{base} \quad (2)$$

$$\Delta T_h = 0 \text{ if } T_h \leq T_{base} \quad (3)$$

Of these cities, Mumbai clearly has the most substantial cooling period, with the highest typical maximum temperature, the most CDD and average relative humidity. Shanghai and Lisbon exhibit the next highest maximum temperatures; however Shanghai exhibits a much higher average relative humidity. Both of these cities have lower CDD totals than Miami, indicating that while their maximum temperature may be higher, the cooling season in Miami is more prolonged. Hourly cooling loads resulting from building simulation take into account ambient temperature, humidity and insolation conditions.

In addition to climate, the quality of the building envelope will influence peak and total cooling loads. A preliminary investigation showed that lower performance envelopes produced higher cooling loads and consequently larger TES investment recommendations [21]. This investigation does not consider recommendations for passive measures, such as improvements to windows and wall insulation, which would likely reduce the optimal TES system size, all else equal.

2.2.2. Electricity Tariff

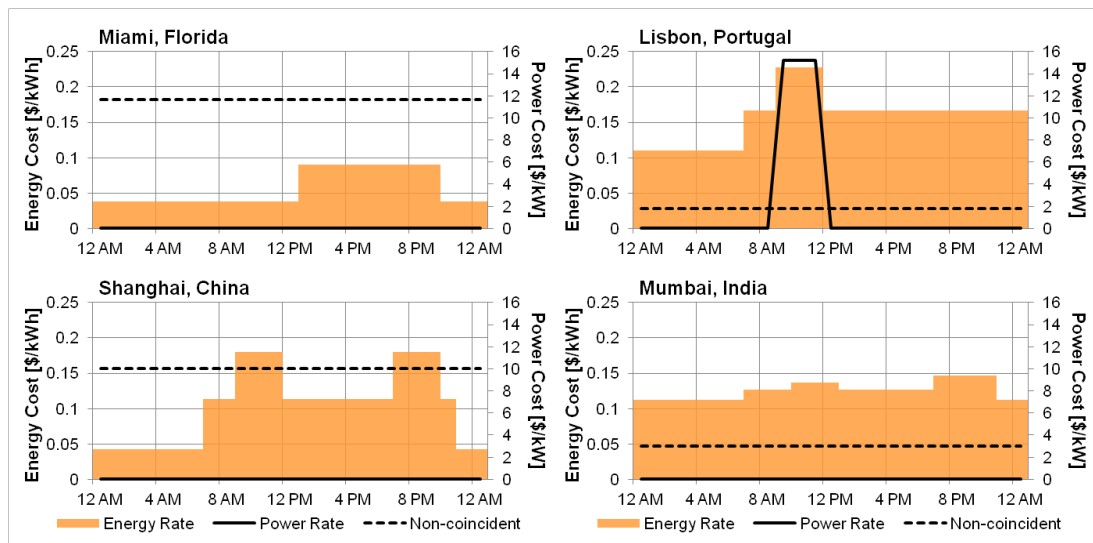


Figure 3. Summer weekday tariff profiles [25-28]. Energy rates are incurred per kWh purchased in each period. Power rates are incurred for maximum power demand within that demand period each month. Non-coincident demand charge is applied to absolute monthly maximum regardless of which demand period it occurs in.

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 [21-23] Tariffs with high on-peak energy rates and on-peak demand charges create opportunities

for economic savings from load shifting. An investigation of a large religious building in Saudi Arabia found that the absence of tariff demand charges significantly reduced the economic feasibility of chilled water TES systems, despite a large disparity between on-peak and off-peak cooling consumption [24]. Figure 3 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 subsequent sections. Tariff data has been collected from Florida Power and Light, Energias de Portugal, Shanghai Electric Power Company and Brihan Mumbai Electric Supply & Transport [25-28]. All tariff values are given in 2013 US dollars using the following exchange rate: US\$1 = €0.75 = ¥6.17 = Rs58.8.

