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# Evaluation of the Energy, Demand, and Performance of Nostromo's IceBrick Cooling Thermal Energy Storage System

Marco Pritoni, Peter Grant, and Brian Woo-Shem - Lawrence Berkeley National  
Laboratory



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For more information contact:

Principal Investigator Name: Marco Pritoni  
Lab: Lawrence Berkeley National Laboratory  
Email: mpritoni@lbl.gov

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GSA's Technology Proving Ground (TPG) program and DOE's Office of Energy Efficiency and Renewable Energy enable federal and commercial building owners and operators to make sound investment decisions in next-generation building technologies based on their real-world performance.

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# Executive Summary

ThermalEnergy Storage (TES) has the potential to reduce energy bills and improve reliability of the electric grid by shifting load away from peak times.

Nostromo Energy produces IceBrick, a modular thermal energy storage system using ice to provide cooling to large buildings. The system consists of 1) a charging and support chiller, 2) one or more modular ice storage units, 3) a cloud-connected control system, and 4) a heat exchanger between the storage system and the facility chilled water loop. The storage units use “encapsulated ice” capsules that are stored in modules called “IceBricks”. These modular units allow for integration with existing buildings, including the ability to place distributed storage in multiple locations and integration with existing facility chillers. The system aims to provide utility cost savings by: 1) reducing peak loads and the resulting demand charges, 2) shifting electricity to lower-cost periods, 3) bidding the capacity in the wholesale electricity market (in states that allow for participation). The system can be added as a retrofit to an existing building or designed-in with new construction, potentially reducing upfront costs by taking the place of backup chiller(s).

The performance of the IceBrick system was measured at an existing non-GSA site: the Beverly Hilton, a large hotel in Beverly Hills, CA. The analysis used data extracted from the vendor’s cloud platform, without addition of external sensors. Preliminary data analysis for the month of August 2024 found that the system was able to reduce peak thermal load by a maximum of 1746 kW<sub>th</sub>, with an average discharge rate during the 4-9pm peak period of 993 kW<sub>th</sub>, representing 38 % of total cooling load during these times, while maintaining a stable chilled water supply temperature to the building of 41.3-43.9 °F, consistent with time periods in which only the facility chillers were active. The overall round-trip efficiency of the system was 94.3 % and maximum depth of discharge was 96.8 %, both exceeding the specifications of 90 % and 94 % over 5 hours, respectively, at the site.

An additional non-energy benefit demonstrated during the monitoring period was improved system reliability. The IceBrick storage can be discharged and/or the charging chiller can be activated to directly serve building loads in the event of facility chiller outages or scheduled maintenance, thereby preventing instances where the building's load requirements are not met. This was observed in two instances during the 1-month period evaluated.

While the project was ended early due to changes in priorities at the federal level, the preliminary analysis of the existing installation suggests that the IceBrick TES system can provide cost saving and can improve reliability for customers. A new installation at an additional facility and M&V process can more thoroughly verify these findings while providing additional insight into system performance, benefits, and costs.

# Introduction

## Background

In many regions in the US, the time of peak grid stress and peak electricity prices coincides with the peak space heating or cooling demand. Buildings with no energy storage experience high heating or cooling loads during these peak times, which can lead to high costs and exacerbation of peak demand on the electric grid during potential shortages. Thermal energy storage can decrease operating costs for building operators by shifting when electricity for space cooling or heating is consumed. HVAC systems can operate during times of low electricity cost and low grid stress ahead of the peak demand period and store the thermal energy. During the peak period, the stored thermal energy is discharged from the TES to meet building loads and ensure thermal comfort for occupants, resulting in significantly reduced electricity usage.

Space cooling in large commercial buildings is often provided using a chilled water system, which typically consist of one or more central chillers, a network of pipes that circulate chilled water through the building, and a cooling tower. Typical systems operate to meet cooling demand at a given time, without any energy storage. Some studies on load flexibility without TES have pre-cooled the air in the building by a few degrees fahrenheit to reduce energy consumption at peak times, but this passive use of thermal storage has limited effect on demand flexibility. Further, pre-cooling may cause thermal discomfort to the building occupants.

## Technology Description

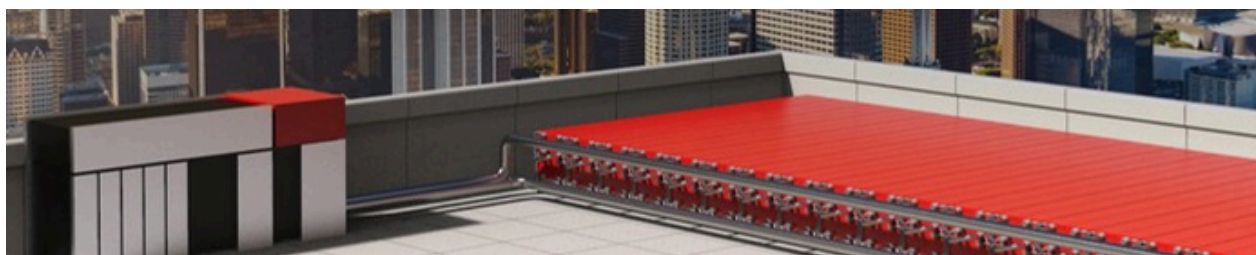


Figure 1. Sample image of Nostromo IceBrick technology [Image credit: Nostromo]

Nostromo's IceBrick is a TES system for large commercial and industrial buildings. IceBrick leverages water as a phase change material, which 1) has a relatively high latent heat of fusion of 333.55 kJ/kg or 92.7 Wh/kg, 2) is less expensive compared to engineered phase change materials such as salt acetate trihydrate, and 3) does not degrade after several cycles, compared to engineered phase change materials. The water is encased in pre-fabricated IceBricks, which each store an equivalent of 8.0 to 12.5 kWh of electrical energy, depending on the avoided cooling loads & facility chiller efficiency, and are stackable 420 by 50 by 25 cm modules enabling construction of different sized systems at deployment sites [1]. To complement this storage, Nostromo provides a dedicated chiller to charge the IceBricks and a proprietary control system (eNvoy) to schedule operation of the chiller and the thermal storage to reduce utility costs.

Nostromo's IceBrick system is custom-designed and sized for each building according to the specific needs of the customer and the economic/financial characteristics of the site, resulting in varying performance based on the design objectives and site specifications. Claims on typical performance include:

- Store thermal energy to replace cooling electrical loads during peak hours.
- Reduce electricity costs for an average 5-year return on investment including incentives and access to wholesale revenue.
- Thermal round-trip efficiency of 90% or greater.
- Discharges >94% over a 5 hour shed period.
- Low-maintenance and reliable system that is easy to operate for building staff.
- Ability to provide turnkey service including design, installation, operation and maintenance, or ability to support building staff and contractors, as preferred by the site.

# M&V Plan

## Testbed

The field evaluation was intended to be performed at two field sites: an existing installation of the technology at the Beverly Hilton Hotel and a new installation at an additional GSA site. Due to changes in priorities at the federal level, the project was ended before a GSA site was selected. The rest of the report describes the characteristics and analysis at the first site.

## Beverly Hilton

Nostromo installed their IceBrick system at a large hotel in Beverly Hills, CA prior to the start of this project, in July 2023. Nostromo has stated the goals of the Hilton project were to 1) demonstrate that it is technologically feasible to retrofit and integrate a large TES into a more than 70 year old iconic building; 2) operate it to meet the mechanical performance targets; 3) optimize the economics to synchronize operation with the electricity prices and the building operation needs; and 4) develop design criteria, methodologies, and forecasting tools for future installations. Since this is the first installation in the US, there were not specific numerical performance targets for installation, peak cooling demand reduction, depth of discharge, and maintenance costs as would be determined for future sites. Nostromo had additionally installed the sensors necessary for M&V of the system when commissioning the equipment, which were utilized in the M&V conducted for this report.



Figure 2. IceBrick equipment at the Beverly Hilton field site. [Photo credit: Nostromo]

## GSA Site

AGSA-owned site was originally intended to be selected as part of this project. While no site was ultimately selected, the criteria are provided for future consideration.

## GSA Site Criteria

Criteria for selecting a GSA site are listed in Table 1. These include parameters necessary for M&V and criteria for a successful installation identified by the Nostromo team. Some factors may be dependent on geographic location and may be adjusted based on target region.

