

Techno-Economic Analysis for Addition of a Thermal Energy Storage System to a Central Plant

1 **Korbaga Woldekidan¹**

2 National Renewable Energy Laboratory
3 15013 Denver W Pkwy, Golden, CO 80401 USA
4 korbaga.woldekidan@nrel.gov

5

6 **Carlo Bianchi**

7 National Renewable Energy Laboratory
8 15013 Denver W Pkwy, Golden, CO 80401 USA
9 Carlo.Bianchi@nrel.gov

10

11 **Zahra Fallahi**

12 University of Colorado Boulder
13 Boulder, Colorado 80309-0428 USA
14 Zahra.Fallahi@Colorado.edu

15

16 **Tim J. LaClair**

17 National Renewable Energy Laboratory
18 15013 Denver W Pkwy, Golden, CO 80401 USA
19 Tim.LaClair@nrel.gov

20

21

22 **Abstract**

23 *Increasing energy demand and rising peak loads present significant challenges for energy*
24 *management in commercial and institutional settings. As climate change drives greater cooling*
25 *needs, central plants must navigate the complex trade-offs between operational efficiency, cost*
26 *control, and grid stability. Thermal Energy Storage (TES) systems offer a viable solution by shifting*
27 *energy consumption from peak to off-peak periods, thereby reducing peak demand, lowering utility*

¹ Corresponding author information can be added as a footnote.

28 *expenses, and improving grid resilience. However, the success of TES implementation hinges on*
29 *appropriate system sizing, effective control strategies, and alignment with local utility rate structures.*
30 *This paper presents a techno-economic analysis of integrating a chilled water TES system into the*
31 *central plant at California State University, Dominguez Hills. Drawing on historical load profiles and*
32 *utility tariffs, we assess three TES sizing approaches and their corresponding control strategies from*
33 *both energy and economic perspectives.*
34 *This paper utilizes a model-based approach to assess the impact of Thermal Energy Storage (TES)*
35 *sizing and control strategies on the techno-economic feasibility of integrating TES into an existing*
36 *central plant. The models employed for this analysis were calibrated using four years of historical*
37 *data. The results demonstrated that utility tariffs and the campus's operational profiles dictate the*
38 *most feasible sizing and control methods.*
39 *The findings offer valuable insights for institutions and commercial building managers exploring*
40 *sustainable energy solutions. By demonstrating how optimized TES strategies can improve*
41 *operational efficiency while achieving financial savings, this study highlights the potential for TES to*
42 *align performance with cost effectiveness in real-world applications.*

43 *Keywords: Thermal energy storage, Load shifting, Central plant*

44

45 **1 Introduction**

46 Commercial buildings account for 75% of all electricity consumed in the United States
47 [1], contributing significantly to global energy consumption and greenhouse gas
48 emissions. As global warming increases, the cooling needs of U.S. buildings are
49 projected to rise by 50-150% between 1964 and 2080 [2], placing substantial strain on
50 power grids and necessitating further investment in more efficient, sustainable cooling
51 solutions. To meet these demands sustainably and advance decarbonization, the
52 integration of renewable energy sources is essential [3], [4].

53 In the U.S., space cooling in commercial buildings represents approximately 15% of total
54 electricity consumption, with higher shares in sectors such as offices, hospitals, and
55 retail stores [5]. Globally, space cooling accounts for nearly 20% of electricity use in
56 buildings, and this demand is expected to more than double by 2050, particularly in
57 developing countries [6]. Space conditioning—including both heating and cooling—
58 continues to be a major contributor to overall energy demand in commercial buildings,
59 especially during peak electricity usage periods [7].

60 Energy Storage Systems (ESS) play a critical role in addressing energy challenges by
61 reducing peak grid demand and optimizing the use of renewable resources through
62 energy storage for later use [8]. Rising peak demand has significant economic
63 implications, as energy tariffs fluctuate throughout the day, with higher costs during
64 peak demand periods. ESS helps mitigate these costs by enabling peak shaving, reducing
65 consumption during high-demand periods, and lowering utility bills [9], [10]. Beyond
66 economic benefits, peak shaving also reduces renewable energy curtailment and
67 improves grid stability [11].

68 A variety of energy storage technologies exist, including Compressed Air Energy Storage
69 (CAES) [12], [13], [14], Flywheel Energy Storage (FES) [15], Phase-Change Materials
70 (PCMs) [16], [17], [18], Pumped Hydro Energy Storage [19], Liquid Air Energy Storage
71 (LAES) [20], and Battery Energy Storage Systems (BESS) [21], and others.

72 Thermal Energy Storage (TES) is a widely adopted approach to tackle energy challenges,
73 especially in buildings. It stores energy in the form of heat or cold, eliminating the need
74 for energy conversion and reducing associated losses [22], [23]. TES systems can reduce

75 energy consumption during peak hours by 15-25%, depending on system size and
76 cooling/heating requirements [24]. Research indicates that TES could help Denmark
77 achieve carbon neutrality by 2050, facilitating greater PV integration and reducing
78 energy curtailment [25].

79 Thermal energy storage (TES) stores energy in three possible forms. Latent thermal
80 storage occurs when a material undergoes a phase change, with energy stored as a
81 result of the enthalpy change during the phase transition, which take place at a single
82 temperature or nearly so. The use of ice for TES in cooling applications [26], [27] is the
83 most common example. Sensible TES stores energy through a temperature change of
84 the storage medium, such as chilled or heated water-based systems used for both
85 heating and cooling. Thermochemical energy storage (TCES) involves storing energy
86 through reversible chemical reactions, where heat is absorbed or released during the
87 decomposition or recombination of chemical compounds [28]. TES systems are
88 employed across various sectors, including both residential [8], [29] and commercial
89 buildings [30].

90 University campuses, given their size, present an ideal opportunity for TES
91 implementation. Studies highlight the energy and economic benefits of TES in campus
92 settings. A water-based TES system on a university campus was shown to reduce
93 heating and cooling costs by €112,000 annually, with a payback period of 13–19 years
94 depending on system size and energy prices [31]. Another study found that a water-
95 based TES system cut peak demand by up to 20%, with potential annual savings of
96 \$496,320 for a 4 MWh system [32].

97 Potter (2005) [33] reported a reduction in electrical peak demand from TES systems
98 installed on university campuses between 1991 and 1993. Further research in 2008 [22]
99 explored the benefits of high-capacity cool TES in universities, particularly as campus
100 populations grow and ambient temperatures rise.

101 The University of Utah recently installed a 400,000-gallon TES tank that stores irrigation
102 water for cooling purposes. The water is stored at night and used during the day,
103 significantly reducing energy consumption as the system operates without compressor
104 energy [34], [35], [36]. Princeton University's Thermally Integrated Geo-Exchange
105 Resource (TIGER) facility integrates TES and geothermal boreholes, enhancing cooling
106 and heating systems while advancing the university's goal of carbon neutrality by 2046.
107 The TES system also demonstrated resilience during Superstorm Sandy by providing
108 uninterrupted essential services [37], [38], [39], [40]. At the University of Texas at
109 Austin, a 4-million-gallon TES facility stores chilled water, shifting 6 MW of peak cooling
110 demand to off-peak hours. This strategy reduces energy costs, qualifies for rebates, and
111 contributes to campus sustainability. The system also incorporates water recovery,
112 using reclaimed water to further enhance efficiency and environmental impact [41],
113 [42].

114 However, the potential for renewable energy curtailment reduction through TES
115 depends on the specific location and utility tariff structures. TES does not always
116 guarantee reduced curtailment, as factors like regional tariffs and grid dynamics play a
117 significant role [43].

118 This paper presents a model-based approach through a case study to evaluate the
119 integration of a Chilled Water Thermal Energy Storage (CW-TES) system into a campus
120 central cooling plant. Mathematical models, calibrated using historical data, are
121 employed to predict the performance of different TES sizing methods and control
122 strategies, including simplified versions designed for practical field implementation.
123 The study focuses on quantifying how these sizing and control approaches affect central
124 plant energy consumption and costs based on an existing utility rate structure. The
125 techno-economic feasibility analysis relies specifically on central plant energy demand
126 and consumption data, making the results particularly pertinent to facilities where
127 central plant energy usage is separately metered or represents the dominant portion of
128 the overall energy load.