2.3. TES Capital Costs

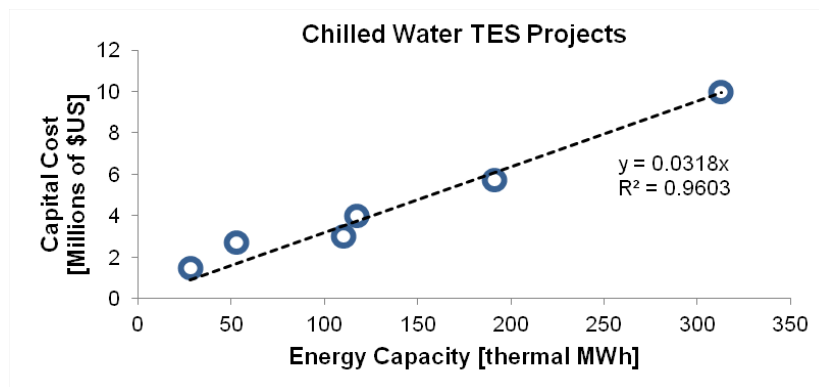


Figure 4. Cost curve of TES projects. Cost curve is developed from public data on recent U.S. TES projects [11, 14-17, 29].

Economical deployment of TES will depend heavily on the capital cost of installation. To determine this cost, a review of chilled water TES projects constructed in the United States over the past 15 years has been conducted [11, 14-17, 29]. While there are many such examples, few have readily available data on both the technical details, such as capacity and total cost of installation. From this limited sample, there does not appear to be strong scale effects for TES systems between 7MWh and 300MWh, so capital costs are assumed to be linear with system size. The linear approximation of cost developed from sufficiently documented projects is given in Figure 4. Capital costs have been adjusted for inflation to 2013 values. From this analysis, it is determined that TES exhibits a turnkey cost of \$31.80 per kWh capacity, including material and installation costs, as well as control system costs. Note this estimate is intended to reflect TES cost as part of new building construction, and neglects other factors such as available space or system integration, which may also constrain deployment. In

addition to materials, the estimated capital costs include cost for labor, which is likely to vary significantly between locations. Because labor cost data were not sufficiently detailed, it is assumed to be constant across locations. Operations and maintenance costs for water storage are typically very low relative to capital costs and are also neglected. [30].

3. Methodology

3.1. EnergyPlus simulation

End-use loads have been determined from building simulations using EnergyPlus 7.1 for a large commercial office building reference file created by the Commercial Building Initiative at U.S. Department of Energy [31, 32]. The 46,000 m² office exhibits an approximately 1.1 MW peak electrical demand for non-thermal loads. To maintain consistency between locations, a single building model is employed, even though building standards vary by country [33, 34]. In reviewing these building standards, it was found that the two developing world cities have quite rigorous prescriptive requirements, however very little data is available on standards enforcement. Despite this, building envelope characteristics are selected such that they satisfy the building code requirements of each location. Details are presented in Table 2.

Table 2. Building envelope characteristics for building energy simulation, including U-factor of various components and window solar heat gain coefficient (SHGC)

U-factor Walls W/m ² K	U-factor Roof W/m ² K	U-factor Windows W/m ² K	SHGC
0.7	0.3	3	0.25

3.2. DER-CAM Optimization

In the absence of detailed, site-specific analysis, some templates for sizing TES systems have been employed, typically using a specified fraction of on-peak demand [13, 24, 35]. Of course, the appropriate fraction and even the definition of “on-peak” will vary from location to location depending on typical summer load profiles and the structures of electricity tariffs. To optimize the sizing of TES systems, this analysis employs the Distributed Energy Resources Customer Adoption Model (DER-CAM). DER-CAM is an optimization tool built to inform decisions of distributed energy resources (DER) planning and operation. 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 [21-23, 36, 37]. DER-CAM is a mixed integer linear programming (MILP) optimization model built using the General Algebraic Modeling System (GAMS). DER-CAM takes as inputs

