Case Study: NREL Campus Chilled Water Storage Potential

Benchmark Datasets Development and Applications, Task 4 - Use Case Demonstration

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National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
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Cover Photos by Dennis Schroeder: (clockwise, left to right) NREL 51934, NREL 45897, NREL 42160, NREL 45891, NREL 48097, NREL 46526.

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1 Introduction

1.1 Background

The Benchmark Datasets Development and Applications project is a three-year collaboration between the National Renewable Energy Laboratory (NREL), Oak Ridge National Laboratory, Pacific Northwest National Laboratory, and Lawrence Berkeley National Laboratory. The project seeks to collect and curate high-resolution, well-calibrated time series of building operational and indoor/outdoor environmental data, which are crucial to understanding and optimizing building energy efficiency performance and demand flexibility capabilities as well as benchmarking energy algorithms. The data are obtained by identifying and processing suitable existing datasets and by launching new instrumentation efforts. The target datasets are carefully selected to have adequate data coverage, resolution, and quality to support crucial use cases including system-level building energy benchmarking and analysis, building energy model calibration, load shape analysis and forecasting, and control optimization. The data are ultimately represented in an enhanced common metadata schema and hosted in a data portal for open access. This project builds upon an initial Fiscal Year 2019 scoping effort that focused on inventorying existing building datasets to identify resources that can be used, characterizing potential use cases for building datasets, and exploring the gaps in the existing data representation tools. Project outcomes include approximately twelve high-fidelity building datasets, enhanced data representation tools, and four case studies to illustrate example applications. The goal of these case studies is to define and execute analyses that demonstrate how one or more datasets collected through this project can address a data gap or challenge historically faced by building stakeholders. This document summarizes the findings of one of these case studies, in which we studied the operational efficiencies of the central cooling system at NREL. Major tasks include analysis of the effects of capacity on operational efficiency and the potential benefits of adding thermal energy storage (TES) to the central plant.

1.2 NREL Campus Chilled Water Plant

The NREL campus has two central thermal plants located at the Field Test Laboratory Building (FTLB) and Solar Energy Research Facility (SERF). The chillers are named after the building in which they are located, but the “plant” serves the whole NREL campus for space cooling, equipment cooling and high-performance computing cooling, and so forth. The FTLB plant has three chillers with a total capacity of 1050 tons and provides cooling for seven buildings (FTLB, Outdoor Test Facility, Thermal Test Facility, Alternative Fuels User Facility, Process Development Unit, Biotechnology Research Facility, and Integrated Biorefinery Research Facility), and the East Campus. The SERF central plant with a total cooling capacity of 1250 tons serves SERF, Science and Technology Facility, and the East Campus buildings. Table 1 summarizes the capacity of each chiller in FTLB and SERF.

The SERF plant has been undergoing a chiller upgrade project to replace chillers 1, 2, and 3 with two new 475-ton chillers. The upgrade process was not completed prior to this case study, and as a result we decided to exclude the SERF chillers and focus on the FTLB chillers only.

Table 1. NREL Campus Chilled Water Systems and Nominal Capacity

FTLB Chillers	Capacity	SERF Chillers (excluded from analysis)	Capacity
Chiller 1	300 tons	Chiller 1	215 tons
Chiller 2	300 tons	Chiller 2	215 tons
Chiller 3	450 tons	Chiller 3	400 tons
		Chiller 4	400 tons

The one-line diagram in Figure 1 shows how the chilled water is distributed into the East and West Campus buildings. The building automation system is used for controlling their operation and the data are continuously stored in the NREL's energy management information system (EMIS) platform.