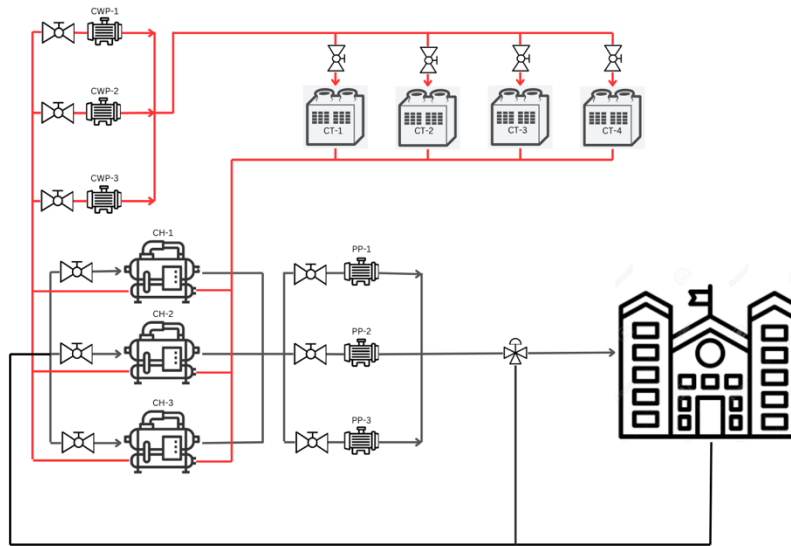
129 **2 System Description**

130 The central plant cooling system at the California State University - Dominguez Hills
131 campus is responsible for providing cooling and heating to 52 air handling units across
132 the different campus buildings, serving approximately 83,612 m² (900,000 ft²) of
133 building space. Table 1 summarizes the major components of the central plant and their
134 capacities and Fig. 1 illustrates the configuration of the central plant. The three chillers
135 are staged based on the cooling load of the campus. During startup, one chiller is
136 activated. Additional chillers are enabled if the cooling load increases and the chilled
137 water supply temp exceeds the chilled water supply setpoint of 6.7°C (44°F) by 1°C
138 (~2°F). Chiller night mode is enabled whenever the cooling load is lower than 1,055kW
139 (300 Ton) and the zone temperatures are below the zone temperature setpoint.

140

Table 1. Central plant summary

Id	Equipment	Quantity	Capacity
1	Chiller	3	3517kW (1000 Ton)
2	Cooling tower (8 fans per tower)	4	5.5kW (7.5 hp) per fan
3	Condenser pump	3	0.215m ³ /s (3400 GPM)
4	Chilled water pump	3	0.095 m ³ /s (1500 GPM)



141

142

Figure 1. Central plant equipment layout

143

Three of the cooling towers run as soon as one chiller starts running. The operating

144

cooling towers alternate every week. Unless some of the fans are down for maintenance

145

reasons, all the fans in the operating cooling towers receive the same speed signal. The

146

fans' speed is modulated based on the condenser water supply setpoint which is

147

continuously updated based on outdoor wet bulb temperature.

148

The condenser pumps are variable-speed and staged based on the number of running

149

chillers-one condenser pump per chiller. The condenser flow is allowed to vary linearly

150

with the chiller load. The chilled water pumps are also variable-speed. If one pump runs,

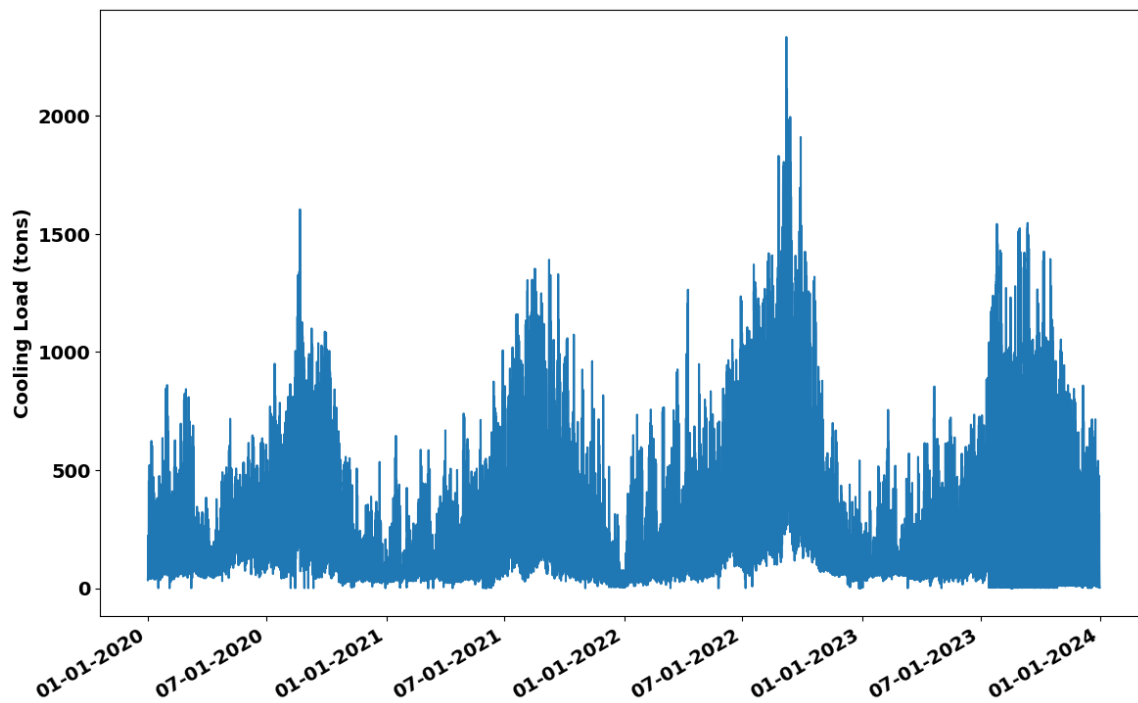
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its speed is controlled based on the loop differential pressure setpoint, which is reset

152 seasonally. If more than one pump runs, their speeds are modulated based on flow
153 setpoint.

154 Fig.2 shows the cooling load profile from 2020-2023. The year 2022 exhibited the largest
155 peak load 7,850 kW (2,332 Ton) while the remaining years had a relatively similar load
156 profile. The peak coincides with the record-breaking heatwave that was observed in
157 California from Aug 31 to Sep 9. July to October in general have the highest cooling
158 demand. Fig.3 indicates that the central plant electricity demand reaches as high as
159 1,875kW in Sep 2022. The highest total monthly peak electricity consumption of 400
160 MWh was also recorded during the same time. Out of the total electricity consumption,
161 the chillers attribute to 64% followed by the cooling tower as indicated in Fig 4.

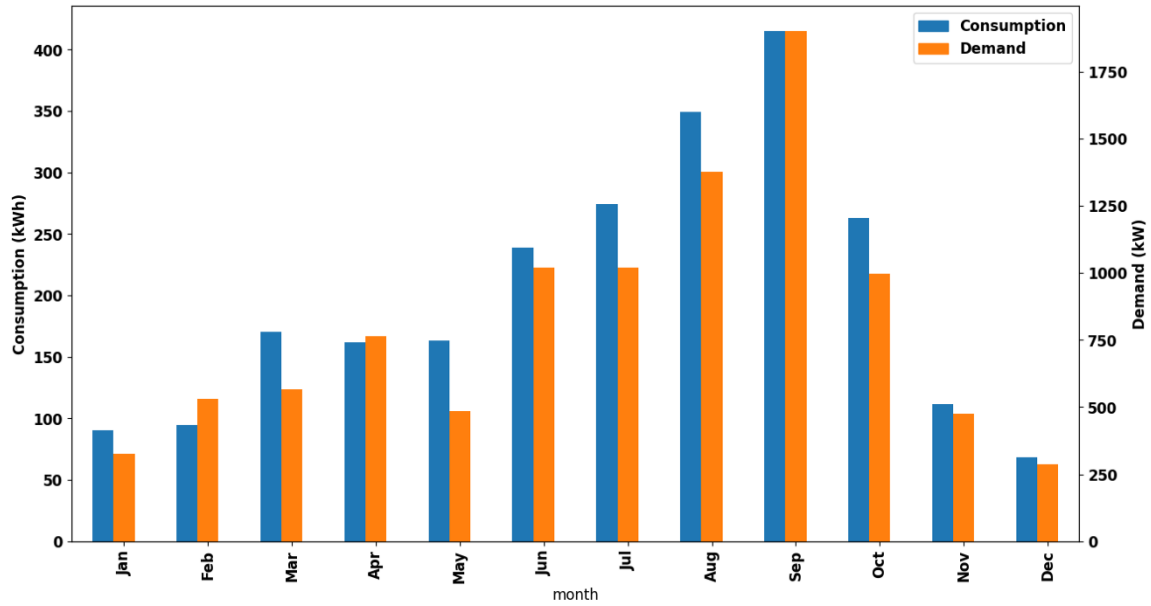
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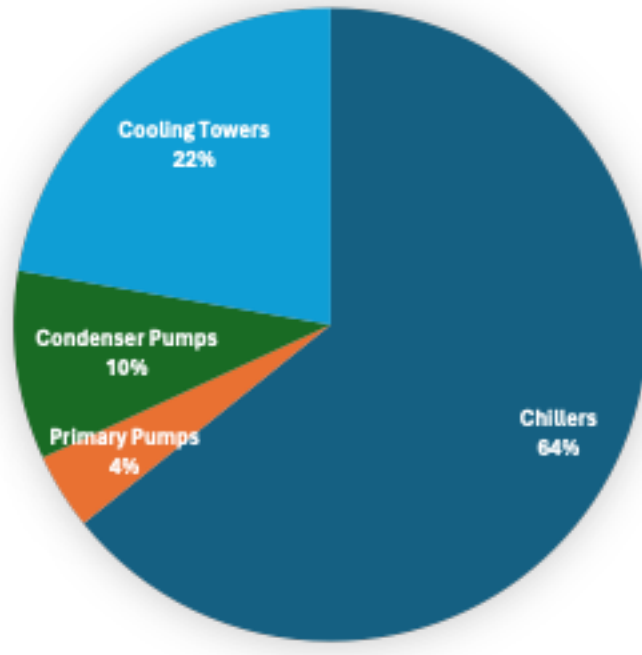
Figure 2. Central plant cooling load