site-specific, historic end-use load data. By applying technology-specific costs and operating characteristics, DER-CAM is able to determine cost or carbon-minimal DER investment and operation strategies. Because this investigation is intended to assess the role of external drivers on the economics of TES deployment, DER-CAM considers TES exclusively. DER-CAM is capable of selecting from a diverse array of distributed energy technologies including others related to building cooling, however deployment of these technologies is not considered in the scope of this investigation. It may be that by exploring TES exclusively, the DER-CAM recommendations misses some synergies between different DER technologies (for instance solar thermal and absorption cooling) and fails to reach the true cost-minimal solution. A more detailed DER-CAM analysis would be required to determine how other DER technologies may compliment or compete with TES. DER-CAM is able to determine cost minimal solutions that satisfy end-use demands by minimizing annual total cost, given in Equation 4, with cost components including energy cost and amortized DER capital costs, described in Equations 5-7.

$$C_{annual} = C_{electricity} + C_{TES} + C_{OM} \quad (4)$$

$$C_{electricity} = \sum_m \sum_h (C_{P,m} + C_{E,m,h}) \quad (5)$$

$$C_{TES} = (C_{TES\ var} * S_{TES}) * \frac{r}{1 - \frac{1}{(1+r)^{L_{TES}}}} \quad (6)$$

$$C_{OM} = 0 \quad (7)$$

where:

C_{annual}	total annual cost
$C_{electricity}$	annual cost for electricity
C_{TES}	annualized capitalcosts for TES
C_{OM}	annual operations and maintenance cost for TES
m	month
h	hour
C_P	power demand costs for electricity
C_E	energy costs for electricity
$C_{TES, var}$	variable capital cost of TES (\$/kWh)
S_{TES}	size of installed TES system
r	interest rate
L_{TES}	lifetime of TES system

3.3. Modeling TES in DER-CAM

Hourly end-use loads from EnergyPlus are used to generate typical load profiles for each month and day type: weekdays, weekends and high demand, peak days. 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. 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 0.1% per hour, because temperature differences are low, typically only 15-20°C lower than ambient temperatures [8]. 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. The system lifetime of chilled water TES is assumed to be 30 years. The electric chiller is also given a variable chiller coefficient of performance (COP) to describe its thermodynamic efficiency. There are many factors that will influence chiller COP, including ambient temperature and full/part load conditions, and determining the effective COP can be quite complicated [38]. Thermodynamically, it becomes more difficult for the chiller to reject heat as the ambient temperature increases, and its COP will decrease. To capture this effect, an efficiency penalty of 3% per °C is imposed to the reference COP (3.5) for temperatures above the chiller reference temperature (assumed to be 35 °C). When ambient temperatures fall below the reference temperature, the effective chiller COP will increase. The relationship is described in Equation 8, and conforms to previous experimental data on chiller performance under variable load conditions [38]. The effect of partial loading on chiller COP is not captured in this investigation. In real applications, both effects are likely to benefit a system with TES, which typically operates chillers during cooler, off-peak periods at full output levels.

$$COP_T = COP_{ref} * (1 - p * (T - T_{ref})) \quad (8)$$

where:

COP_T	effective COP at temperature T
COP_{ref}	reference COP
T	temperature
T_{ref}	reference temperature
p	COP penalty

3.4. Scenarios

To assess the effectiveness of TES under diverse conditions, a number of scenarios have been developed to explore sensitivities to key inputs. As stated earlier, Miami, Lisbon, Shanghai and Mumbai have been selected as scenario location. While each experiences a substantial cooling period, well suited for TES deployment, the electricity tariff structures in each of these cities are quite different, varying from low energy and high power costs (Miami) to the opposite (Mumbai). Sensitivities to capital costs are also considered by varying installation cost and the interest rate. The first scenario uses the previously determined capital cost of \$31.80 per kWh TES and an interest rate of 3%. Next, a high price scenario increases the TES capital costs 50% to a value of \$47.70