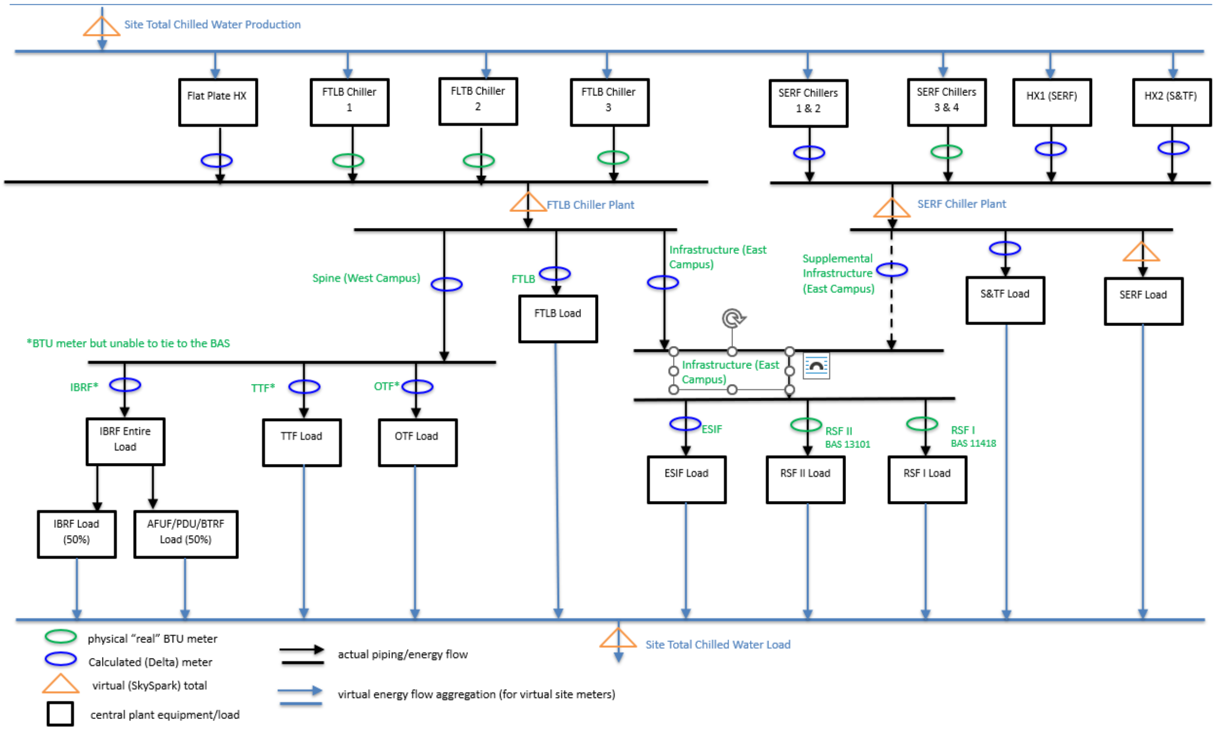

Figure 1. NREL central plant chilled water distribution

For this case study we chose to analyze time-series data collected from NREL's chilled water central plant. We looked at three years of data from the three FTLB chillers, from 2019 to 2021, to compare equipment operation and demand throughout the time period.

1.3 Scope of the Chilled Water Storage Case Study

NREL site operations was interested in analysis to improve chiller system performance by investigating the potential savings of integrating chilled water storage into the system to counter high cooling demand on campus. Our primary research questions were focused on improvements related to operation controls and TES:

- Is increased capacity needed to improve the performance of the central plant?
- What is the potential saving from load shifting using TES?
- What size TES system would be appropriate to add and what is the estimated cost?
- What is the potential for improved operational efficiency of chillers using staging and sequencing controls?

The goal of this exercise was to make a preliminary assessment of the current operation of the equipment using the detailed campus metering data, and then to determine whether the incorporation of chilled water storage at NREL merits further investigation.

2 Data

2.1 Data Overview

The data related to NREL campus chilled water plants are stored and managed through the whole-campus data management system built upon the EMIS platform. Table 2 lists all data points related to chillers.