\*Required \*\*Preferred

Table 1. Site criteria

System	Portfolio-Wide Deployment	Testbed Pilot
<p><b>Facility Characteristics</b></p>	<p>* Large commercial building with chiller-based cooling system.</p> <p>* High cooling load during at least a portion of utility peak periods (typically mid-day or 4-9pm, depending on local utility)</p> <p>** Cooling loads for the entirety of the peak period.</p> <p>** If the cooling system turns off before the end of the peak period, the other electric loads should get lower correlation until the end of the peak period.</p> <p>** Year-round cooling loads.</p>	<p>* Large commercial building with chilled water circulation cooling system. Most GSA buildings &gt; 250k SF are suitable. Smaller buildings with higher load variability are also suitable.</p> <p>* High cooling load during at least a portion of utility peak periods (typically 4-9pm, depending on local utility)</p> <p>** Cooling loads for the entirety of the peak period.</p> <p>** If the cooling system turns off before the end of the peak period, the other electric loads should get lower in correlation until the end of the peak period.</p> <p>** Year-round cooling loads.</p>
<p><b>Location</b></p>	<p>* Area serviced by utility with either:</p> <ul style="list-style-type: none"> <li>● TOU rate and large variation between peak and off-peak prices, or</li> <li>● large peak period demand charges.</li> </ul> <p>** Ability to participate in the wholesale electricity market</p> <p>* Adequate space to install equipment **</p> <p>Sites in California, to match the vendor’s target market and business considerations. ** Climate zones with higher cooling loads and large day-night temperature variation.</p>	<p>* Area serviced by utility with either:</p> <ul style="list-style-type: none"> <li>● TOU rate and large variation between peak and off-peak prices, or</li> <li>● large peak period demand charges.</li> </ul> <p>LBNL could perform postprocessing analysis to extrapolate the impacts to different utility prices if necessary due to utility rates at the selected site.</p> <p>** Ability to participate in the wholesale electricity market. For sites in California, Nostromo currently recommends SDGE, PG&amp;E, SCE, and certain MOUs that are part of CAISO to enable wholesale market integration. (Utilities outside CAISO, including LADWP and SMUD, are strongly discouraged).</p> <p>* Adequate space to install equipment</p> <p>** It would be ideal to perform M&amp;V at a site in a climate zone different from that of the Hilton site.</p>

System	Portfolio-Wide Deployment	Testbed Pilot
		<p>** Sites in California, based on vendor target market and business considerations.</p> <p>** Climate zones with higher cooling loads and large day-night temperature variation.</p>
<b>Site Engagement</b>	<p>Minimal</p> <p>**Collaboration to install initial equipment and sensors</p>	<p>* Ability to survey and/or interview building staff, particularly management and maintenance personnel.</p> <p>** Building management who are interested in testing &amp; early adoption of new technology.</p>
<b>Whole-Building Electricity Data</b>	<p>* Whole-building electricity data (hourly sampling or less).</p>	<p>* Whole-building electricity data (15-minute sampling or less, ideally 1-minute sampling)</p>
<b>Historical Electricity Data</b>	<p>* Whole-building electricity data (hourly sampling or less).</p> <p>**Sub-metering for HVAC (see “HVAC” section below; hourly sampling or less).</p> <p>** 12 months of data preferred</p>	<p>* Whole-building electricity data (15-minute sampling or less, ideally 1-minute sampling)</p> <p>**Sub-metering for HVAC (see “HVAC” section below; 15-minute sampling or less, ideally 1-minute sampling).</p> <p>* 6-12 months of data required</p>
<b>Documentation</b>	<p>* Mechanical drawings of &amp; sequence of operations of currently installed equipment.</p> <p>** Manufacturer documented performance map (kW/Ton)</p>	<p>* Mechanical drawings of &amp; sequence of operations of currently installed equipment</p> <p>* Manufacturer documented performance map (kW/Ton)</p>
<b>Control System</b>	<p>*Existing HVAC (i.e., chiller + pumps + cooling tower fans) sequences of operation</p>	<p>*Existing HVAC (i.e., chiller + pumps + cooling tower fans) sequences of operation</p>
<b>Lighting Controls</b>	N/A	N/A

System	Portfolio-Wide Deployment	Testbed Pilot
<b>HVAC</b>	<p>* Cooling load (thermal) data (hourly sampling or less)</p> <p>** Chillers, pumps and fans electricity consumption (hourly sampling or less).</p> <p>* Actual cooling demands for peak loads &gt;500RT</p> <p>* Variable load</p> <p>** Load factor between 0.6-0.7</p>	<p>* Cooling load (thermal) data (15-minute 1-minute or less, ideally 1-minute sampling). Note that a smart chiller with additional flow metering (which can be added by the vendor upon site selection) provides this data.</p> <p>** Chillers, pumps and fans electricity consumption (15-minute sampling or less, ideally 1-minute sampling).</p> <p>* Actual cooling demands for peak loads &gt;500RT. If peak cooling demand data is not available, Nostromo recommends at least 750 tons capacity air cooled or 1000 tons water cooled, subject to initial sales review.</p> <p>* Variable load</p> <p>** Load factor between 0.6-0.7</p>
<b>Building Size</b>	<p>** No specific building size is required, however as a general rule, large buildings with facility chillers, &gt;200k sq ft or campuses with Central Utility Plant will have sufficient loads to meet the facility characteristics requirements.</p>	<p>** No specific building size is required, however as a general rule, large buildings with facility chillers, &gt;200k sq ft or campuses with Central Utility Plant will have sufficient loads to meet the facility characteristics requirements.</p>

## M&V Design

### Definitions

- **Thermal load:** Amount of thermal energy removal required to cool the building to maintain zone temperature at the zone setpoint. This will be measured between the inlet and outlet of the cooling plant. For the performance period, this also includes all retrofit components installed as part of IceBrick. **Electric Cooling Load:** Electricity consumption used for satisfying the thermal load of the building. This includes chillers, pumps, fans, cooling tower, and other systems in the cooling plant. For the performance period, this also includes all retrofit components installed as part of IceBrick. **Electricity Consumption:** The amount of electricity consumed (kWh) over a period of time. **Electric Demand:** The rate at which electricity is consumed (kW) to meet building needs. **On-Peak Hours:** Hours when electricity prices are greatest per unit, according to the electric rate structure at the site, and when the controls determine it makes sense to reduce electricity consumption. Peak hours are typically defined for demand charges and for time-of-use rates. The on-peak hours for demand charges and time-of-use rates are typically the same, but they could be different, depending on the specific Utility and Tariff. For dynamic wholesale rates, “on-peak” will be defined as the Y number of highest price hours, where Y is the design duration of the TES.

- **Off-Peak Hours:** Hours when electricity prices are lower per unit, according to the electric rate structure at the site. Similarly to On-Peak Hours, the Off-Peak Hours are defined by the utility rate structure and the design duration of the TES. Some utility tariffs have three or more pricing periods (e.g. “Mid-Peak”). Since TES systems are typically designed around On-Peak time periods, this document lumps Mid-Peak into Off-Peak. Cost saving calculations will consider all pricing periods, including Mid-Peak, as defined by the utility tariff structure.

This report uses the following nomenclature.

<b>Subscripts</b>	
$c$	Indicates that a term is related or refers to the cooling system of the building
$FC$	“Facility Chiller only” data during times that only the original facility cooling equipment is providing cooling load to the building, including prior to installation and post-installation when the TES units are isolated from the rest of the building
$IB$	Data occurring when the TES system is actively providing cooling to the building
$eq$	Equivalent or projected value for what the system would have used during times IceBrick is active, if IceBrick had not been active
<b>Variables</b>	
$C_c$	Total monetary cost of all operating expenses for cooling (including but not limited to electricity, operations staff, maintenance, and repairs) during a given time period, USD
$C_{demand}$	Total cost of demand charges, USD
$C_{Installation}$	Capital cost of system installation and commissioning, USD
$C_{kWh}$	Total cost of electricity per kWh consumed, USD
$C_p$	Specific heat capacity, J/g°C
$\zeta OP$	Coefficient of Performance
$DOD$	Depth of discharge, defined as the change in state of charge throughout a given charge-discharge cycle of the TES
$ES$	Energy cost savings using TES compared to the facility without IceBrick, USD
$IRR$	Internal Rate of Return
$LR$	Electric cooling load reduction with TES compared to the facility without IceBrick, %
$\dot{m}$	Mass flow rate, kg/s
$P$	Electricity consumption, kWh
$p_{kWh}$	Electricity price per kWh consumed, USD
$p_{demand}$	Electricity demand charge price, USD
$PBP$	Payback period, years
$P(t)$	Denotes electricity consumption during a given time range t, kWh
$Q$	Thermal energy, kWh
$RA$	Resource Adequacy capacity credit
$ROI$	Return on Investment

<i>RTE</i>	Round trip efficiency, %
<i>SOC</i>	State of charge, %
<i>U</i>	Cooling electric utility bill costs for the site, USD.
<i>VPP</i>	Virtual Power Plant

## Metrics

LBL, in collaboration with GSA and Nostromo, identified several key quantitative and qualitative performance metrics. These metrics define the impact of a thermal energy storage system, and can be used to evaluate the performance of an installation. Table 2 presents the quantitative performance and Table 3 presents the qualitative metrics used in this project.