per kWh. The interest in the high price scenario remains at 3%. Finally, a high interest rate scenario doubles the interest rate to 6%, while maintaining a capital cost of \$31.80 per kWh. These three scenarios allow for the influence of capital cost and interest rate to be explored independently. For each scenario and location, a comparison is made between the optimally sized TES system and two TES systems sized heuristically using the maximum on-peak cooling demand. Using the typical monthly cooling load profiles, the maximum daily on-peak cooling loads are determined for each city. The on-peak period is assumed to be 10am-6pm. This definition is arbitrary, and may not reflect the on-peak period as defined by the local utility, but it is selected to be consistent between locations and capture most of the daytime activity at the test building. Using this heuristic, two TES systems are explored, a full on-peak system sized at 100% of each locations demand value, and a partial on-peak system, sized at 50% of the demand value (Table 4). While each of these systems has been sized without the aid of optimization, DER-CAM is used to optimize their charging/discharging schedules.

4. Results

Table 3. Base case electricity cost and consumption results for each location

Location	Annual Electricity Costs (\$)	Annual Electricity Consumption (GWh)	Peak Electricity Demand (MW)
Miami	\$613,200	7.13	1811
Lisbon	\$1,262,000	6.00	1751
Shanghai	\$948,300	6.23	2444
Mumbai	\$1,084,800	7.80	2172

Table 4. Installed TES capacity for each location and scenario. Note that the system size Peak-100% and 50% cases do not change regardless of cost scenario.

TES Capacity (MWh)	Peak-100%	Peak-50%	Low Cost Optimized	High Cost Optimized	High Interest Optimized
Miami	20.2	10.1	22.4	16.6	17.2
Lisbon	17.5	8.7	13.1	8.1	8.8
Shanghai	31.5	15.8	21.6	14.6	16.1
Mumbai	28.5	14.2	19.0	9.6	11.9

Table 5. Annual electricity cost savings normalized by TES system size

Annual Electricity Cost Savings per TES Capacity (\$/MWh)	Peak-100%	Peak-50%	Low Cost Optimized	High Cost Optimized	High Interest Optimized
Miami	\$4328	\$5647	\$4110	\$4764	\$4682
Lisbon	\$4854	\$7973	\$6019	\$8361	\$7902
Shanghai	\$3741	\$5928	\$4882	\$6178	\$5856
Mumbai	\$2533	\$3433	\$3088	\$3882	\$3629

A summary of results for the base case, with no installed TES, is given in Table 3. Annual and peak electricity consumption gives an indication of the relative intensity of the cooling season for each city. Annual electricity costs illustrate how these loads interact with local tariffs. Note that consumption and cost do not necessarily scale directly with one another. Lisbon, for instance, exhibits the lowest annual consumption, but the highest annual costs. For Miami the opposite is true; the second highest annual consumption incurs the lowest annual cost. Shanghai exhibits the highest peak demand along with the second lowest annual consumption. Mumbai experiences high values in all categories, indicating a prolonged and costly cooling period.

Table 4 gives the TES system size for each scenario and location. Systems sized as a fraction of peak cooling demand do not change between cost scenarios. By examining relative system sizes, these results give some indication of how effective the simple heuristic method for sizing TES. Beginning with the low-cost scenario, the optimized system falls between the 100% and 50% peak sizes in three of four locations. Only Miami sees a recommended installation above 100% of peak period cooling load, at approximately 111%. Note that because on-peak cooling only includes cooling from 10am-6pm, the optimally sized TES system can exceed 100%, and will be used to meet cooling loads outside of this time period. The other optimized systems come in at 75%, 69% and 67% for Lisbon, Shanghai and Mumbai, respectively. Among the optimized results, the low cost scenario will necessarily have the lowest amortized TES system cost, and therefore produces the largest system size across all locations. In each location, it appears that increasing the capital cost by 50% has a stronger influence on optimal TES sizing vis-à-vis increasing the interest rate 100%. In most locations, the high cost scenario pushes the optimal system size below 50% peak. Once again, Miami is the outlier, with an optimal TES system size of 82% of peak cooling. The effect of increasing the interest is less pronounced, where all optimal system sizes fall between the two heuristically sized systems.