Table 2. Available Data Points for FTLB Chillers

ID	Data Name	Units	Description	Type	Time Range and Resolution
1 & 2	CHW Energy Rate	kBTU/h	Chilled water energy rate	Calculated	2019/01/22 – 2021/12/31 Interval: 1 hour
	CHW Flow	gpm	Chilled water flow rate	Measured	
	CHWRT	°F	Chilled water return temperature	Measured	
	CHWST	°F	Chilled water supply temperature	Measured	
	CHLR Elec Power	kW	Chiller electric power	Measured	
	CHLR Load	%	Chiller percent load with respect to max power	Measured	
3	CHW Energy Rate	kBTU/h	Chilled water energy rate	Calculated	
	CHW Flow	gpm	Chilled water flow rate	Measured	
	CHWRT	°F	Chilled water return temperature	Measured	
	CHWST	°F	Chilled water supply temperature	Measured	
	CHLR Load	%	Percent load with respect to max power	Measured	

There are dedicated BTU meters for cooling load measurements of the chillers (reported as “CHW Energy Rate”) The input powers (“CHLR Elec Power”) and percentage load (“CHLR Load”) are reported directly from the device by several chillers (Chillers 1 & 2 of FTLB). However, Chiller 3 of FTLB only reports percentage load with respect to max electric power. In the building automation system, each chiller’s BACnet interface reports “percentage full load amperage,” which is mapped to the “Load” in the EMIS. As indicated in Figure 2, there is a linear correlation between the percentage load and input power of chiller 2 in FTLB. This correlation helps us to estimate the actual power of chiller 3 using the measured percentage load of chiller 3 and its rated /design power.

Figure 2. Correlation between FTLB Chiller 2 CHLR Elec Power and CHLR Load

Finally, we can use the measured or inferred input power and measured output power to perform efficiency analysis on the target chillers (see details in Section 3).

2.2 Data Pre-Analysis

The data time range covers three years from 2019 to 2021, a time period that includes a whole-campus transition in early 2020 from normal office and lab loads to low-occupancy or equipment-only loads due to the COVID-19 pandemic. By investigating the load profile, we observed that the total cooling load of the campus in 2020 (Figure 3), served by FTLB, dropped by 38% from 18,175 MBTU in 2019 to 11,240 MBTU in 2020 because of lower occupancy.

In contrast to the difference in cooling load, the difference between peak values for power usage between 2019 and 2020 is not significant. The data from FTLB chiller plant shows considerable differences between peak values and average values in every month, which makes it a good candidate for the application of TES.

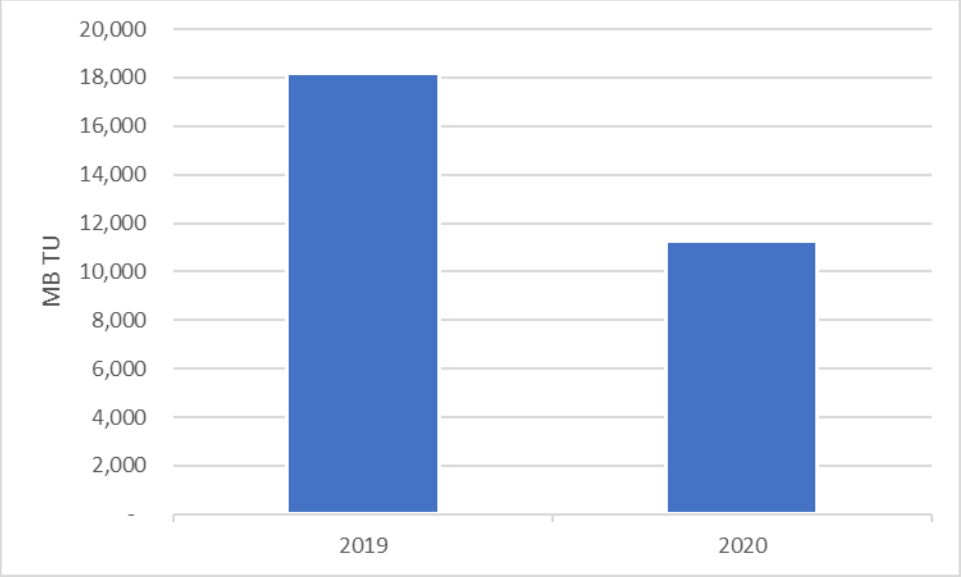

Figure 3. Comparison of FTLB cooling load in 2019 and 2020

During the evaluation of the data, we observed a data quality issue, and we performed data filtering before performing the data analysis discussed in Section 3.2. The data filtering included:

- Excluding negative cooling load and power readings
- Zeroing power readings corresponding to zero cooling load readings.