Table 2. Quantitative Performance Objectives

Quantitative Objectives	Metrics	Required Data
<b>1. Peak cooling demand reduction</b>	<p>Actual cooling supplied by the ice TES system (RT and kW) when discharging, as a percent of the total cooling demands (consisting of building chillers and ice TES discharge) at the time of peak.</p> <p>Note: The target for a given site is determined during system sizing to optimize for the customer's goals (such as cost savings)</p>	<p>Storage Chiller electricity consumption Storage system pump electricity consumption Building Chiller electricity consumption Building pumps electricity consumption Building Cooling Tower electricity consumption kW/Ton performance mapping for Chillers as function of load and outdoor conditions (plate and derived from data) Outdoor air temperature Building annual cooling load profile (from BMS if available, otherwise generated based on seasonal peak cooling loads) Utility meter (which includes the building's cooling consumption) electricity consumption Electricity prices (retail/wholesale) projections (20 years)</p>

<b>2. Peak electric demand reduction</b>	Cost savings based on the difference Electricity consumption of all HVAC components used between the electric cost to provide for space cooling equivalent cooling without the system, compared to the electricity cost with the technology installed. The vendor expected up to 30% cooling electricity cost savings in the RFI, and has since updated this to 30-60% cost savings. Note that the cost savings target will vary per site, depending on the size of the TEW system. Savings include retail savings (energy and demand charges), wholesale revenue from Resource Adequacy (RA) capacity credits and Virtual Power Plant (VPP) agreements for bidding into the CAISO day-ahead market as a demand response resource.	Electricity consumption of all HVAC components used for space cooling Electricity bills for the site Electricity price structure
<b>3. Return on Investment</b>	Financial payback period of approximately 5 years, dependent on design goals, including incentives available in CA at time of writing such as ITC and SGIP.	(All utility cost reduction parameters above) Entire cost to install the TES system  Annual maintenance cost of the cooling system with IceBrick Annual maintenance cost of the baseline cooling system before IceBrick was installed.
<b>4. Round-trip efficiency (Thermal)</b>	RTE, the amount thermal energy is wasted in parasitic losses in the TES units and heat exchanger. The manufacturer claims a thermal Round-Trip efficiency of approximately 90%.	System drawings, operation modes, etc Inlet and outlet temperatures and mass flow rates of the IceBrick and the heat exchanger. State of charge of the TES system
<b>5. Depth and speed of discharge</b>	Depth of Discharge and State of Charge, as described in the Depth of Discharge section. For the Hilton site, demonstrate 94% depth of discharge over a 5-hour period. Up to 80% depth of discharge over a 2.5 hour period. For the GSA site, specific depth of discharge numbers will vary with the design of the system.	State of charge (SOC) of the system, as described in the Depth of Discharge section. Control signals for charge and discharge operation modes.

Table 3. Qualitative Performance Objectives

Qualitative Objectives	Metrics	Required Data
<b>Installation</b>	Installation time of the technology for a new site.	<ul style="list-style-type: none"> <li>● Timeline of key milestones such as <ul style="list-style-type: none"> <li>○ permitting</li> <li>○ construction start</li> <li>○ commissioning</li> </ul> </li> <li>● Surveys of facility staff</li> </ul>

Qualitative Objectives	Metrics	Required Data
<b>Maintenance</b>	Duration and frequency of maintenance procedures. The goal is that the system does not create additional burden on maintenance personnel compared to the baseline system.	Surveys of maintenance staff Maintenance service bills, including any potential required maintenance changes for both the IceBrick and facility systems
<b>Operations</b>	Perceived reliability and resilience benefits by building staff.	Surveys of operations staff. Cooling service outage or issue logs
<b>Occupant Satisfaction</b>	Survey scores by building occupants to demonstrate that the system maintains thermal comfort and does not create adverse effects such as noise, aesthetics, safety, etc.	Surveys of various staff, both technical and nontechnical, of the building.

## Metrics Calculations

The following plan addresses the use cases and metrics identified by LBNL to evaluate Nostromo’s IceBrick technology. This plan represents an ideal scenario, where any sensors, instrumentation, and data acquisition equipment required is available. Only a reduced subset of the plan was able to be conducted before the project was ended; this subset is described in the Results section. The entire plan is provided as a starting point for future evaluations of the technology. For all metrics, the ideal baseline period is one year prior to implementation, and the performance period is one year after installation, assuming a site has year-round cooling demand.

The general approach is to use measured data from the site during TES operation to calculate thermal metrics, and combining this with pre-installation data for electrical metrics, making adjustments to account for the impact of the TES on performance. An overview of the process for calculating metrics 1-3 is given in Figure 3.

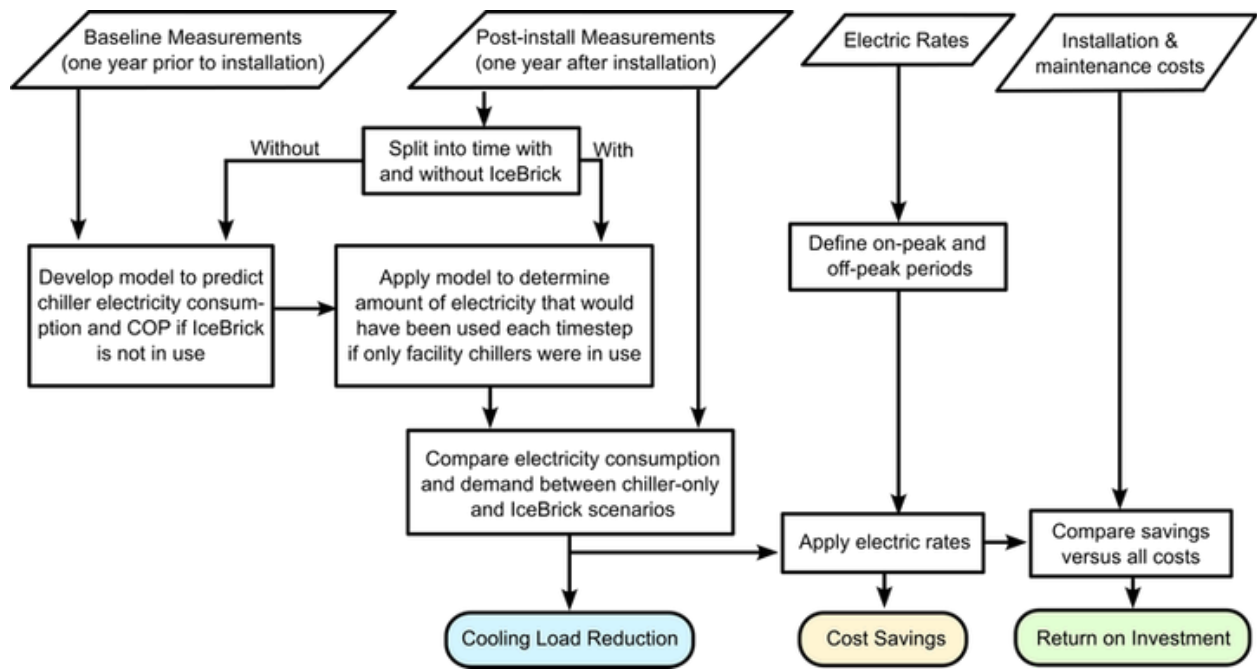


Figure 3. Overview of the workflow to calculate Cooling Load Reduction, Cost Savings, and Return on Investment.

## Cooling Load Reduction

The IceBrick system is designed to perform load-shifting and reduce operating expenses by decreasing the HVAC load and peak electrical demand during higher-cost on-peak hours and shifting them to lower-cost hours. The peak period is defined by the utility tariff, and typically occurs during the late afternoon/evening period when grid-level demand is highest. Peak demand for a specific building is the time when the building most rapidly consumes electricity from the grid, and typically occurs during times of high occupancy and high outdoor air temperatures.