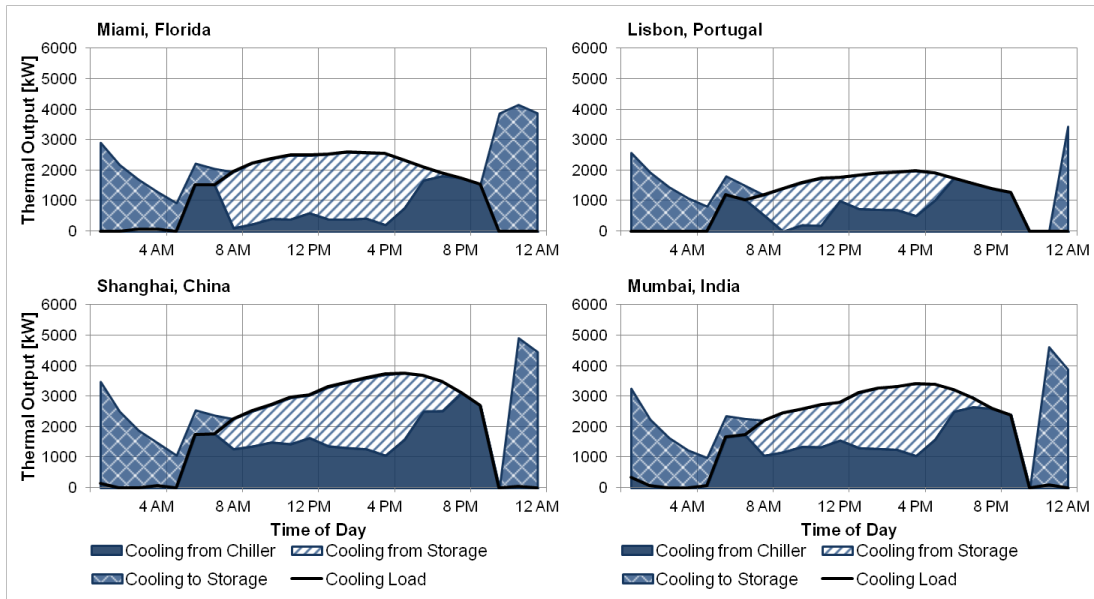


Figure 5. Summer peak cooling load profiles. The above shows the optimal capacity of TES being dispatched to meet summer peak cooling demand.