The EMIS system has cooling load and power consumption data for Chiller 1 and Chiller 2, but it only has cooling load information for Chiller 3. As indicated in Figure 2, there is a linear correlation between power and percentage loading, and we used this approach to estimate the power consumption as indicated in Equation 1. Chiller 3 has a rated power of 258 kW.

$$\boldsymbol{Electric\ Power\ (kW) = Rated\ Power\ (kW) * Percent\ Loading} \qquad (1)$$

A metadata file was then generated for the data, and the data was organized and uploaded to the Benchmark Datasets Data Portal.[1]

3 Analysis Approach and Results

3.1 Chiller Efficiency Analysis

To maximize energy efficiency in a multiple-chiller system, understanding both the chiller-level and system-level performance is essential. In this study, we analyzed three years of time-series data (2019, 2020, and 2021) for Chillers 1 and 2, and two years of data (2019 and 2020) for Chiller 3, to evaluate the operation of the central plant chilled water system. Figure 4 through Figure 6 show how the coefficient of performance (COP), Equation 2, for the three FTLB central

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[1] https://bbd.labworks.org/

plant chillers changes with part load ration (PLR), Equation 3. PLR is a ratio that indicates how much the chiller is loaded compared to its design cooling capacity. Studying chiller performance at partial loads is very important as chillers rarely run at their nominal load (only a few hours per day). In general, chillers have a specific range of PLR where they operate most efficiently. Using control strategies that take this concept into consideration during chiller sequencing and staging could significantly improve the system efficiency.

$$\boldsymbol{COP} = \frac{\textit{Cooling Produced } (kW)}{\textit{Power Input } (kW)} \tag{2}$$

$$\boldsymbol{PLR} = \frac{\textit{Cooling Produced } (kW)}{\textit{Design Cooling Capacity } (kW)} * \mathbf{100} \tag{3}$$