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166

Figure 3. Central plant electric demand and consumption



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Figure 4. Electricity use by equipment

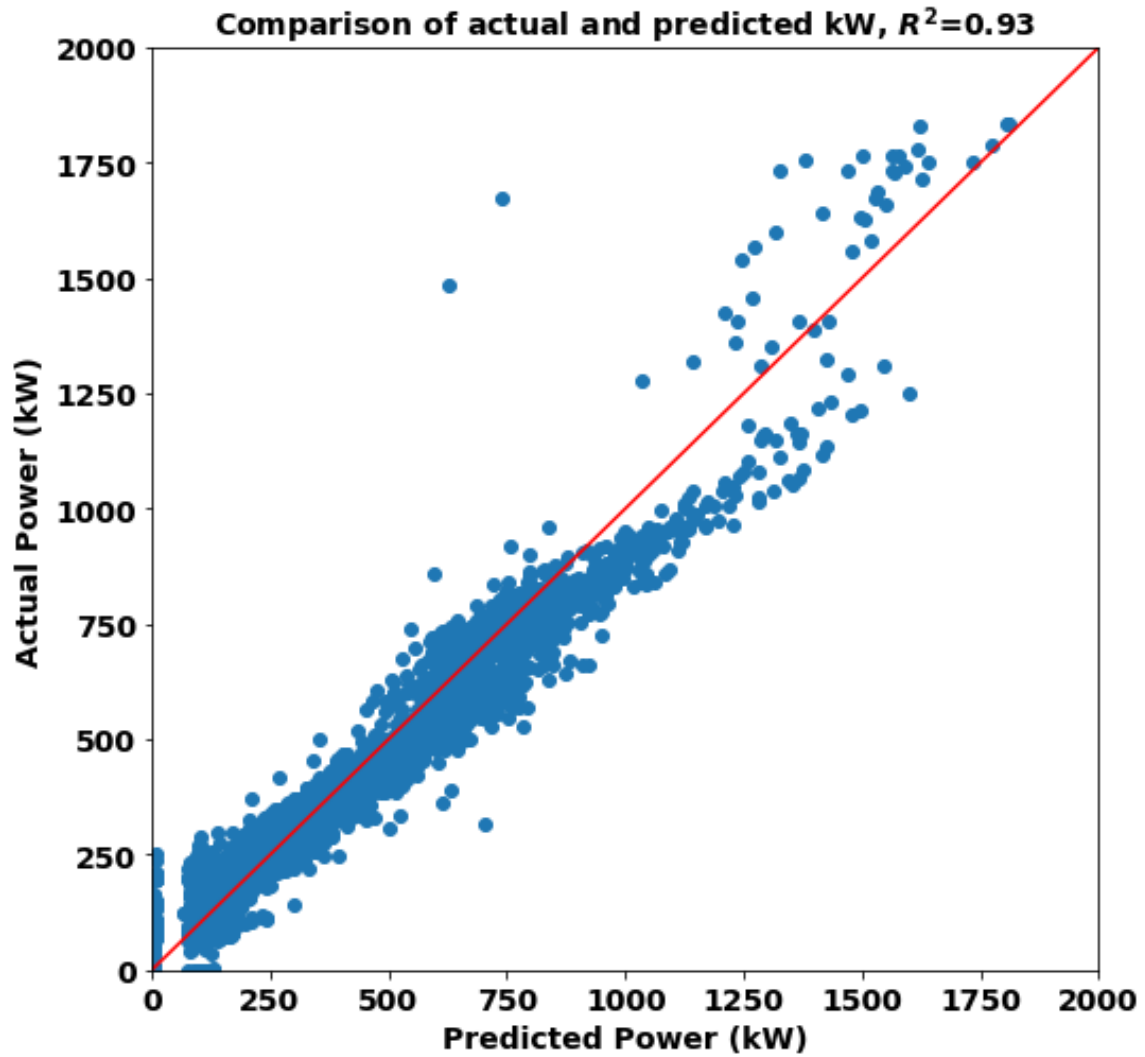
169 **3 Central Plant Modeling**

170 **3.1 Chillers**

171 To comprehensively assess the effectiveness of various control strategies on central
172 plant electricity consumption, mathematical models were employed to analyze key
173 components including chillers, pumps, and cooling towers. Fig.5 demonstrates a strong
174 correlation between the predicted and real power demand of the central plant in
175 FY2022, with an R^2 value of 0.93. The following section provides a brief overview of the
176 models for each component

177 Fig.6 shows the variation of chiller efficiency (kW/Ton) with part load ratio for four
178 different condenser water temperatures (CWT). During periods of low part load ratio
179 operation, which often occur during chiller startup or when the cooling load in the loop
180 is significantly low, chiller efficiency reaches as high as 2.5 kW/Ton. As expected,
181 efficiency decreases as the condenser water supply temperature drops due to the
182 reduced temperature lift required by the compressor to reject heat to the ambient air.

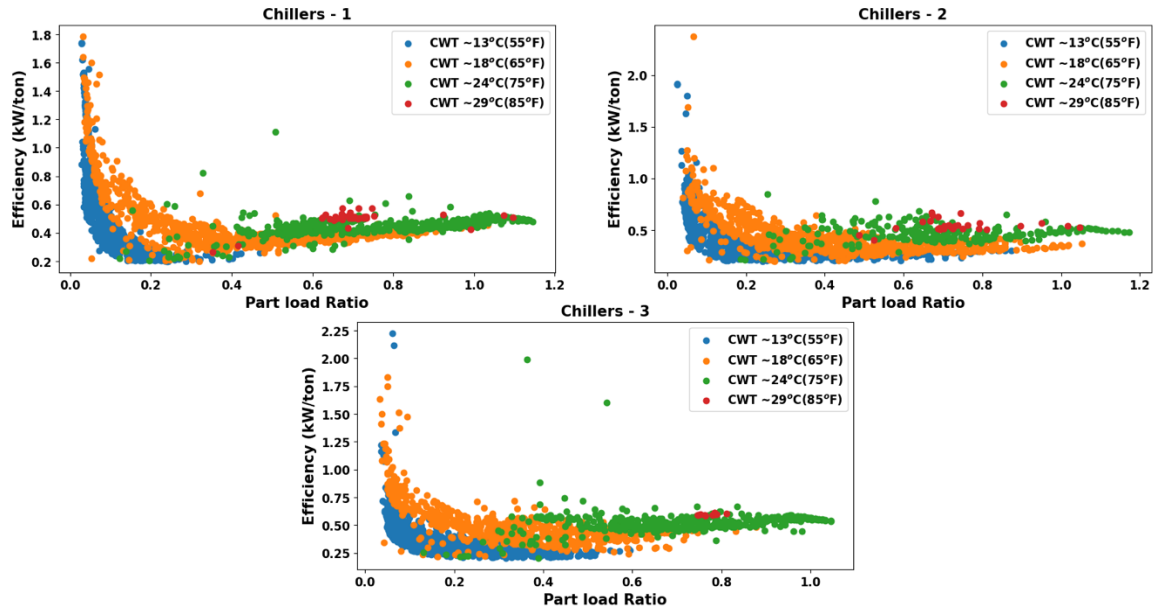
183 Overall, chiller performance is influenced by chilled water supply temperature,
184 condenser water supply temperature, and chiller loading. To capture the variation of
185 chiller power demand with these parameters, we have employed an empirical model,
186 shown in Eq.(1)