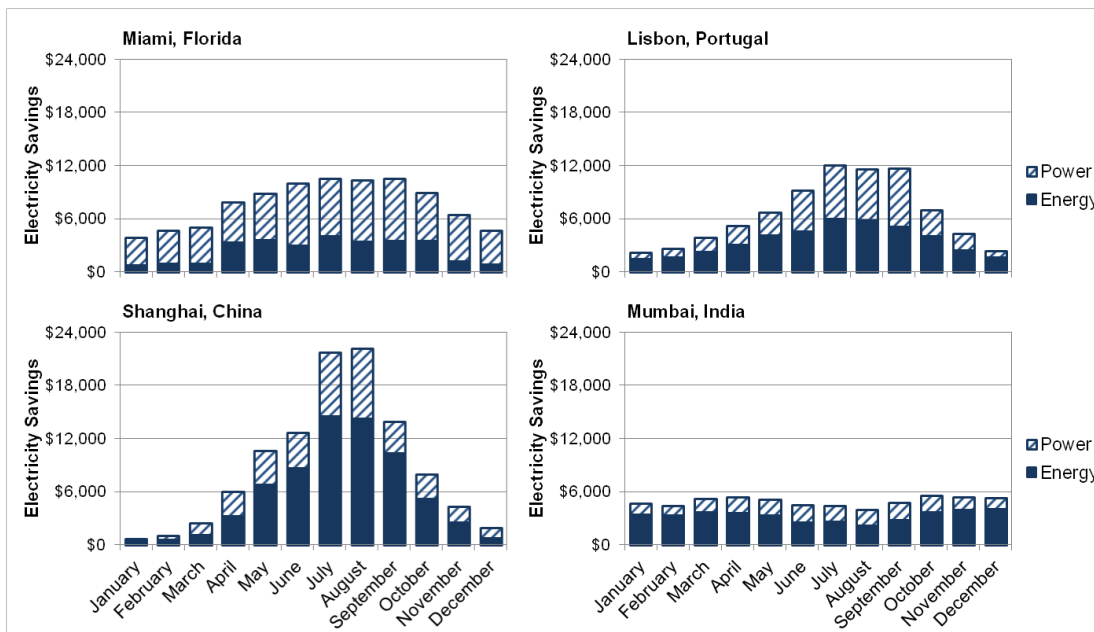


Figure 6. Monthly electricity cost savings. Savings from monthly electricity are broken down between energy and power charges. Shape and magnitude of savings depend on local tariff structure.

The annual electricity cost savings per MWh of installed TES capacity is given in Table 5. In general, smaller systems, particularly the 50% peak systems, have higher savings per unit TES. Smaller systems are only used to meet the most lucrative cost-saving opportunities. Larger systems begin to experience diminishing returns, though still produce comparable savings. Tables 6-10 give additional details on the cost and electricity savings for each scenario. These results are explored on a location by location basis in the following sections. Typical summer peak day cooling profiles are given in Figure 5 to illustrate the amount of on-peak cooling demand that

can be met with the low-cost optimal TES system. The impact of TES on monthly electricity costs is examined in Figure 6, which designates savings from energy and power charges separately.

Table 6. Percent reduction in annual electricity cost, relative to base-case, from deployment of TES

Annual Electricity Cost Reduction (%)	Peak-100%	Peak-50%	Low Cost Optimized	High Cost Optimized	High Interest Optimized
Miami	14.3%	9.3%	15.0%	12.9%	13.1%
Lisbon	6.7%	5.5%	6.2%	5.4%	5.5%
Shanghai	12.4%	9.9%	11.1%	9.5%	10.0%
Mumbai	6.6%	4.5%	5.4%	3.4%	4.0%

Table 7. Percent reduction to total annual energy use from TES deployment relative to base case

Annual Electricity Consumption Reduction (%)	Peak-100%	Peak-50%	Low Cost Optimized	High Cost Optimized	High Interest Optimized
Miami	0.3%	0.2%	0.4%	0.3%	0.3%
Lisbon	0.9%	0.6%	0.8%	0.5%	0.6%
Shanghai	0.3%	0.2%	0.2%	0.2%	0.2%
Mumbai	1.1%	0.8%	1.0%	0.6%	0.7%

Table 8. Percent reduction to peak electricity demand from TES deployment relative to base case

Annual Electricity Peak Reduction (%)	Peak-100%	Peak-50%	Low Cost Optimized	High Cost Optimized	High Interest Optimized
Miami	30.7%	19.3%	32.8%	26.9%	27.6%
Lisbon	29.9%	14.5%	22.7%	13.2%	14.8%
Shanghai	39.7%	27.4%	32.5%	26.4%	27.7%
Mumbai	36.2%	24.9%	29.1%	20.7%	22.8%

4.1. Miami, Florida

Relative to the other cities here, Florida has low energy rates, both on and off peak, and no TOU demand charges (Figure 3). 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, indicating a prolonged cooling season. During this time, the peak-flattening capabilities of TES will reduce costs incurred from the high NCDC. Consequently, the optimal TES installed capacity is typically the highest relative to its peak cooling load among all locations. Across cost scenarios, optimal system size ranges from 82%-111% and reduce annual electricity costs by 13%-15% (Table 6). As Figure 6 indicates for Miami, these savings come predominately from power savings from the NCDC. In Miami, as with the other locations, the change in total electricity consumption is very small (Table 7). The

small efficiency boost from operating the chiller at night is effectively offset by the small pumping cost necessary to charge TES. The impact of TES on peak load is quite substantial, ranging from 27%-32% (Table 8). The extent of peak load reduction correlates well with TES system size. Under low cost inputs, the payback period for optimally sized TES in Miami is 11.1 years (Table 9). This is slightly more than the smaller, heuristically sized systems. This period increases to 14.4 under higher cost conditions. The net present value (NPV) of each TES investment is given in Table 10. NPV is positive for each system size and scenario in Miami, indicating profitable investments. In all scenarios, the optimized TES system produces the highest NPV, though in many instances it is only slightly better than one of the heuristic methods. However, given the strong tariff drivers for TES deployment, the additional value of optimization is small (1%-30%).