Figure 4. Chiller 1 performance

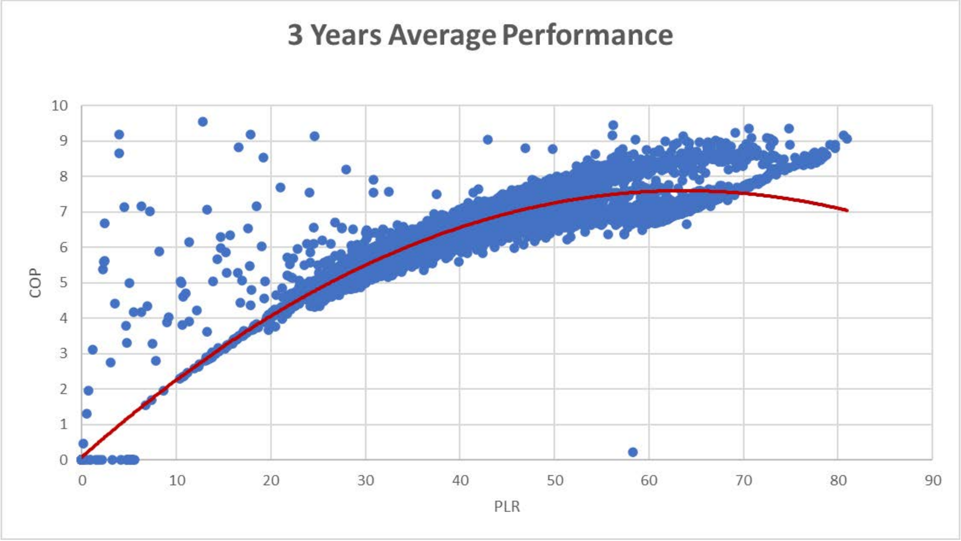

Figure 5. Chiller 2 performance

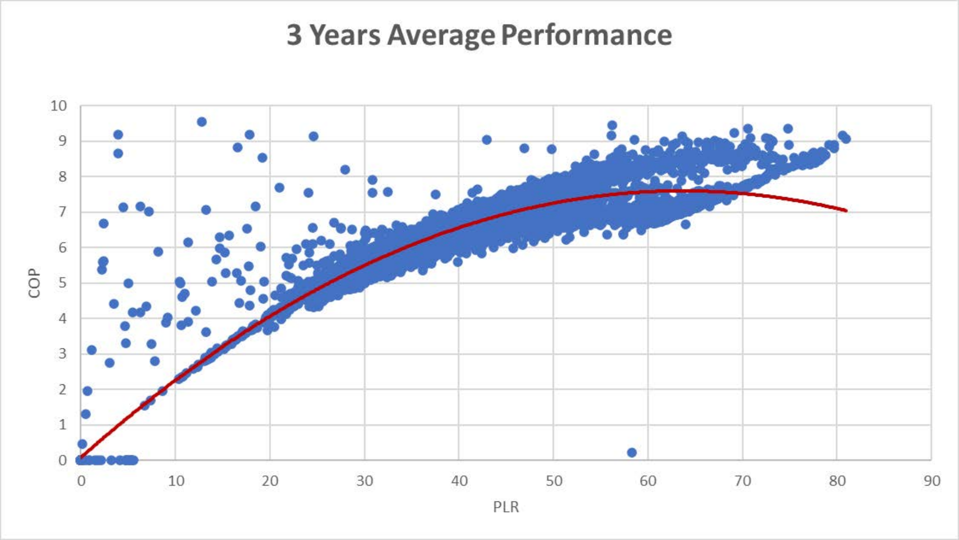

Figure 6. Chiller 3 performance

As shown in the figures, the PLR values that correspond to peak COP differ from chiller to chiller—71% for Chiller 1, 62% for Chiller 2, and 86% for Chiller 3. Table 3 summarizes the proportion of time where the chillers were operating at or above the peak value.

Table 3. Percentage of Chiller Operation Hours Above the Peak COP

FTLB Chiller	% Operation Time Above Optimal COP Value
1	3%
2	10%
3	2%

As indicated in the table, the chiller loads reflected a PLR lower than the PLR corresponding to the peak COP for most of the time. The most likely explanation is that a capacity upgrade is not a pressing need for the central plant. (It is also possible that the cooling towers do not have enough capacity to reject the full heat load of all three chillers, or that the system flow rates are not optimized in a way that allows the chillers to run at full output.) When there is a need for more cooling, the chiller is expected to load more, even if loading them close to their full capacity comes with a drop in efficiency. However, the data show that this rarely happens. Instead, the chillers were loaded below the PLR associated with peak COP, which indicates room for improvement in the control logic. Instead of running multiple chillers at a low PLR, higher system efficiency could be achieved by running fewer chillers at higher PLRs corresponding to peak COPs.

3.2 Analysis: Adding Thermal Energy Storage

TES systems are useful in many commercial and industrial facilities to shift cooling energy use to nonpeak times. Application of TES is more economically feasible when the maximum cooling load is significantly higher than average load. High demand charges, and a significant differential between on- and off-peak rates, also help make TES systems economic. Besides shifting load, TES systems are also used to reduce energy consumption, depending on site-specific design, notably where chillers can be operated at their most efficient PLR during the night.

In this study, we analyzed the potential savings from load shifting using TES. We used the Xcel primary general rate structure, summarized in Table 4. In addition to providing peak demand saving by shaving electric demand during peak hours, the TES also provides energy consumption charge reduction by shifting the energy consumption from on-peak hours to off-peak hours.