Cooling load reduction is relevant only during times that IceBrick is discharging. Cooling load reduction will be examined using two submetrics, (1) thermal and (2) electrical. Thermal cooling load reduction can be calculated directly from metering data as the amount of thermal energy transferred by the IceBrick, compared to the total thermal cooling load of the building. Thermal load,  $Q$  is first calculated using Equation 1, based on measurements where  $\dot{m}$  is the mass flow rate through the loop and  $T_{in}$  and  $T_{out}$  are the fluid temperatures entering and leaving a given system.

$$(1) Q = \dot{m} c_p (T_{in} - T_{out}) \quad (1)$$

Thermal load is calculated for two components, (1)  $Q_F$ , the chilled water supply and return lines to the facility to represent the total building load, and (2)  $Q_{IB}$ , the glycol across the Nostromo heat exchanger lines to and from the IceBrick. The thermal load reduction is then determined by Equation 2.

(2)

$$LR_{thermal} = Q_{IB} / Q_F$$

Electrical cooling load reduction follows several steps. In order to accurately estimate power over time, for all of the points listed in this section, data in intervals matching the utility charge timestep, typically 15-minutes, is necessary. Smaller intervals such as 1-minute resolution data will allow for additional verification steps but are not required. The current IceBrick system at the Beverly Hilton is collecting this data, and Nostromo expects future installations to have this as well.

The current M&V guidelines and standards such as ASHRAE Guideline 14 and IPMVP assume that the retrofit could alter performance at all times once installed, and that only electricity consumption data is available. According to these, to calculate the reduction in electricity usage during on-peak hours, power consumption by the HVAC system with the IceBrick system will be compared to the projected power consumption with the pre-retrofit system [2]. The most similar method is an adaptation of IPMVP Option B: retrofit isolation with all parameter measurement [3]. This method requires historical electricity consumption of the chiller system for preferably one year before and after the retrofit and operation schedules. The load reduction is based on a comparison of cooling energy consumption with and without IceBrick for each hour of the day. To handle differences over time, a model of the pre-retrofit system would be created to normalize for differences in expected cooling load due to weather conditions, occupancy changes, and the setpoint schedule. This method will not be the primary method for determining cooling load reduction and cost savings, but may be performed as a comparison to the proposed thermal load-based method described in the following paragraph.

For the IceBrick system specifically, there are two key differences in the operation and data that allow for more accurate projections for the energy consumption by the facility if IceBrick were not present. First, the IceBrick system is completely isolated from the original facility cooling system except when actively discharging. Thus, measurements of the facility chiller-only system may be conducted after retrofit, whenever IceBrick is not discharging. Note that when charging, the electricity consumption of the IceBrick charging chiller and other components are measured separately, and there is no heat exchange or other interaction between the IceBrick and facility systems. Second, the temperature and flow sensors on the inlet and outlet to the building added by Nostromo allow for direct measurement of the thermal load of the building. For this project, the concept of comparing the energy consumption with and without the technology will be adapted to use the more accurate data focused on the chiller plant specifically that is available. Instead of predicting the baseline electricity consumption based on weather, the equivalent electricity consumption of the original system without IceBrick can be modeled using the thermal load as an input and determine the electricity that the facility chillers would have required to meet that thermal load based on their projected COP. Operating the facility chillers with a lower inlet temperature and at a lower capacity due to discharging the IceBrick may impact COP [5]. This method models the change in COP, resulting in the expected electricity consumption by the facility chiller-only system to meet the measured cooling load during times of IceBrick discharge.

Several models will be developed and tested using the pre-install and facility chiller-only data as a training set, then the best performing model will be selected. These models may include gradient boosting regressor [6], polynomial regression, random forest [7], support vector regression [9], and K-nearest neighbor [8], which have been used successfully by other M&V projects involving chiller energy measurement but not specifically for thermal energy storage applications. ASHRAE Guideline 14 and IPMVP specify that Cv(RMSE) must be within 30 % and 20 % respectively, and R-squared should be greater than 75 % [3]. LBNL will report the actual accuracy of each model based on the results once data is received and examined.

Once the IceBrick is installed, the electricity consumption of the IceBrick system (including pumps and peripherals),  $P_{IB}$  will be recorded and calculated. The avoided electric cooling load, AE at a given time can then be determined by Equation 1, in which  $P_{FC, meas}$  is the measured electricity consumption of the facility chillers, pumps, cooling tower, and peripherals in kWh,  $P_{FC, eq}$  is the equivalent chiller electricity consumption projected by model if IceBrick were not running in kWh. Note that Equation 1 will be applied when IceBrick is discharging, and when  $P_{IB}$  represents electricity consumption of only the pumps and  $P_{IB}$ peripherals required for IceBrick discharge.

$$AE = P_{FC, eq} - P_{FC, meas} - P_{IB} \quad (3)$$

Note that an alternative way to express this method for load reduction is shown in Equation 4, where  $L_{IB}$  is the thermal load that is satisfied by IceBrick in kWh,  $COP_{eq}$  is the equivalent COP projected by the model if IceBrick were not running.

$$AE = COP_{eq} * L_{IB} - P_{IB} \quad (4)$$

The cooling load reduction is then the avoided electricity divided by the equivalent chiller energy consumption under the facility chiller-only model, as in Equation 5.

$$LR = AE / P_{FC, eq} \quad (5)$$

The cooling load reduction for a given discharge event will be calculated over the duration of the discharge period, which will be the peak price period in the utility tariff in most situations. Thus, equations 1 and 4 will be a summation over the entire discharge period. Cooling load reduction will be analyzed for three submetrics: (1) The overall cooling load reduction for the site over all discharge periods available for each billing period in the data, which can be used to calculate cost savings in the following section, (2) the average cooling load reduction, and (3) the reduction in the maximum electricity demand during a 15-minute interval during select demand response events. These submetrics will be calculated for electric cooling load, either as demand or consumption, depending on the targets used when designing the IceBrick system for each particular installation.

## Electricity Cost Savings

After the cooling load reduction is determined as described in the above section, the electricity consumption of the cooling system will be isolated from the total site electricity bill. The electricity consumption data and site's electricity tariffs will be used to calculate the electricity costs in both the facility chiller only and test scenarios. Comparison between the two cases will provide electricity cost savings from the system. Electricity costs are expected to include (1) a per kilowatt hour charge for total consumption that varies throughout the day according to a time of use schedule, (2) demand charges for the maximum facility electricity consumption during a 15 minute meter interval each billing period during different time windows. If applicable to the site, wholesale revenue including RA capacity credits and VPP agreements will be included and be calculated using Equation 6 or a site-specific formula.

$$C_{kWh} = \Sigma \begin{cases} p_{kWh,retail} * P & P \geq 0 \\ p_{kWh,wholesale} * P & P < 0 \end{cases} \quad (6)$$

As an example, Southern California Edison's TOU-8 rate plan, which is used for most large commercial buildings, features demand charges for the maximum energy consumption used a 15-minute interval over the billing period in (a) peak hours, (b) off-peak hours, and (c) any hours. Since demand charges are billed over the entire site's energy consumption, the analysis will calculate the portion of the demand cost contributed by the cooling system, as shown in Equation 7, where  $P_d$  is the demand charge price at peak, offpeak, and all times; and  $\max(P_c(t))$  is the largest cooling electricity consumption of the 15-minute intervals in a billing period during peak, offpeak, or all times.

$$C_{demand} = p_{d,peak} * \max(P_c(t_{peak})) + p_{d,offpeak} * \max(P_c(t_{offpeak})) + p_{d,all} * \max(P_c(t_{all})) \quad (7)$$

For this rate structure, the total electric utility cost for cooling,  $C_c$ , is the sum of the result of Equations 6 and 7, as shown in Equation 8. Note that these equations will be adjusted to match the actual cooling electricity cost at each site based on the price structure at the site.

$$C_c = C_{kWh} + C_{demand} \quad (8)$$

Equations 6, 7, and 8 will be calculated for both the facility chiller-only model and the system with IceBrick as described in the Cooling Load Reduction section. The total electric utility costs for cooling under the facility chiller only and IceBrick scenarios,  $C_{c,FC}$  and  $C_{c,IB}$  are then compared using Equation 9 to yield the energy cost savings,  $ES$ . The costs for the facility chiller scenario will be calculated using load data  $ES$  estimated using the regression model of the facility chiller system as described in the Cooling Load Reduction section.

$$ES = C_{c,FC} - C_{c,IB} \quad (9)$$

The equations for the electricity costs at each site will be determined by the price structure at the to-be-selected GSA site and at the Beverly Hilton.