187

188 Figure 5. Comparison between actual and predicted central plant power demand

189



190

191

192

Figure 6. Variation of chiller performance with operation conditions

$$\begin{aligned}
 P_{ch} &= \frac{Q_{ch,ref}}{COP_{ref}} (CAPFT)(EIRFT)(EIRPLR) \\
 CAPFT &= a_1 + a_2 T_{chws} + a_3 T_{chws}^2 + a_4 T_{cws} \\
 &\quad + a_5 T_{cws}^2 + a_6 T_{chws} T_{cws} \\
 EIRFT &= b_1 + b_2 T_{chws} + b_3 T_{chws}^2 + b_4 T_{cws} \\
 &\quad + b_5 T_{cws}^2 + b_6 T_{chws} T_{cws} \\
 EIRPLR &= c_1 + c_2 PLR + c_3 PLR^2 \\
 PLR &= \frac{Q_{ch}}{Q_{ch,ref}}
 \end{aligned} \tag{1}$$

193

194 Where P_{ch} is chiller power (kW), PLR is part load ratio, CAPFT is a biquadratic curve

195 capturing variation of chiller capacity with temperature, EIRFT is a biquadratic curve

196 capturing the variation of energy input ratio with temperature, EIRPLR is biquadratic

197 curve capturing the variation of energy input ratio with part load ratio, PLR is part load

198 ration, T_{chws} is chilled water supply temperature ($^{\circ}C$), T_{cws} is condenser water supply199 temperature ($^{\circ}C$), Q_{ch} is cooling Load (kW), $Q_{ch,ref}$ is nominal Chiller cooling capacity

200 (kW), COP_{ref} is nominal coefficient of performance. The coefficients in Eq.(1) are
 201 identified using historical data and are summarized in Table 2.

202 Table 2. Model parameters for chillers

	Chiller 1	Chiller 2	Chiller 3
a_1	1.048286	-0.042280	-0.084019
a_2	-0.137182	0.104638	0.031329
a_3	0.006949	-0.011896	-0.003824
a_4	-0.086767	-0.080356	-0.028021
a_5	0.001177	-0.000931	-0.001574
a_6	0.003310	0.010263	0.005703
b_1	-20.501347	-4.169202	-3.195562
b_2	3.418319	1.249661	-0.214760
b_3	-0.168699	-0.409748	-0.198676
b_4	0.382152	-0.269168	-0.421322
b_5	-0.002229	-0.003953	0.007368
b_6	-0.063731	0.104296	0.070187
c_1	0.036291	0.0307032	0.021965
c_2	0.071487	0.078430	0.0754571
c_3	0.172031	0.086993	0.074297

203 3.2 Pumps

204 Both the condenser and primary chilled water pumps are variable-speed. The primary
 205 pumps are controlled using a chilled water loop pressure setpoint while the condenser
 206 pumps are controlled based on flow which changes linearly to the chillers' load. Both
 207 pumps are modeled using a third order polynomial equation as indicated in Eq.(2). The
 208 model parameters are identified using historical data and are summarized in Table 3.

209

$$Power = c_1 + c_2 flow + c_3 flow^2 + c_4 flow^3 \quad (2)$$

210

211

Table 3. Pump model parameters

	c_1	c_2	c_3	c_4
Primary Pumps	4.382	-0.116	0.002	-1.064e-6
Condenser Pumps	20.46	-0.317	0.002	3.192e-6

212 3.3 Cooling Towers

213 The cooling tower fan speed is modulated based on the condenser water setpoint which
 214 tracks the outdoor air wet bulb temperature with an offset of $5^{\circ}F$. The cooling tower's
 215 electricity consumption depends on the fans' airflow (speed). The fan speed depends on
 216 the required heat rejection, condenser water flow, outdoor air wet bulb temperature,
 217 and condenser water supply temperature. The correlation between the fan speed and
 218 these parameters is estimated using a feed-forward artificial neural network method
 219 called multilayer perceptron (MLP). Once the fan speed is predicted, the cooling tower
 220 fan power is estimated as indicated in Eq.(3). Similarly, the model parameters are
 221 identified using historical data and are summarized in Table 4.

222

$$Power = c_1 + c_2FS + c_3FS^2 + c_4FS^3 \quad (3)$$

223

224 Where FS is the fan speed in %.

225

Table 4. Cooling tower fan model parameters

	c_1	c_2	c_3	c_4
Cooling tower fan	1.256	-0.075	0.002	-5.38e-6

226

227 **4 TES Sizing Methods and Control Approaches**

228 We considered three TES sizing methods, Full storage, Load leveling, and Peak demand
 229 limiting. Table 5 summarizes the storage sizes in gallons. This section describes the sizing
 230 methods and the corresponding control approaches in detail.

231

Table 5. TES sizing comparisons

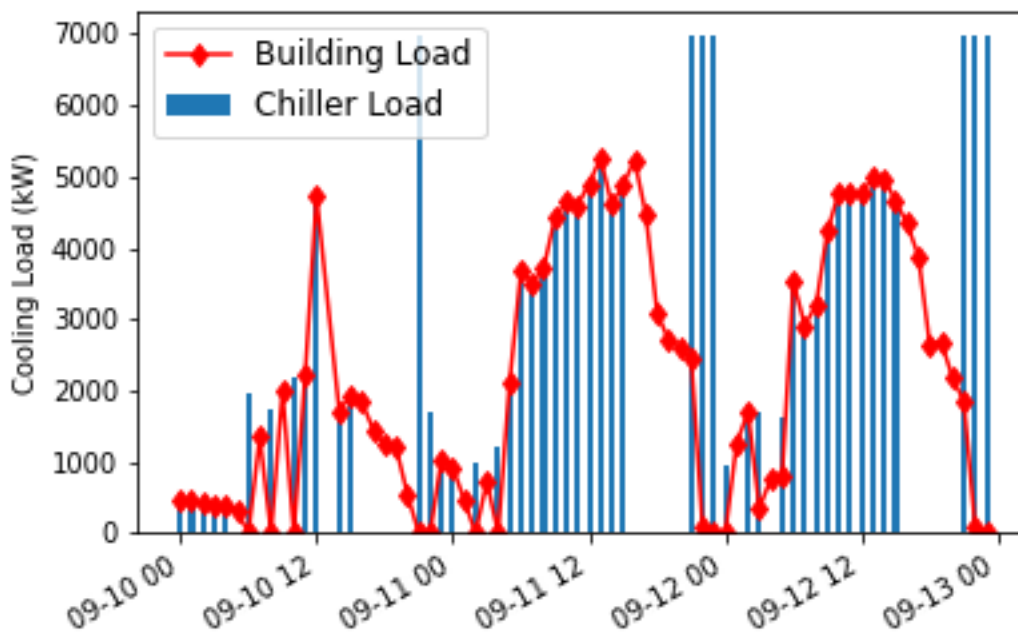
TES Sizing Method	TES size m³ (Gallons)
Full Storage	4.258 (1,124,715)
Load Leveling	1,204 (318,057)
Peak Load Limiting	2,175 (574,688)

232 **4.1 TES Sizing**

233 Depending on space availability, utility rate structures and other specific needs of the
234 site, different approaches could be used for TES sizing.

235 4.1.1 Full Storage

236 A full storage approach is typically used for load shifting. It involves moving the entire
237 on-peak load to off-peak hours and stopping chiller operation during peak hours. This
238 approach could be beneficial when there are (1) high on-peak demand charges, (2) a
239 significant difference between on-peak and off-peak electricity cost, (3) and/or short on-
240 peak periods [44]. In this approach, the TES is sized to store enough cooling capacity to
241 allow all chillers to be turned off during peak hours when demand charges are notably
242 high. As shown in Fig.7, the cooling load during peak hours is entirely shifted to off-peak
243 hours, and the demand during peak hours is supported by the energy stored in the TES.
244 The chiller load that is above the building load is what is stored in to the TES.



245

246 Figure 7. Load shifting using full storage
 247 As shown in Fig.2, the average summer peak cooling load is approximately 5,276 kW
 248 (1500 Ton). However, FY 2022 saw a peak of 8,001kW (2,275 Ton), attributed to the
 249 September 2022 heat wave. For TES sizing, we utilized FY 2023 data as it represents the
 250 campus's most recent cooling load. While sizing the TES based on the FY 2022 data
 251 could enhance resiliency and provide enough room for future expansion, it would
 252 necessitate a significantly larger capacity than typically required, resulting in a longer
 253 payback period.
 254 The peak cooling demand in FY 2023 was 5,437 kW (1,546 Ton). Assuming this load
 255 remains constant throughout the peak demand period, which runs from 4 p.m. to 9 p.m.
 256 (Table 6), the total thermal energy storage required to support the campus during these
 257 five hours is 27,285 kWh (7730 Ton-hour).