Table 4. Xcel Energy Rate Structure[2]

Xcel Energy Primary General	Electrical Energy Rate	Demand Charge Rate	
On-Peak Hours: 9am–5pm	$ 0.0419/kWh	$ 23.75/kW Summer	$ 18.12/kW Winter
Off-Peak Hours: Other hours	$ 0.0310/kWh		

3.2.1 Estimated Peak Shaving Capability and Savings

One critical question to be addressed during TES design is the amount of load that could be shifted to off-peak periods. This has implications for both cost savings and TES sizing. To estimate the load shifting, we used a month-by-month approach as the peak demand charge is based on monthly peak kW use. For each month, we estimated the maximum possible cooling load that could be iteratively shaved. Note that the peak demand saving is estimated based on the chillers peak demand, not on the campus peak demand. We used the following steps for estimating this percentage:

1. Find the maximum cooling load in each month
2. Start with a shaving percentage of 50%
3. Accumulate the cooling loads above the shaved peak for each day
4. Distribute the accumulated cooling loads to hours with lower cooling load than the shaved peak
5. If the accumulated cooling load in each day is not fully distributed to hours with lower cooling load in the same day, return to step 2 and decrease the shaving percentage

Figure 7 shows the comparison of the actual cooling load and the estimated cooling load with TES for 2019 and 2020 data. The peaks are different for each month, which will provide different savings in peak demand (kW). Operating the chillers in off-peak hours also resulted in extra savings in energy consumption (kWh). Figure 8 and Figure 9 show comparisons of the monthly peak power demands with and without addition of TES for 2019 and 2020.

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[2] https://www.xcelenergy.com/staticfiles/xe-responsive/Company/Rates%20&%20Regulations/Regulatory%20Filings/PSCo_Electric_Entire_Tariff.pdf