## Return on Investment

Compute annual net benefit by comparing total operating costs before and after IceBrick is installed. Then compute 1) return on investment (ROI, Equation 10) & 2) payback period (PBP, Equation 11) as the number of years of annual net benefit required to meet the entire installation cost.

$$ROI = \frac{C_{c,FC} - C_{c,IB}}{C_{Installation}} \quad (10)$$

$$PBP = \frac{C_{Installation}}{C_{c,FC} - C_{c,IB}} \quad (11)$$

Where  $C_{Installation}$  is the cost to install the system. The payback period from Equation 11 will be compared to the payback period specified by Nostromo.

Additionally, the Internal Rate of Return (IRR) will be calculated and reported, which accounts for incentives such as ITC, SGIP, and depreciation based on when incentives are paid.

## Round-Trip Efficiency

Thermal round trip efficiency (RTE) for a TES system can be calculated by the total thermal energy extracted from the IceBrick TES when discharging divided by the energy put into the TES when charging, as in Equation 12 [10].

$$RTE = \sum_{cycle} \frac{Q_{out}}{Q_{in}} \quad (12)$$

Where  $Q_{out}$  and  $Q_{in}$  are the total heat transfer (load) exiting and entering the IceBrick system and are calculated using Equation 1. RTE may be calculated over one or more charge-discharge cycles, however the period must start and end at points with equal state of charge. Details for SOC calculations are described in the Depth of Discharge section. For this analysis, RTE will be based on cumulative thermal energy over a given billing period, with adjustments made if necessary to ensure the starting and ending SOC are the same. Individual cycles from the time IceBrick begins to discharge until it recharges again to the same level may also be analyzed to determine a range of RTE for the system that can be expected in a given day.

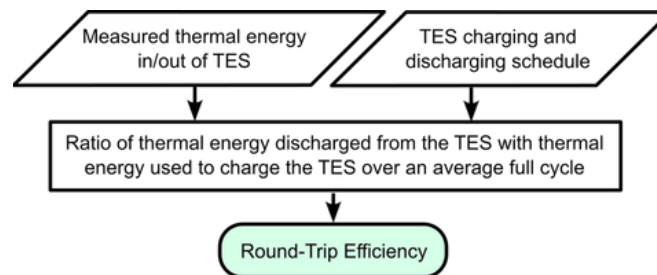


Figure 4. Process for calculating the RTE.

Note: It is also possible to calculate electrical RTE, which would account for changes in chiller COP due to adjusting the time of operation, as opposed to thermal RTE which isolates only the TES. GSA, LBNL, and Nostromo discussed the different options and the initial indication is that only thermal RTE is of interest for this study. Electrical RTE may be added or substituted upon request.

## Depth of Discharge

Depth of discharge (DOD) and state of charge (SOC) are related terms, per Equation 13.

$$DOD = (SOC_{initial} - SOC_{final}) \text{ over a discharging cycle} \quad (13)$$

State of charge analysis can be conducted using temperatures, flow rates, and power consumption through the system. Temperature and flow rate can be used to calculate the amount of heat removed from the fluid by each chiller. This accounts for any cooling done by the TES before it reaches the chiller.

State of charge can be determined through an energy balance across the glycol heat transfer fluid using the temperatures on the inlet and outlet, flow rate, and properties of the system [11]. For the system, all IceBricks will be evaluated as a single unit. First, the total thermal energy storage capacity will be determined. For the scope of this M&V, the design target set by Nostromo and the customer can be used, and then DOD will show how much of that target is met. If the theoretical maximum storage capacity is not provided and must be calculated, the recommended method is using the volume of ice in the IceBrick and the design maximum and minimum temperatures, Equation 14.

$$Q_{max} = V_{ice} c_{p,ice} (T_{fully\ discharged} - T_{fully\ charged}) \quad (14)$$

Note that there are also methods to calculate maximum thermal energy experimentally, however this would be impractical for most sites, as it would adversely affect the customer savings.

Starting with the total thermal energy storage capacity, the current state can be determined by comparing the maximum storage to the summation of all thermal energy gained or lost by the IceBrick system during a charge and discharge cycle. The net thermal energy is calculated in Equation 15 using heat transferred to the building based on flow rate through the heat exchanger and temperatures  $T_{in}$  and  $T_{out}$  on the inlet and outlet of the heat exchanger respectively [12], [13], [14].

$$Q = \sum \dot{m} c_p (T_{in} - T_{out}) \quad (15)$$

Where  $\dot{m}$  is the mass flow rate and  $C_p$  is the specific heat.

For verification purposes, this calculation can be performed for both the glycol/IceBrick and chilled water/facility sides of the heat exchanger, as shown in Equation 16.

$$Q_{facility} = Q_{IB} - Q_{losses} \quad (16)$$

Some thermal losses, represented by  $Q_{losses}$  are to be expected, however they may or may not appear in the  $Q$  resulting data depending on the efficiency of the heat exchanger and accuracy of the sensors used to record temperature and flow rate. If data for both  $Q_{facility}$  and  $Q_{IB}$  is available  $Q_{facility}$  will be used because it represents the thermal energy in the facility cooling loop that goes directly to the building.

Then state of charge is calculated as the ratio between the actual heat provided,  $Q$ , from Equation 15 and the design maximum storage capacity,  $Q_{max}$  [11]. The resulting state of charge for a given time  $t$ , while charging, assuming constant fluid properties is shown in Equation 17.

$$SOC = \frac{Q}{Q_{max}} \quad (17)$$

State of charge should always be between 0 and 1. The state of charge when discharging is calculated using Equation 18.

$$SOC=1-\frac{Q}{Q_{max}} \quad (18)$$

Finally, the depth of discharge is calculated using Equation 13. In this project, the average depth of discharge will be reported to show what portion of the TES capacity is utilized under typical operation. Maximum observed depth of discharge will also be reported and used to compare to the time-based performance metrics specified in Table 2.

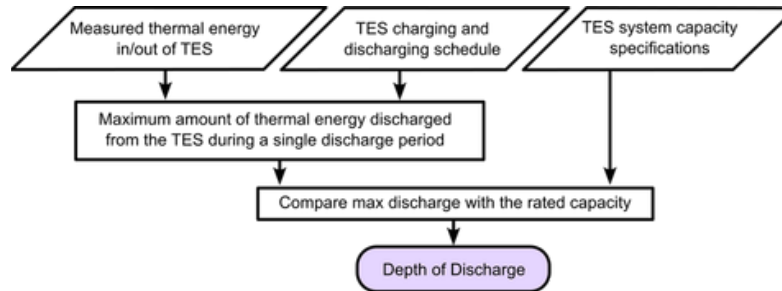


Figure 5. Process for calculating depth of discharge. Note that another method for calculating SOC is through the volumetric expansion of the storage medium during phase change [11]. Provided that there are sensors to measure volume of water or ice in the expansion tanks directly or through the increase in pressure in the tanks, then the ratio of ice and water can be determined. The amount of ice can be combined with temperature sensors throughout the IceBrick storage to determine the thermal energy stored in the system at a given time.

### Qualitative Metrics: Ease of Installation, Maintenance, and Non-Energy Benefits

Surveys will be sent to building maintenance staff and to other building staff. LBNL will create online and/or phone surveys targeted for each type of building staff who interacts with or maintains the system, such as management, repair technicians, custodial services, other building occupants, etc. Surveys will gain information about user experience, availability of resources to understand the equipment, and other impacts. Methods are adapted from the system usability and technology acceptance scores developed in [15], [16].

The first question will be a simple yes or no, asking if the respondent is aware of the IceBrick system or has noticed any disruptions in cooling/HVAC service since the date of installation. Since Nostromo’s business model involves full service, it is possible that most building staff will be unfamiliar with the system. For those who are not aware of IceBrick, the survey will end here. These responses are helpful to identify if the IceBrick is functioning without causing disruption to occupants, as non-technical staff would have no reason to interact with the system.

For respondents who are aware of the IceBrick system, further questions will ask about their reception to the system. These will be scored on a five-point Likert scale, a quantitative scale of 1 to 5, where 1 indicates strongly disagree, and 5 indicates strongly agree. Technology acceptability questions will be based on characteristics including noise, light, thermal comfort, interior design, ease of installation, disruptions due to installation and maintenance, maintenance requirements/burden, reliability, and safety [16]. System usability questions will be adapted from the System Usability Scale, and are listed in the Appendix [15][17].

# Extrapolating Results

## Incumbent Technologies for Impact and Savings Comparisons

The baseline technology is one or more central chillers without any thermal energy storage. The buildings may be able to pre-cool by a few degrees Fahrenheit but otherwise have little to no load flexibility. Peak cooling load reduction and cost savings relative to the system without IceBrick may be calculated as part of the project scope, and described in detail in the Approach to M&V section.

Costs for installing and operating the IceBrick system that will be used to determine cost savings and return on investment are listed Table 4.