4.2. 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. Lisbon also incurs high energy rates for mid-peak and on-peak periods, which suggests favorable conditions for TES deployment. However, of the cities investigated, Lisbon has the least intense summer cooling period. Its on-peak demand period is only 3 hours and occurs earlier in the day, before cooling loads reach their peak. Its NCDC is low relative to the other locations. This means that TES systems that can offset cooling load during the short on-peak period will capture most of the demand-charge related cost reductions. This exact behavior is exhibited in Figure 5. Consequently, the optimal TES systems will be smaller than those determined for Miami, and range from 47%-75% of on-peak cooling loads. Given the smaller system sizes, annual electricity cost savings are also smaller, coming in between 5% and 7% (Table 6). The smaller systems are still able to capture much of the peak demand reduction, seeing savings as high as 23% for optimally sized TES (Table 7). Given lower capital costs, payback period for Lisbon are smaller than Miami (Table 9), and surprisingly, the NPV are among the highest for any city (Table 10). Again, the optimized TES systems realized higher NPV than heuristically sized systems by as much as 20%.

4.3. Shanghai, China

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. 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. Revisiting the temperature duration curves in Figure 2, 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 larger

potential for savings during a few summer months, and diminishing savings at other times throughout the year (Figure 6). Ultimately, these factors interact to produce optimal TES systems that are large in absolute terms (15MWh-22 MWh) but small relative to the maximum on-peak cooling demand (46%-69%). The systems are quite effective at reducing peak electricity demand, lowering the peak demand 26%-33% (Table 8). The higher rates of the Shanghai tariff produce higher cost savings (Table 5) and shorter payback period (Table 9) than comparably sized TES systems in Miami. These rates contribute to making the NPV of TES deployment in Shanghai the highest of all four locations (Table 10).

4.4. Mumbai, India

None of the components of the Mumbai tariff are particularly favorable to TES installation. It includes no TOU power rates, a low NCDC rate, and TOU energy rates that vary 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. This is reflected in Figure 6, which shows consistently monthly cost savings. Given the weaker economic drivers, TES installation is the smallest as a percent of peak load, ranging from 34%-67% (Table 4) and savings per installed capacity are the smallest observed (Table 5). Despite the smaller systems, with lower cost savings potentials, TES deployment in Mumbai is able to reduce peak loads 21%-29% for optimally sized systems (Table 8). With lower savings though, payback periods are prolonged (Table 9), and may become prohibitively long to attract broad investment. Despite this, as Table 10 shows, all of the optimally sized systems and many of the heuristically sized systems still produce positive NPV. Only the high cost 100%-peak system produces a negative NPV, indicating a bad investment. This system is nearly three times as large as the optimally sized TES system for this cost scenario.

Table 9. Payback period determined for each case and cost scenario, given amortized capital costs and annual electricity costs savings

Payback Period (years)	Scenario	Peak-100%	Peak-50%	Optimized
Miami	Low Cost	10.5	8.1	11.1
	High Cost	15.8	12.1	14.4
	High Interest	14.4	11.0	13.3
Lisbon	Low Cost	9.4	5.7	7.6
	High Cost	14.1	8.6	8.2
	High Interest	12.8	7.8	7.9
Shanghai	Low Cost	12.2	7.7	9.4
	High Cost	18.3	11.6	11.1
	High Interest	16.6	10.5	10.6
Mumbai	Low Cost	18.0	13.3	14.8
	High Cost	27.0	19.9	17.6
	High Interest	24.6	18.1	17.1

Table 10. Net present value (NPV) of TES deployment for each location and cost scenario. NPV indicates the present value of an investment, given the costs and benefits across its entire lifetime