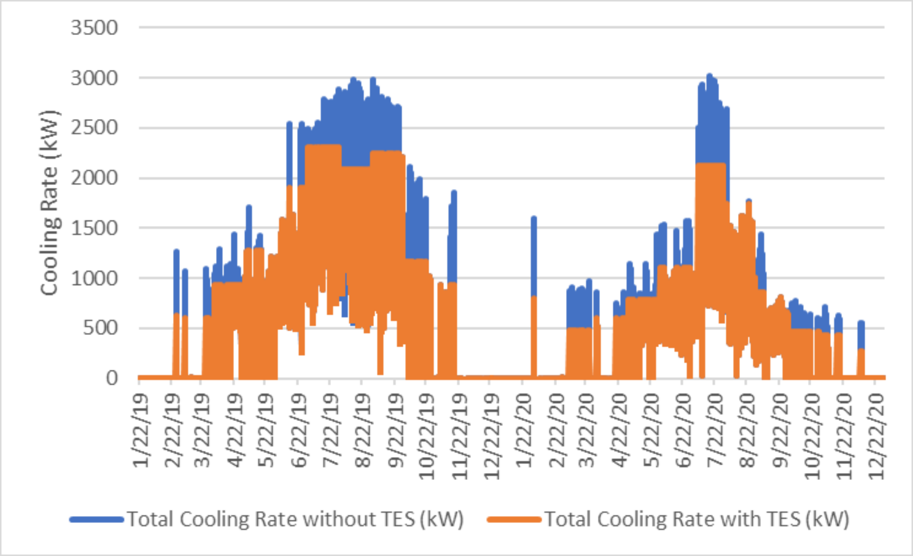

Figure 7. Cooling load with and without TES

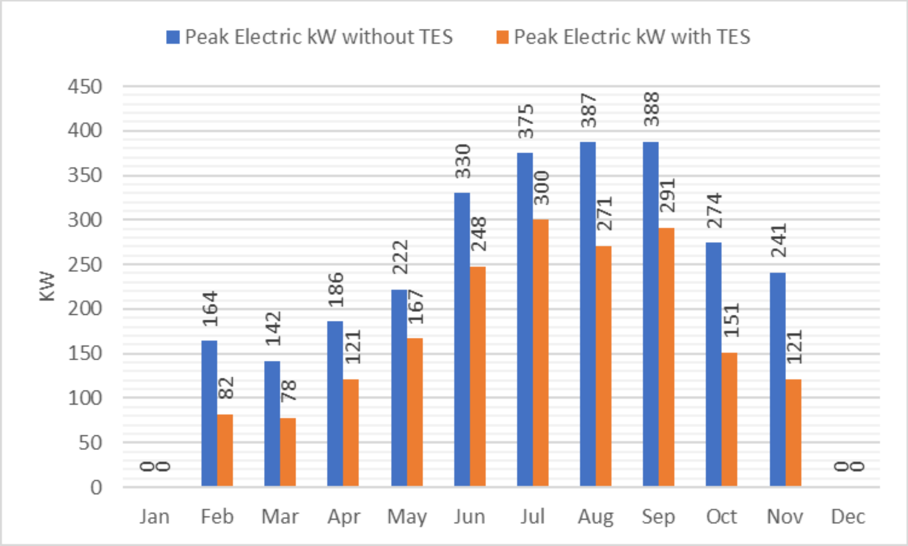

Figure 8. 2019 monthly peak power demand with and without TES

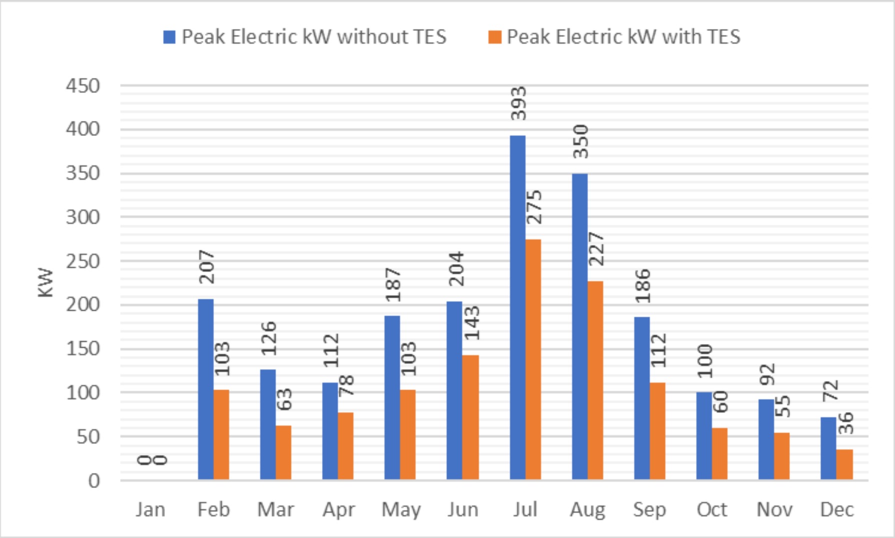

Figure 9. 2020 monthly peak power demand with and without TES

Table 5 shows monthly peak electric demand (kW) and total electric consumption (kWh) with and without TES for the years 2019 and 2020 respectively.

Table 5. Monthly Peak kW and Total Electric Consumption

Month	Peak Electric kW Without TES 2019	Peak Electric kW With TES 2019	Peak Electric kW Without TES 2020	Peak Electric kW With TES 2020
Jan	0	0	0	0
Feb	164	82	207	103
Mar	142	78	126	63
Apr	186	121	112	78
May	222	167	187	103
Jun	330	248	204	143
Jul	375	300	393	275
Aug	387	271	350	227
Sep	388	291	186	112
Oct	274	151	100	60
Nov	241	121	92	55
Dec	0	0	72	36

Table 6 summarizes the savings in power demand and consumption. The total saving from the two years data was $34,709 which is equivalent to 24.5% of the total energy cost. Most of the saving comes from reducing the peak demand. Further savings than what is indicated in Table 6 could be achieved by upgrading the control strategy to do more TES charging during night, when the chillers are more efficient due to lower condenser temperatures because of lower outdoor temperatures.