258 The TES volume in m³ that is needed to store a cooling load of Q kWh is estimated as:

259

260

$$V = \frac{3600Q}{\rho_w C_p \Delta T \eta} \quad (4)$$

261

262

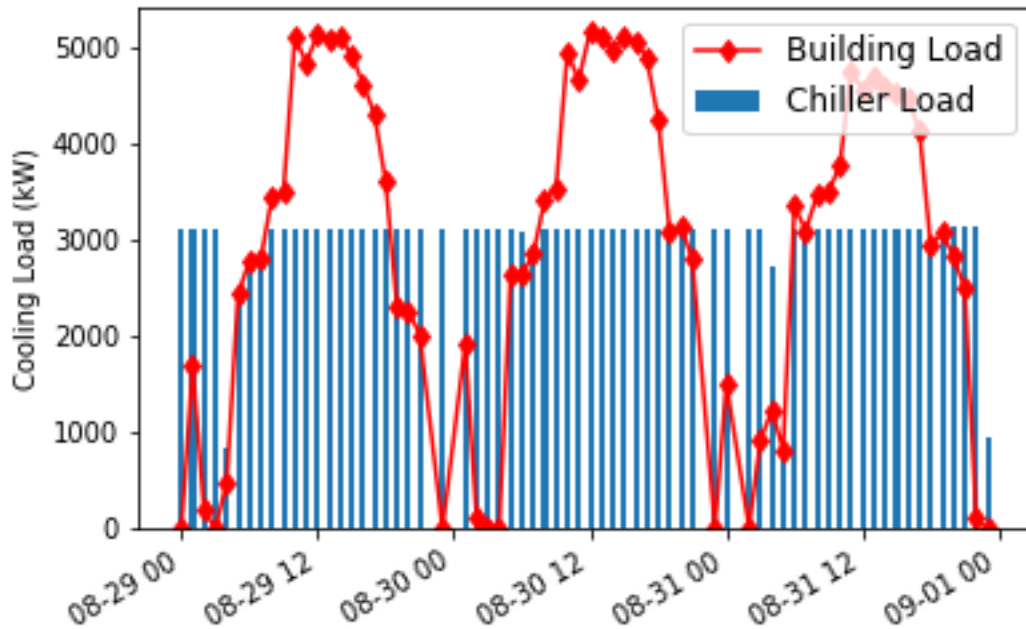
263 Where V is the TES volume in gallons, ρ_w is the density of water (1000kg/m³), C_p is the
 264 specific heat of water (4.18 kJ/kg.K), ΔT is the chilled water loop temperature
 265 differential, and η is the round-trip efficiency of the storage tank (0.9). The historical
 266 data indicated a yearly and summer average chilled water loop temperature difference
 267 of 4.5°C (8°F) and 6.1°C (11°F) respectively. Since the peak cooling load is during

268 summer, the TES is sized based on the summer average temperature difference, and the
269 values are indicated in Table 5.

270 **4.1.2 Load Leveling**

271 The load leveling or partial storage approach allows for discharging the TES while some
272 of the chillers are in operation. This approach is often used for demand-limiting
273 purposes and is particularly beneficial when there are moderate electric rate incentives
274 for load shifting, significant differences between peak and average loads, and/or
275 prolonged on-peak hours [44]. The TES is sized to reduce the monthly peak by a specific
276 amount, which depends on the chillers' capacity and the building load. The chillers can
277 produce cooling equal to or less than the determined monthly peak value. Any required
278 electricity that exceeds the pre-determined peak value is shifted to hours with a lower
279 cooling demand. Determining the peak value is an iterative approach that requires the
280 aggregated daily shaved load (i.e., loads above the peak value) to be distributed to
281 hours with lower than the peak cooling demand. This ensures that the building's cooling
282 needs are met at all times while minimizing peak demand [45]. If the chillers lack the
283 capacity to handle the shaved loads during low cooling load hours, the allowable
284 monthly peak value is increased until the condition is met. The TES is sized based on the
285 peak daily accumulated shaved load. Analyzing 2023 historical data, this iterative
286 approach suggests that 20 % of the monthly peak load can be effectively shaved,
287 resulting in a peak daily accumulated value of 7,688 kWh (2,186 Ton-hour). The required
288 TES size to store this daily accumulated kWh of cooling is estimated using Eq.(4) and

289 summarized in Table 5. Fig.8 displays the cooling load distribution for a 20% peak
 290 shaving.



291

292

Figure 8. Load shifting using load leveling

293

4.1.3 Peak Demand Limiting

294

The peak demand limiting application is a sizing method that falls between the full

295

storage and demand leveling approaches. While analogous to the load leveling method,

296

this approach is distinguished by a greater reduction in chiller operation during the peak

297

period, as shown in Fig.9. This results in a higher daily accumulation, which in turn

298

influences the required TES size. On-peak and off-peak hour demand limits are

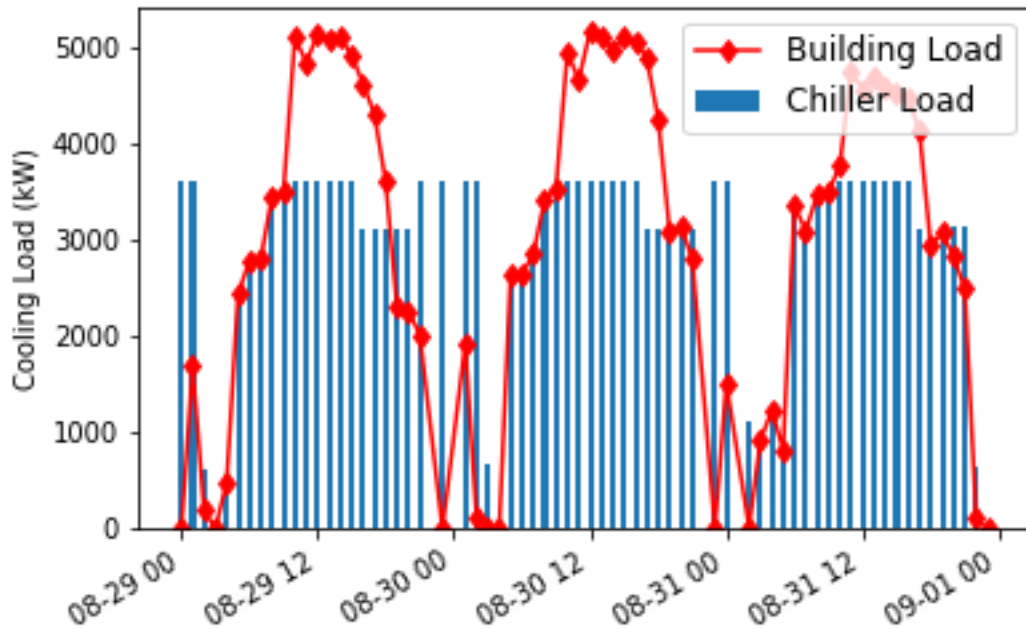
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iteratively determined based on the chiller capacity and building loads as discussed in

300

section 4.1.2. The estimated peak daily total cooling load accumulation using this

301 method is 13,888 kWh (3,949 Ton-hr), and the resulting TES sizing is summarized in
 302 Table 5.



303

Figure 9. Load shifting using peak demand limiting

304

305 **4.2 TES Control**

306 This section details the control methods corresponding to each sizing method. Control

307 methods play a major role in ensuring safe operation and maximizing energy savings

308 from the application of a TES. This study prioritizes simplified methods that can be easily

309 applied, although advanced model-based optimal control methods could be

310 implemented to achieve greater savings.

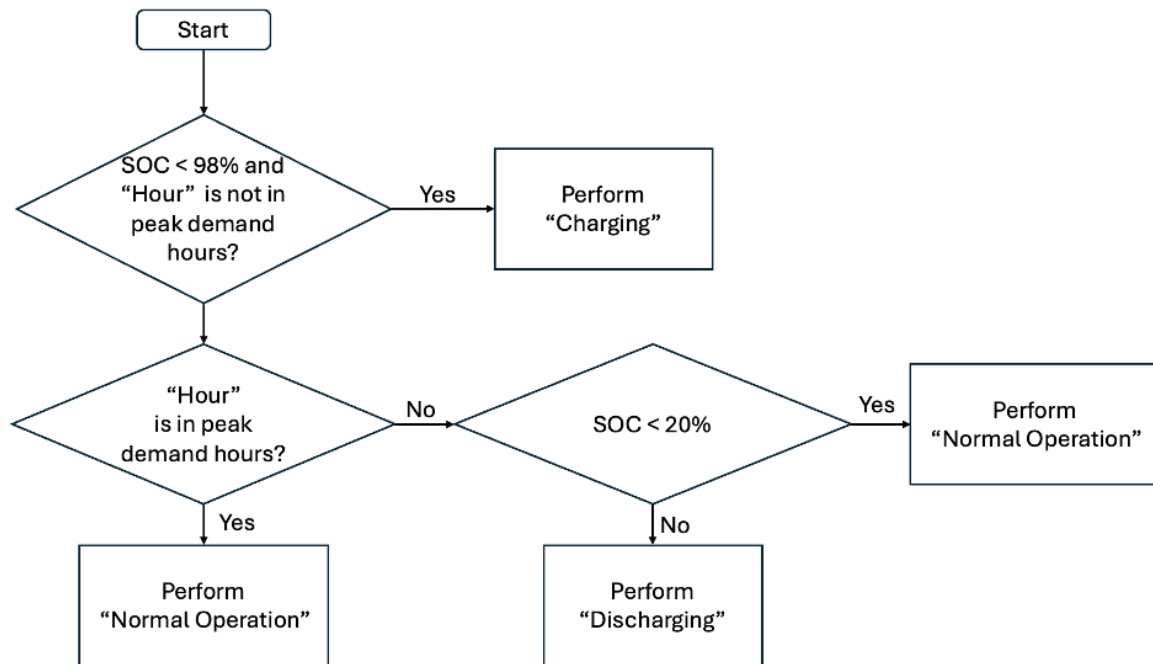
311 **4.2.1 Full Storage Control Method**