Table 4. Cost Data to be Tracked During M&V

Cost Element	Data Tracked During M&V
<b>Hardware Capital Costs</b>	Component costs will be obtained from the vendor invoices for the demonstration.
<b>Installation Costs</b>	Labor and material required to install
<b>Electricity Costs</b>	Electricity consumption and corresponding cost will be monitored during the field demonstration through sensors and access to utility statements.
<b>Facility Operational Costs</b>	Facility operational costs consist of electricity and maintenance, which are tracked as part of other cost elements.
<b>Maintenance Costs</b>	Frequency of required maintenance Labor and material per maintenance action Nostromo's maintenance service fees
<b>Hardware Lifetime</b>	Any degradation during the demonstration will be recorded and extrapolated to estimate lifetime.

# Results

The analysis focuses on data from August 2024, which represents part of the peak cooling season in Southern California. To accommodate the limited resources available, metrics that don't require a baseline model were selected and examined. These preliminary results are presented here, noting that a more comprehensive analysis would be possible with additional data and resources to complete a full M&V project.

## Quantitative Results

The ice-based TES operates by storing energy (charging) during off-peak hours, then releasing the energy stored (discharging) during peak times, to reduce the load on the facility chillers. The plot in Figure 6 spans from noon on August 14 to noon on August 17 to show three complete charge-discharge cycles. The black solid line is the thermal load for the building, the blue shaded region is the portion of the thermal load met by the facility chillers, and the red shaded area is the thermal energy being supplied by or used to charge the ice TES. Two notable days in the dataset include August 14 (first day in Figure 6), a relatively low load day, and August 16 (the last day in Figure 6), the highest peak load day in the dataset, which had a special event at the site which led to increased occupancy. The TES was controlled to discharge from approximately 4-9pm each day, then recharge starting at 9pm and continuing into the next day until fully recharged.

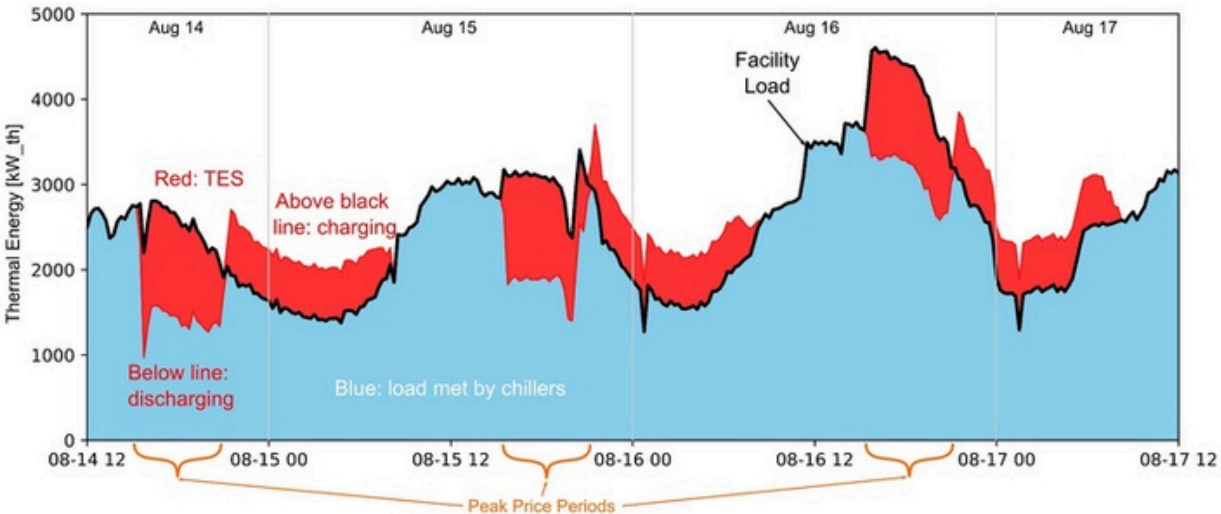


Figure 6. Thermal load to the building, chiller load, and TES charging and discharging load for three days (Aug 14-17, 2024).

The maximum cooling load reduction, see metric 1 in Table 2, was estimated by finding the largest averaged thermal power (kW\_th) discharged by the TES during a 15-minute period during the evaluated period. The maximum cooling load reduction measured during any 1 minute interval was 1746 kW\_th, on August 23, 2024 at 3:40 pm, as shown in Figure 7. The data for this analysis was averaged into 15 minute timesteps, matching the electric meter billing interval. The largest measured thermal load discharged from the TES during a 15 minute interval was 1306 kW\_th on August 7, 2024 between 3:45-4pm, as noted in Figure 8, which shows the discharging behavior of the TES for the entire evaluation period with 15 minute intervals. During the peak electricity price period of 4:00pm to 9:00pm on all days evaluated, the average cooling load reduction is 993 kW\_th.

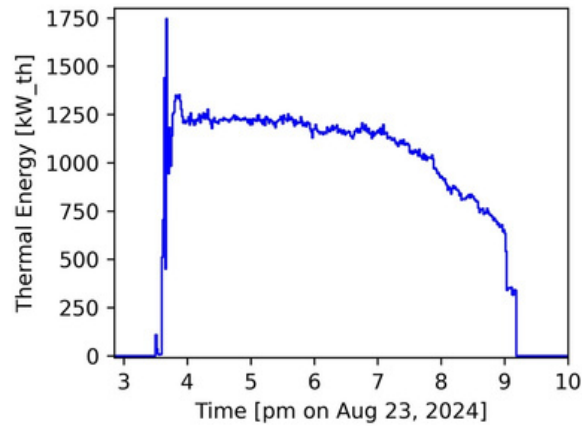


Figure 7. The maximum thermal energy discharged in a 1 minute measurement interval, 1746 kW<sub>th</sub> at 3:40pm on Aug 23, 2024.

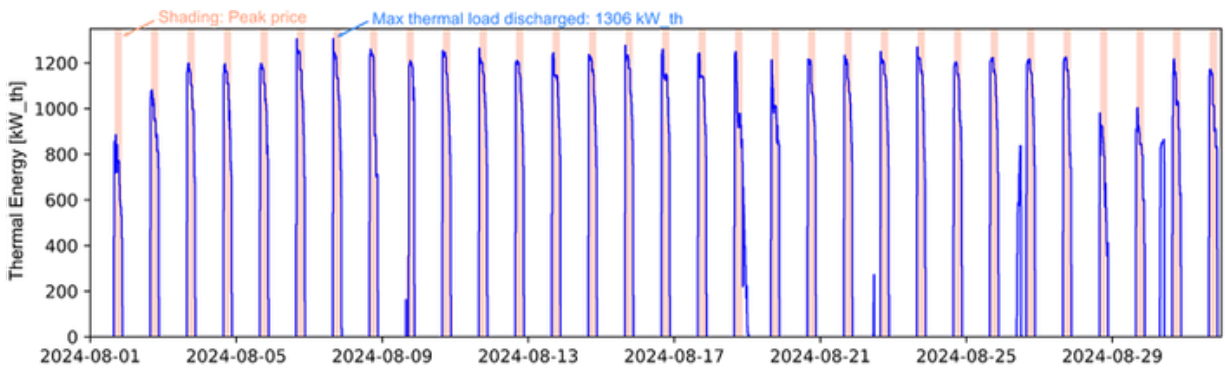


Figure 8. Thermal energy discharged from the ice TES in August 2024. The red shaded areas indicate the peak price period, 16:00-21:00.

The TES charged and discharged consistently every day for the entire month of August 2024. A total of 184,006 kWh<sub>th</sub> were provided to the TES by the charging chiller, and 173,538 kWh<sub>th</sub> was transferred from the TES to the chilled water loop of the building, for a thermal RTE of 94.3 %. Thermal RTE is discussed in metric 4, Table 2.

The depth of discharge, metric 5 in Table 2, was measured against the total specified capacity of the TES installation at the site, 6,476 kWh<sub>th</sub>. For the preliminary analysis, the assumption is that the TES is charged to full capacity, SOC = 1, before the peak period, then discharged during the peak period, for a single charge-discharge cycle every day. However, some days had multiple cycles or periods of simultaneous charging and discharging; these days were ignored for the purpose of this metric. Note that for a more thorough analysis we recommend identifying the exact state of charge at each point in time to verify that the TES is actually charged to full capacity at the start of the experiment. The maximum depth of discharge on a day with a single charge-discharge cycle was 96.8 % over 5.5 hours, and the average for all days with only a single charge-discharge cycle was 89.1 %.