Table 6. Electricity Charge Savings Comparison Over Two Years

Metric	Electrical Energy (based on kWh consumed)	Demand Charge (based on kW demand)	Total Cost (consumption charge + demand charge)
Baseline (without TES)	$40,972	$100,584	$141,556
With TES	$40,431	$66,416	$106,847
$ Savings	$541	$34,168	$34,709
% Savings	1.3%	34%	24.5%

3.2.2 Thermal Energy Storage System Sizing and Cost

TES is sized based on the maximum accumulated cooling demand above the capped cooling demand after application of the shaving percentage discussed in Section 3.2.1. Unlike other storage systems such as the battery, TES has an excellent roundtrip efficiency, or the percentage of electricity put into storage that is later retrieved. In this study, sizing assumptions are based on 100% roundtrip efficiency.[3] A more detailed investigation would be needed to calculate more realistic roundtrip efficiency values, but this was outside the scope of this study. Using 132 gallons of water per ton-h cooling,[4] we estimated the TES size as 254,000 gallons. Table 7 summarizes the values used.

Table 7. Thermal Energy Storage Sizing

Metric	Storage Size
Maximum accumulated cooling demand per day	6749 kW-h (1919 ton-h)
TES sizing assumption	132 gallons/ton-h
TES size	254,000 gallons

For chilled water TES, the storage tank is typically the single largest cost. The installed cost for chilled water tanks typically ranges from $100 to $200 per ton-hour.[5] Costs decline as capacity increases but can vary significantly based on the design temperature difference, tank material, shape, insulation, foundation design, site soil conditions, local labor costs, and special aesthetic considerations.

Using the $100–$200 per ton assumption, TES for the central plant would cost $192,000 to $384,000, offering a payback period of 11 to 22 years.

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[3] https://www.dntanks.com/wp-content/uploads/2016/07/DN_Tanks_TES_Data_Sheet.pdf

[4] https://www.cedengineering.com/userfiles/Air%20Conditioning%20with%20Thermal%20Energy%20Storage%20R1.pdf

[5] https://www.energy.gov/sites/default/files/2021/03/f83/Thermal_Energy_Storage_Fact_Sheet.pdf

4 Conclusions and Future Work

This case study shows how a selected dataset is used to solve a practical building problem—learning the operational status of its components, analyzing the effectiveness of a proposed new technique, and aiding decision-making for the building operations and maintenance team. The study demonstrates the capabilities of the BBD project in building applications where building datasets are curated, inventoried, and fitted in characterized use cases.

The data analysis indicated that all three chillers are operating at or below the optimal loading conditions for most of the operation time. This is an indication that there was no efficiency drop due to loading of the chillers at full capacity. This answers one of the research questions—whether capacity increase is needed to boost the efficiency of the central plant. Our recommendation is that no chiller capacity increase is needed; instead, the central plant could benefit from adopting advanced control logics for optimal sequencing of chillers during part load operations.

Analysis of adding chilled water thermal storage to the central plant indicated significant savings. Peak demand shaving is the major factor contributing to savings, while some savings were also obtained from charging during off-peak hours. The analysis shows 34% savings in demand cost and 24.5% savings in total cost (energy consumption and demand charge cost). The payback period is estimated to be 11–22 years with an assumed TES cost of $100–$200 per ton.

The case study is limited to part of the central plant of the NREL campus due to the chiller upgrade work currently underway for SERF chillers; therefore, we could not show whole-campus-level chilled water storage opportunities. The indicated payback period could be shortened if it is designed to include the SERF chiller loads. However, the study workflow and results of chiller performance and saving analysis could serve as a good starting point for further investigation. The study will be shared and discussed with the NREL campus site operator to gain more feedback about next steps.

The next major step will be integrating advanced control algorithms for chiller sequencing in the study. Chilled water storage could grant potential extra load shifting capability and energy savings via optimized controls including staging and sequencing control, demand response strategy, and load prediction capabilities. This would require developing performance models for COP based on PLR and temperatures (both chilled water supply temperature and condenser water supply temperature). In the absence of these data, it should be possible to develop maps of operating conditions that are optimal for each combination of chillers.