312 This method prioritizes efficient charging during off-peak hours. Charging begins

313 immediately after peak hours and continues until the State of Charge (SOC) reaches 98%

314 or higher. To manage electricity demand, charging is limited to two chillers during
315 summer and one chiller during winter and shoulder seasons. The control system
316 updates hourly, dynamically adjusting the number of operating chillers based on the
317 current TES SOC. For example, during summer, if the TES can accommodate the output
318 of two chillers for an hour, both will operate; otherwise, only one will run.
319 Three chiller loading levels (70%, 80%, and 100%) are compared for charging efficiency.
320 While chillers operate most efficiently between 40-70% capacity, a lower loading
321 percentage extends charging time. Historical data indicates a minimum of 70% loading is
322 required for sufficient charging during peak load days. The cooling tower operation
323 remains unchanged, responding passively to the chillers' demands. During discharge
324 mode, all cooling needs are met by the TES, with no chillers running. The central plant
325 operates in normal mode between full TES charge and the start of discharge during peak
326 hours. Normal mode is an operation mode where the central plant is operating based on
327 its existing control strategy without the TES. To prevent insufficient cooling capacity
328 during discharge, the chillers are also allowed to operate in normal mode if the TES SOC

329 falls below 20%. The summary of the control logic is shown in Fig 10.



330

331

Figure 10. Control logic for full storage method

332

Fig.11 illustrates the comparison of the chiller load with the addition of the TES and the

333

building load. The typical daily operation profile for this method is indicated in Fig.7. As

334

can be seen in the figure, the peak cooling load during summer is 7,034kW (2000 Ton),

335

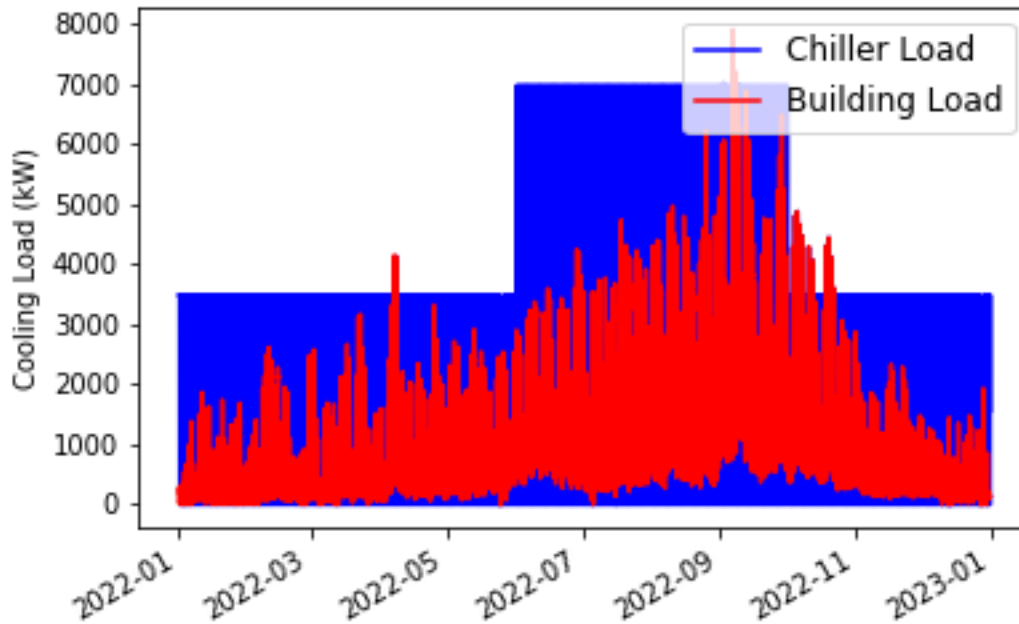
which is equivalent to running two 3,517kW (1000 Ton) chillers. During the remaining

336

months, the peak load drops to 3,517kW (1000 Ton), as only one chiller is permitted for

337

operation during winter and shoulder seasons.



338

339

Figure 11. Comparison of chiller and building cooling load

340

4.2.2 Load Leveling Control Method

341

This approach, unlike the simpler full-storage method, requires predicting both the

342

monthly peak cooling load and the daily accumulated load exceeding the allowable

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monthly peak. This necessitates a more complex control logic, as accurate predictions

344

rely on prior knowledge of the expected cooling load. Several advanced methods can be

345

employed for prediction, or a simplified rule-based approach can be used, utilizing

346

historical monthly peak values and previous day cooling load data, augmented with a

347

safety buffer. In this paper, we present a methodology where the chillers are operated

348

at a capacity equal to or lower than the allowable monthly peak until the thermal

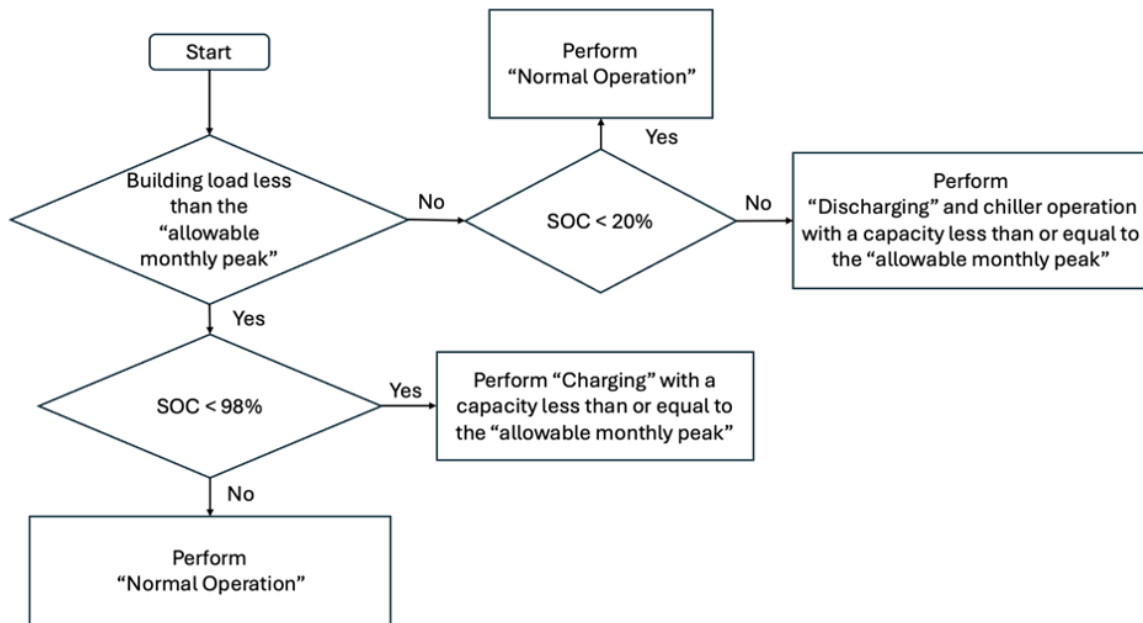
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energy storage (TES) is fully charged. When the cooling load surpasses the allowable

350

peak, the TES provides the excess demand.