Measurements of the temperature of chilled water supplied to the building show that the temperature was between 5.2 °C and 6.6 °C, with a mean of 5.9 °C and standard deviation of 0.15 °C during the TES discharge periods. During time periods when the system was being served solely by the facility chillers, the

chilled water supply temperature was an average of 5.9 °C and standard deviation of 0.20 °C although temperatures above the 5.2 °C - 6.6 °C range were seen during 0.2 % of the total evaluated time, up to 13.2 °C. The relative stability in temperature indicates that the operation of the TES is unlikely to negatively affect thermal comfort of building occupants.

An additional non-energy benefit of the TES was improved cooling system reliability, as evident from the data analyzed. On two occasions, one of the facility chillers shut down during periods of high cooling demand, leaving the remaining chiller unable to meet the building's needs on its own. We do not know if these were unexpected or planned events, but, in both cases the TES system was activated to cover the shortfall and meet the building demand. One of these events, August 26 from 09:30 to 11:53 is displayed in Figure 9. In this case the TES charging chiller was turned on as well as the TES was discharged to respond to the emergency.

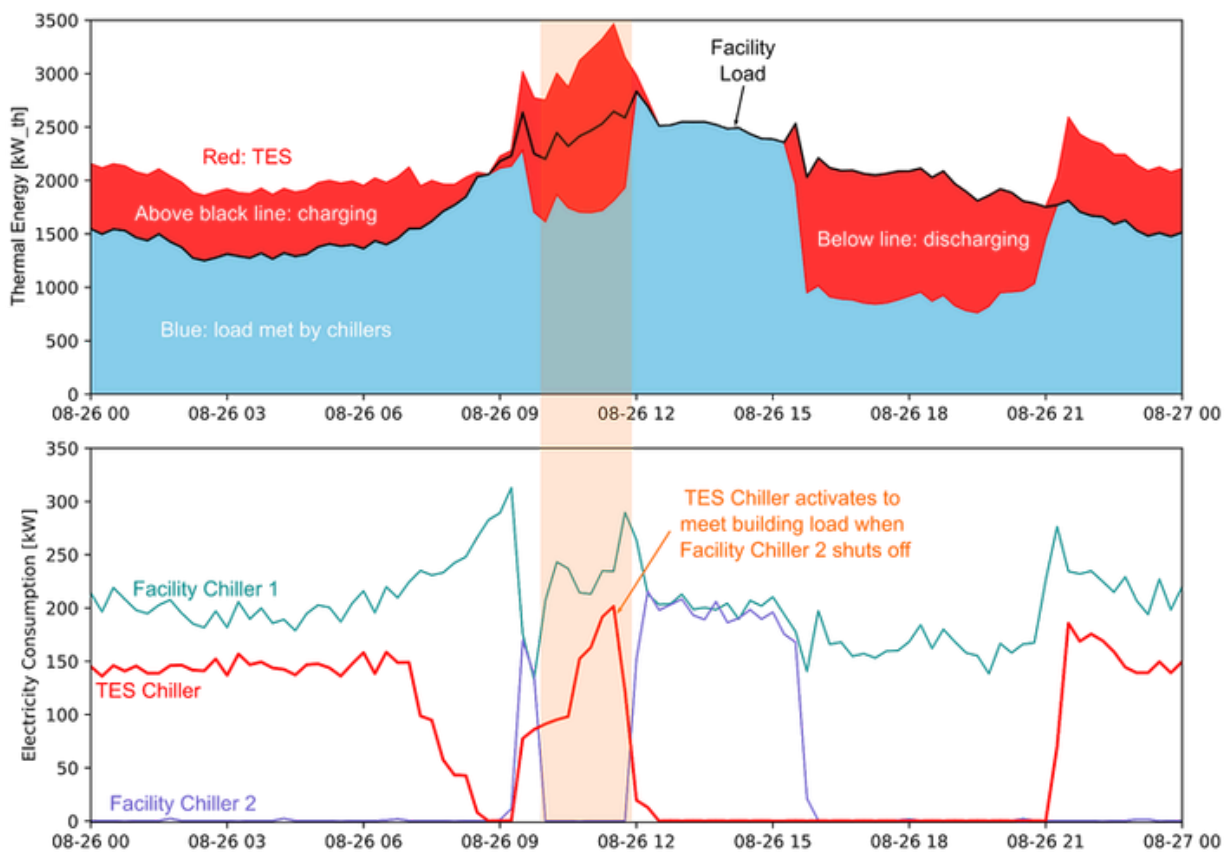


Figure 9. Period when one facility chiller is inactive and the TES chiller activates to satisfy building load. The TES chiller also charges the TES during this time.

Key quantitative findings are summarized in Table 5.

Table 5. Summary of preliminary findings over August 1-31, 2024 for the Ice TES installation at the Beverly Hilton site.

Metric	Result
Maximum cooling load reduction, thermal, 15 minute interval	1,306 kW_th
Maximum cooling load reduction, thermal, instantaneous (1 min interval)	1,746 kW_th
Average cooling load reduction during peak period, thermal	993 kW_th
Average percentage of facility cooling load provided during peak period	38.2 %
Thermal RTE	94.3 %
Maximum depth of discharge	96.8 %
Average depth of discharge	89.1 %
Duration of Ice TES chiller directly supplying building load in place of inactive facility chiller	5.5 hours

## Qualitative Results

While planned surveys, interviews, and other qualitative research activities were not possible, due to the project ending early, a site visit to the existing field installation on December 9, 2024, provided some insights on the system operation. The TES system is installed in a basement area, out of the normal occupied section of the hotel. The vendor noted that the ice storage units were initially considered for installation on the building roof, however the building owner requested to keep it in a single location to use it as a showcase of the technology and help promote the hotel to customers interested in these technologies. According to the vendor, the system is unnoticeable to regular building occupants and does not impose additional maintenance burdens, while also providing valuable data and monitoring capabilities for the cooling system. A vendor representative noted that all system components were easily transported into the installation location through a standard-sized door and hallway, as shown in Figure 10.

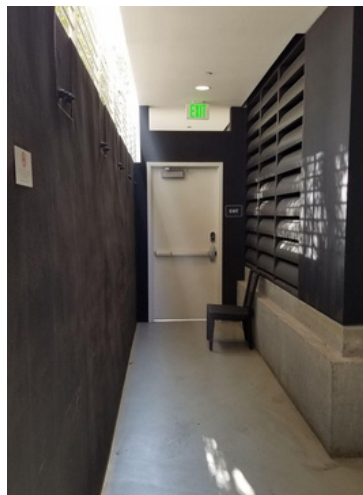


Figure 10. The door and hallway through which all components were brought into the installation site.

Compared to the facility chillers, the TES modules and charging chiller, pictured in Figure 11, were quieter. Though decibel level was not measured, when the system was in idle mode, visitors including GSA and LBNL

staff were able to conduct a conversation while speaking at a normal volume. There were informational placards posted to explain the function of different components.



Figure 11. The pipes leading to the IceBricks and the charging chiller.

There were multiple screens and displays on equipment that showed the current operating status, one which enabled building staff to control and override the system through a “manual” setting, shown in Figure 12. Such displays were useful to help visitors understand the system and provide transparency that may increase trust in the system with building staff.

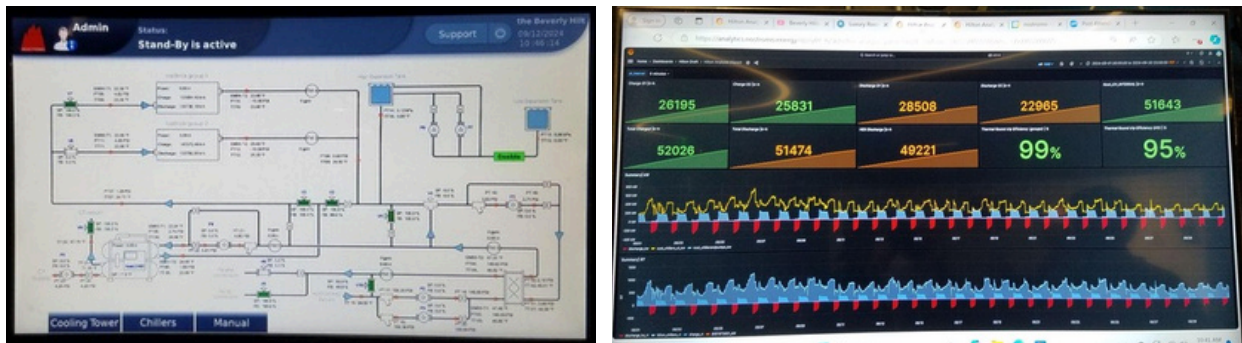


Figure 12. Control and monitoring screens at the field installation.