Net Present Value (\$)	Scenario	Peak-100%	Peak-50%	Optimized
Miami	Low Cost	\$881,900	\$673,600	\$890,000
	High Cost	\$560,000	\$512,600	\$584,600
	High Interest	\$648,700	\$557,000	\$657,800
Lisbon	Low Cost	\$920,100	\$934,100	\$954,100
	High Cost	\$642,600	\$795,300	\$796,100
	High Interest	\$719,100	\$833,600	\$833,600
Shanghai	Low Cost	\$1,051,400	\$1,126,000	\$1,150,400
	High Cost	\$550,100	\$875,400	\$876,400
	High Interest	\$688,300	\$944,500	\$945,400
Mumbai	Low Cost	\$350,100	\$398,200	\$417,700
	High Cost	-\$102,500	\$171,900	\$191,000
	High Interest	\$22,300	\$234,300	\$237,500

4.5. Valuating Optimization of TES

In general, the heuristically sized TES systems are able to capture much of the cost and energy benefits of optimal systems, ranging from 60% to 100% of the optimal NPV. Of the 12 specific instances (locations and cost scenario) investigated, the optimal size falls between the 50% and 100% peak values in seven instances, below the 50% peak in four instances, and above the 100% peak in only one instance. Examining Table 10, it appears that most cases of heuristic sized systems achieve comparably high NPV to optimally sized systems: 76%-99% in Miami, 81%-100% in Lisbon, and 63%-99% in Shanghai. Among these locations, Mumbai is a

unique case. Here there is a significant risk of heuristic sizing recommending an over-sized TES system. In unfavorable cost conditions, such methods could lose a vast majority of NPV of investment, capturing only about 9% vis-à-vis optimal systems, or losing money outright over the life of the system. The effectiveness of these specific sizing metrics depends on the presence of certain drivers, including high power demand rates, large differences in on and off-peak rates, and the intensity and duration of the cooling season. Where these conditions do not clearly exist, there remains the risk that simple sizing metrics can result in over-sized or under-performing TES deployment. In such instances, the detailed optimization results, such as those generated by DER-CAM, become extremely valuable by ensuring that any TES deployment is financially beneficial, amounting to hundreds of thousands of dollars in additional NPV over the lifetime of the system.

By examining the results over the four locations, the strength of each TES driver can be assessed in relative terms. In looking at optimal TES deployment as a fraction of on-peak cooling load, Miami, Lisbon and Shanghai all outperform the much hotter Mumbai. Miami also outperforms Lisbon and Shanghai, even without a large difference between TOU energy rates. This suggests that tariff structure is a more influential driver than climate, and within the tariff structure, demand charges are the more influential than TOU energy rates. In general, tariffs which employ high demand charges to disincentivize peak in conjunction with high on-peak energy rates will be the most influential in driving TES adoption. As tariffs evolve to better reflect the real cost of electricity during peak periods, the economics of TES deployment will likely only become more favorable.

5. Conclusion

This investigation has demonstrated the feasibility of TES deployment across a variety of economic and climatic contexts. The most significant drivers of feasibility are 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 conjunction 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. The effectiveness of heuristic methods for TES system sizing has also been investigated. When clear drivers for TES exist, these methods capture many of the cost and energy benefits of optimally sized TES systems. When these drivers are not consistently present, the simpler sizing metrics have a tendency to over-size deployment. In terms of NPV of investment, the costs can be quite substantial.

Across locations, the benefits of deployment are clear. Economically, TES has the ability to generate substantial savings to annual energy costs of 5.4%-15% under low cost inputs. Payback periods for TES investment ranged from 8-15 years, and expanded to 15-18 years under higher capital costs. Additionally, the functional link between TES and cooling demand makes it uniquely positioned to reduce cooling-driven peak electricity demand. This investigation observed a peak electricity demand reduction ranging from 29% to 33%. While overall energy consumption with TES remains nearly constant, its dynamic load shifting ability make it a promising technology throughout the world.

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