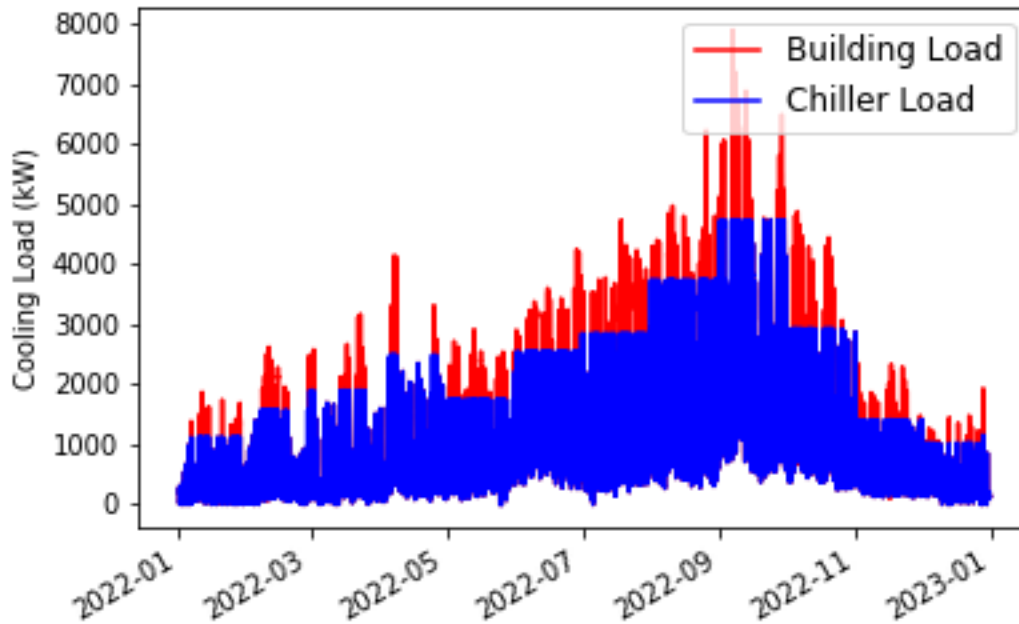
351 As discussed in section 4.1.2, the allowable monthly peak load is established through an
 352 iterative process. This ensures that the daily accumulated loads, which represent the
 353 aggregated daily cooling load exceeding the allowable monthly peak, are distributed to
 354 non-peak hours—hours when the cooling load falls below the allowable monthly peak.
 355 The simplified control logic employed in this study is illustrated in Fig 12.



356

357 Figure 12. Control logic for load leveling method

358 Fig.13 shows the comparison of the baseline building cooling load and the chiller load
 359 after application of a TES for the year 2022. The daily profile comparison is indicated in
 360 Fig.8. After multiple iterations, the maximum monthly peak shaving is determined to be
 361 40%. Beyond this, the chiller won't have enough capacity to store the peak daily
 362 accumulated load into the TES within the hours available for charging.



363

364 Figure 13. Comparison of building and chiller cooling load after load leveling

365 **4.2.3 Peak Demand Limiting Control Method**

366 The control approach for this method is similar to the load-leveling method. Once the
 367 off-peak and on-peak monthly allowable cooling load limits are determined as discussed
 368 in section 4.1.3, the chillers will run in charging mode until the TES is full. Depending on
 369 the hours of the day, the chillers' load won't be allowed to exceed the off-peak or on-
 370 peak values. When the building load is more than these peak values, the TES will be
 371 used to supply the value exceeding the peak.

372 **5 Techno-Economic Analysis**

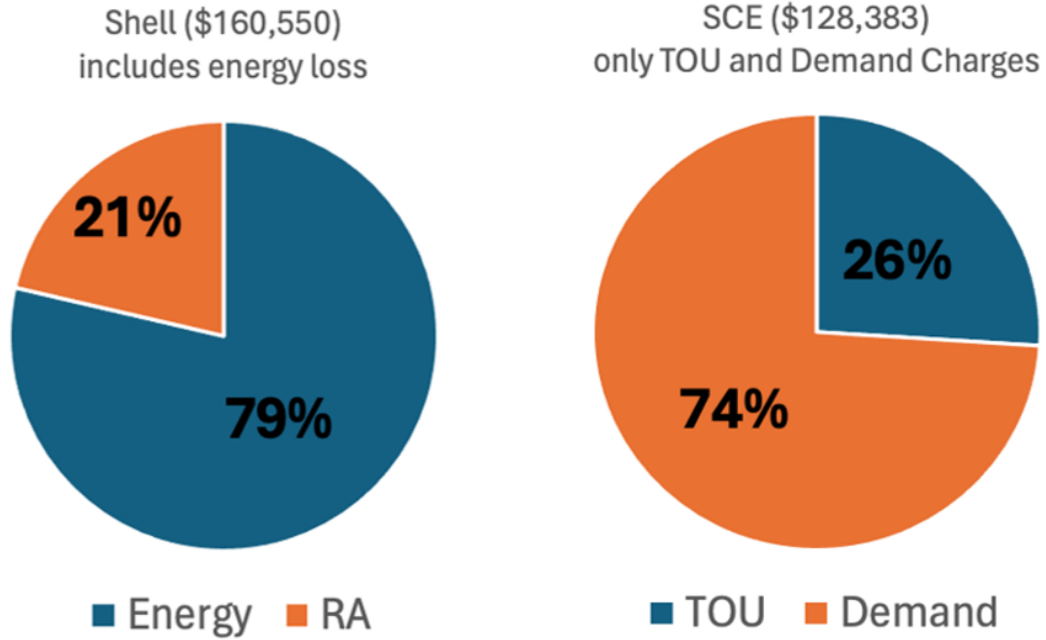
373 This work evaluates the annual impact of operating a TES on the electricity consumption
 374 of the central plant and the consequent operational cost. We evaluated the rate
 375 structure and electricity pricing for CSUDH. This section describes the rate structure,

376 electricity consumption and demand impacts on monthly bills, and the resulting cost
377 savings in various modeled scenarios.

378 **5.1 Electricity Bill Analysis**

379 Analyzing the CSUDH historic electricity bills showed that the University uses Direct
380 Access (DA). DA allows customers of a certain size to purchase wholesale electricity
381 from an Energy Service Provider (ESP) and to have the utility provide Transmission and
382 Distribution (T&D) services to them. Fig.14 shows the comparison of electricity
383 consumption and demand components of the electricity cost from the wholesale
384 provider (Shell) and the utility (Southern California Edison (SCE)) for August 2023. In this
385 paper, we only evaluate the impact of CP changes in the energy use profile for the T&D
386 portions of the cost billed by SCE. The university's electricity consumption is priced by
387 the rate structure described in Table 6.

388 Any changes in the load profile can impact the electricity use and the monthly peak
389 demand of the central plant. Demand charges have a larger share in the monthly cost of
390 electricity. It should be noted that demand charges are also time-sensitive. If the
391 monthly highest demand occurs during peak hours the central plant is charged at the
392 rate of facility plus summer or winter peak demands. Evaluating the time and value of
393 the peak demand is crucial in estimating the cost savings.



394

395 Figure 14. Comparison of electricity use and demand components in wholesale (Shell)
 396 and Utility (SCE) bills

397

398 Table 6. Time of Use (TOU) and demand charge rates from the utility for 2023

Rates reflecting 2023 prices		Weekdays		Weekends	
TOU (\$/kWh)	Summer	On Peak 4PM – 9PM	0.03020	On Peak	NA
		Mid Peak	NA	Mid Peak 4PM – 9PM	0.02909
		Off Peak 12AM-4PM 9AM-12AM	0.02909	Off Peak 12AM-4PM 9AM-12AM	0.02909
	Winter	Mid Peak 4PM – 9PM	0.03068	Mid Peak 4PM – 9PM	0.03068
		Off Peak 12AM-4PM 9AM-12AM	0.02976	Off Peak 12AM-4PM 9AM-12AM	0.02976
		Super Off Peak 8AM-4PM	0.02919	Super Off Peak 8AM- 4PM	0.02919
Demand Charge (\$/kW)	Facility	20.68			
	Winter peak	2.59			

	Summer peak	14.5
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399

400 **5.2 Operational Cost Saving**

401 We calculated annual potential savings based on the electricity consumption at the
402 central plant. We analyzed hourly electricity usage data from three scenarios: (1) load
403 leveling, (2) peak demand limiting, and (3) full storage. These scenarios were used to
404 calculate monthly and annual cost savings for the central plant. For the full storage
405 scenario, we investigated three chiller loading levels during thermal energy storage
406 (TES) charging: 70%, 80%, and 100%. Lower chiller loading generally reduces power
407 demand but extends charging hours. The minimum loading limit of 70% was iteratively
408 determined from historical data and represents the lowest loading that could be used
409 without depleting the TES. Table 7 and Table 8 compare annual electricity and demand
410 costs against the baseline. Savings are primarily influenced by the existing rate structure
411 and the campus's cooling demand. Of the three methods, the full storage method
412 generally performed least effectively while the peak demand limiting method
413 performed the best. In fact, the 100% chiller loading scenario for 2023 resulted in higher
414 costs than the baseline. This is mainly due to a significantly higher off-peak demand
415 charge compared to baseline, as indicated in Fig.7. As discussed in section 4.1.1, the full
416 storage method is typically a preferred approach when there is a substantial difference
417 between on-peak and off-peak hour charges. This method shifts peak demand to off-
418 peak hours. However, running chillers at 100% during charging increases the off-peak
419 demand compared to the baseline, leading to the observed negative savings in 2023. In
420 the remaining full storage scenarios, the savings achieved by avoiding chiller operation

421 during on-peak hours were partially offset by increased peak demand during off-peak
 422 hours.