Note that these insights are based on inferences from a single field site visit, and should not be considered as a substitute for results obtained from surveys, interviews, and other sources as described in the M&V plan.

# Conclusion

## Summary of Findings

This project achieved the following objectives: (1) developed a M&V plan for an ice-based TES system such as Nostromo IceBrick for large commercial buildings; (2) identified key factors when selecting installation sites; and (3) performed preliminary analysis of a system previously installed at a large hotel in Beverly Hills, CA. Analysis of site data for the month of August 2024 showed that the system effectively reduced the thermal load on the facility chillers during the daily 5 hour peak period. Additionally it provided a stable chilled water supply temperature to the building during TES operation, and met performance targets for depth of discharge and round trip efficiency. The analysis also uncovered additional reliability benefits, as the TES and the charging chiller can serve as a backup source of cooling for the facility chillers.

Although the findings are promising, they are still preliminary. To gain a deeper understanding of the technology's year-round performance, we recommend completing analysis at the existing site and conducting a follow-up study at an additional site, using the M&V plan developed for this project. This would enable a comprehensive assessment, including a full quantification of the economic benefits, identification of installation barriers, and evaluation of the technology's impacts on facility maintenance and occupants, ultimately increasing confidence in the technology among building managers and grid operators.

## Lessons Learned and Best Practices

The installation of sensors required for M&V during design and commissioning of the system at the existing field site allowed for ongoing monitoring and some initial analysis early in the project. Key sensors and data points listed in the Appendix can continue to be installed in early deployments when economically and practically feasible to allow for future M&V projects.

Systems do not need to be sized to entirely meet peak load to create some value for the customer. The existing field installation was undersized relative to peak loads; in the period examined, it provided an average of 38.3 % of the thermal load during the peak period. For this installation the system was sized based on available space in the demonstration room, not sized to provide full peak load reduction. Future work could include conducting analysis on M&V results of initial installations to create an independently verified tool to model and estimate the return on investment for potential new sites to help building managers make informed, economically beneficial decisions.

An open line of communication between the vendor and M&V team led to more valuable findings and increased confidence in the results. Being able to get clarification on mapping of datapoints, access to data acquisition, information about known issues and an explanation of the vendor's understanding of how the system operates provided a good starting point for the analysis. Maintaining direct collaboration is recommended for potential future projects.

## Deployment Recommendations

These deployment recommendations are based on a series of conversations with the vendor combined with LBNL's expertise. The system is suitable for deployment in both new construction and retrofit with the key technical requirement being a building with a chilled water cooling system.

Economically, the building must have a time-varying electricity rate with significant variation between peak and off-peak electric prices, peak demand charges, and/or ability to participate in the wholesale market as a VPP, as well as cooling loads during the peak price periods. Additional site selection considerations are outlined in the Site Criteria section. These recommendations should be further validated through a more comprehensive project.

# Appendices

## Data Sources

The existing field site at the Beverly Hilton has pre-existing and fully commissioned M&V instrumentation configured by the vendor and the field site operations. LBNL obtained access to this data to complete the initial evaluation. This field site cannot be shut down or significantly modified in order to install additional monitoring equipment, and LBNL performed analysis using only existing data.

Table A1 shows the instrumentation that would be installed in an ideal site for M&V. “Entire study duration” refers to data with at least one summer and shoulder season before and after installation of IceBrick, and ideally one year before and after. “Post-install” is data collected for at least one summer and shoulder season and ideally an entire year after the installation of IceBrick.

\*Indicates preferred monitoring points

\*\*indicates backup or alternative monitoring points if the preferred ones are not available

+ indicates data points that the team has confirmed are available at the Beverly field site. However time range, accuracy, and reliability of these have not been confirmed.

Table A1. Monitoring Points and Instrumentation

Monitoring Point	Logging Equipment Description	Location	Collection Period
+Electricity consumption of the charging chiller, facility chillers, pumps, and control equipment.	Electricity meters on equipment. Total energy consumption (kWh) per period preferred, or power with 1 minute timestep.	In controls or power connections to each facility chiller and the charging & support chiller.	At least one summer and shoulder season before and after installation of IceBrick. Ideally one year before and after.
* Indoor air temperature (optional, allows for verification that demand is met)	Thermostat or building automation system sensors used for existing controls. 1 minute or smaller timestep preferred.	At least one per thermal zone in the HVAC distribution system	Entire study duration
+Operation mode of IceBrick system	From eNvoy control system. 1 minute or smaller timestep preferred.	eNvoy control system	Post-install

Monitoring Point	Logging Equipment Description	Location	Collection Period
+Temperature of fluid in the supply and return lines	Temperature sensors. 1 minute or smaller timestep preferred.	On the supply and return lines from the IceBrick, each facility chiller, the charging and support chiller, the heat exchanger, and to the building.	Facility chillers: entire study duration. IceBrick and heat exchanger: post-install
+Flow rate through each supply or return line	Flow meters. 1 minute or smaller timestep preferred.	On either the supply or the return line to each chiller, to the heat exchanger, and to the IceBrick.	Facility chillers: entire study duration. IceBrick and heat exchanger: post-install
+Thermal energy measurements	Calculated using combination of flow and temperature sensors	Charging chiller, IceBrick, heat exchanger to facility chiller lines, facility chiller, cooling lines to facility	Facility chillers: entire study duration. IceBrick and components added by Nostromo: post-install
*Outdoor air temperature, relative humidity, solar radiation	Weather monitoring equipment	Exterior of building	Entire study duration
**Historical weather data from nearest weather station	N/A	Within region	Entire study duration

# User Survey

## System Usability Questions

The System Usability Scale (SUS) yields a score from 0 to 100 based on ten questions and is based on [15][17][17]. Respondents rank each of the following using a five point Likert scale.

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

$$SUS = 2.5 * [20 + \Sigma(\text{odd numbered questions}) - \Sigma(\text{even numbered questions})]$$

## Technology Acceptance Questions

Technology acceptance questions are based on the technology acceptance model [17][18]

1. What is your role in the building? (Open response)
2. How long have you been in your current role? (Open response)
3. The building is consistently maintained at a comfortable temperature. (1-5)
4. Have you noticed any change in how the building maintains comfortable temperatures since <date of commissioning>? (Much worse/slightly worse/the same/slightly better/much better)
5. How familiar are you with thermal energy storage systems? 1 (Not Familiar) to 5 (Very Familiar)
6. Have you heard of the Nostromo IceBrick system? (Yes/no)
  - a. if no: end survey.

Rate the following from 1 (Very Negative) to 5 (Very Positive)

7. How would you rate your overall impression of the IceBrick system?
8. How would you rate the system's impact on your building's operations?

Indicate how you feel about the following, from 1-5, where 1 is "strongly disagree" and 5 is "strongly agree". If you do not know about a particular aspect, leave it blank.

9. The IceBrick system does not detract from the building's appearance or aesthetics.

10. The IceBrick system does not create noticeable noise or vibration.
11. I am satisfied with the IceBrick system.
12. I would recommend Nostromo and the IceBrick system to others.
13. Do you work directly with the IceBrick system? (yes/no)
  - a. If no: end survey.
14. The training and instructions provided were sufficient for me to work with the IceBrick system.
15. The control system is user-friendly and easy to understand.
16. The IceBrick system has reduced the cost of building operation related to HVAC.
17. The IceBrick system is reliable and has improved chiller system reliability.
18. The maintenance requirements of the Nostromo IceBrick system are reasonable and do not burden my workload.
19. Maintenance of the IceBrick system causes minimal disruption to building operations.
20. Nostromo's technical support is responsive and helpful.
21. Nostromo responded to design criteria such as desired utility bill savings, limited availability of space to store IceBrick, or scheduling challenges when designing the IceBrick system.
22. Nostromo led the design and installation process with minimal involvement from our team.
23. Installation caused minimal disruption.
24. I feel safe working around the Nostromo IceBrick system.

## References

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## Manufacturer Cut Sheet

Please refer to Nostromo IceBrick Technical System Specifications:

[https://assets.ctfassets.net/mkpd5031oeke/45NRxwKYDKtPPAPMCMGwsD/7e2902f05df99f4a9d872a5eeafae6a5/Nostromo\\_1-pager\\_Icebrick\\_2\\_1\\_.pdf](https://assets.ctfassets.net/mkpd5031oeke/45NRxwKYDKtPPAPMCMGwsD/7e2902f05df99f4a9d872a5eeafae6a5/Nostromo_1-pager_Icebrick_2_1_.pdf)