423 Table 7. Central plant cost comparison for all scenarios in 2022

	Total Cost	Demand Charge (kW) Cost	Electricity Consumption (kWh) Cost	Savings (%)
Baseline	\$422,069	\$341,372	\$80,697	
Peak Demand Limiting	\$297,209	\$217,151	\$80,058	30
Load Leveling	\$299,536	\$219,302	\$80,234	29
Full Storage, Chiller Loading 70%	\$325,811	\$247,229	\$78,582	23
Full Storage, Chiller Loading 80%	\$329,723	\$250,920	\$78,803	22
Full Storage, Chiller Loading 100%	\$344,373	\$265,095	\$79,278	18

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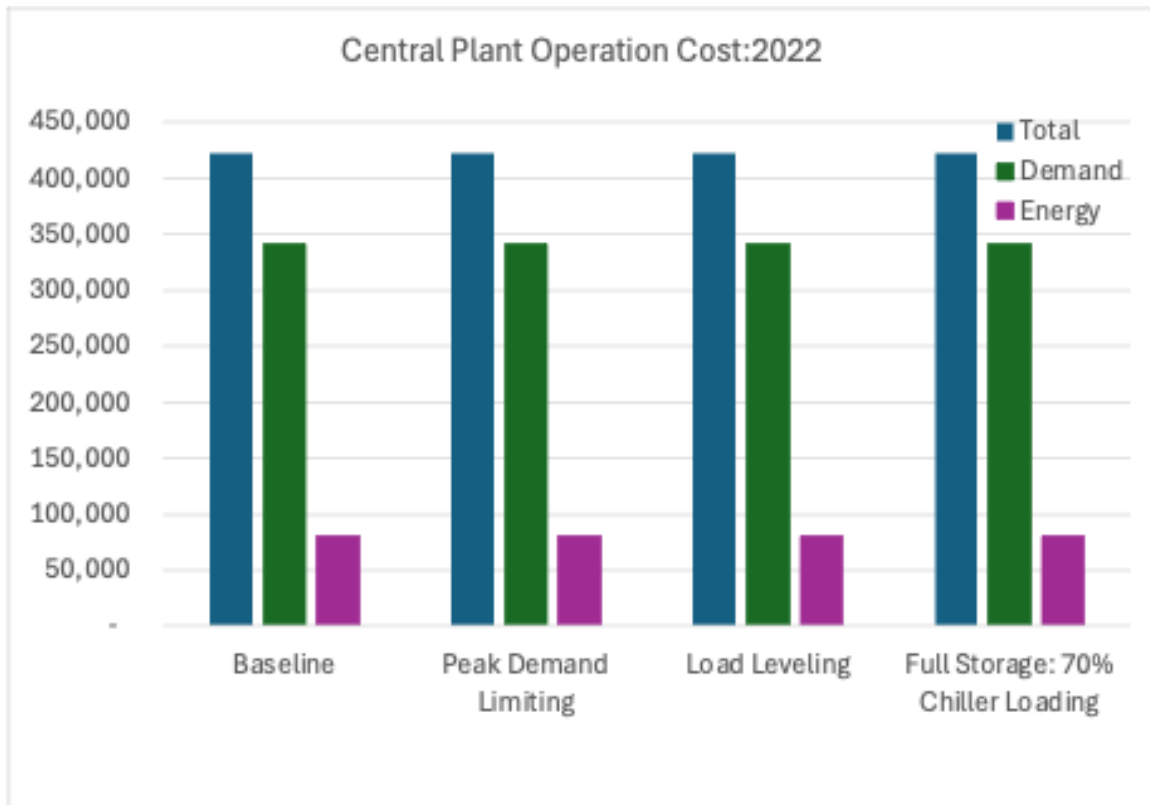
425 Table 8. Central plant cost comparison for all scenarios in 2023

	Total Cost	Demand Charge (kW) Cost	Electricity Consumption (kWh) Cost	Savings (%)
Baseline	\$345,497	\$282,917	\$62,580	
Peak Demand Limiting	\$263,426	\$200,644	\$62,782	24
Load Leveling	\$289,463	\$226,958	\$62,505	16
Full Storage, Chiller Loading 70%	\$294,643	\$233,474	\$61,169	15
Full Storage, Chiller Loading 80%	\$308,551	\$247,298	\$61,253	11
Full Storage, Chiller Loading 100%	\$347,045	\$285,602	\$61,443	-0.4

426

427 In contrast to completely shifting on-peak hours cooling load to off-peak hours, as in the
 428 full storage method, load leveling and peak demand limiting methods level the central
 429 plant load to a certain percentage of the historical peak. These methods are
 430 recommended when there is a moderate incentive for load shifting. Both outperform
 431 full storage and provide considerable savings against the baseline. Peak demand limiting

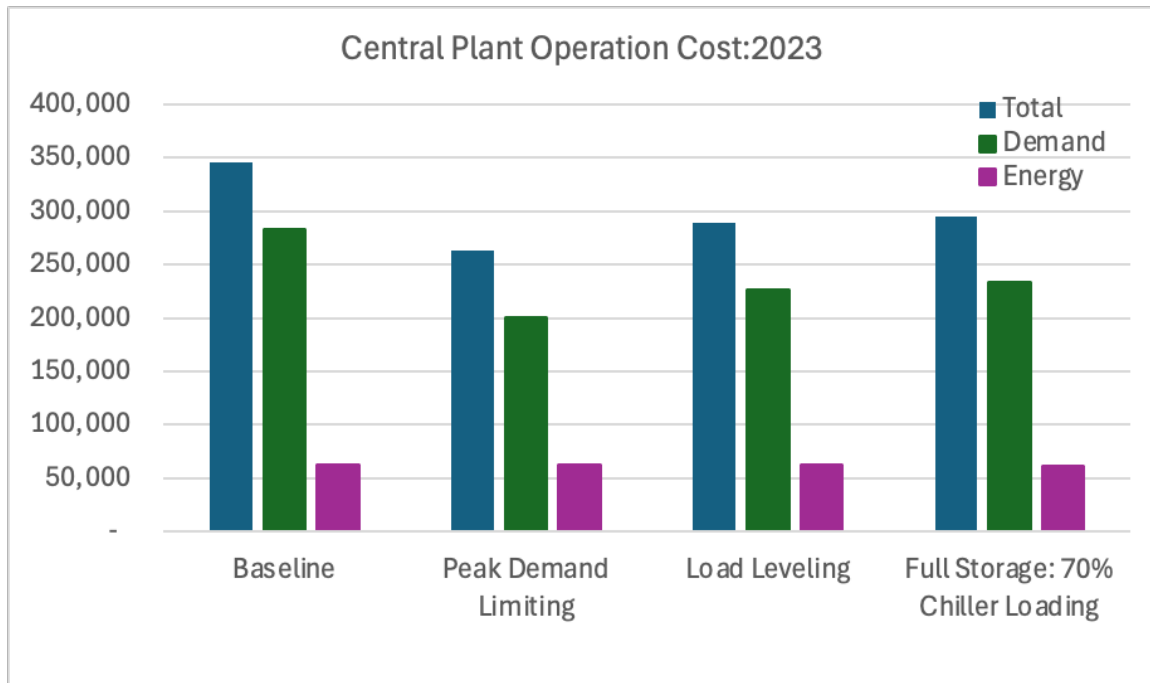
432 is superior because it enables a greater reduction in chiller operation during peak hours
 433 compared to load leveling, an effect shown in Fig. 9.
 434 Figs.15 and 16 present a comparative analysis of the total cost, the demand cost, and
 435 the electricity cost for the three methods. In particular, there are no substantial
 436 differences in electricity consumption between the methods compared to the baseline.
 437 This is mainly due to the nature of thermal energy storage (TES), which primarily shifts
 438 energy use rather than reducing load. The only potential for energy reduction through
 439 TES in this case stems from increased efficiency gains achieved by operating chillers
 440 during night when outdoor air temperatures are cooler.



441

442

Figure 15. Central plant electricity cost comparison in 2022



443

444

Figure 16. Central plant electricity cost comparison in 2023

445

5.2.1 Payback Period

446

In order to calculate the payback period of the TES we have considered the capital cost

447

of the tank, and annual operational cost savings over a 30-year period. The annual cost

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saving used predicted rates for electricity demand. An exponential Smoothing algorithm

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has been used to predict the future rate based on a decade of historic rates seen in

450

Fig.17. Since the 2022 load profile was unrepresentative of typical plant operation due

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to a heat wave, the 2023 electricity consumption data was used instead to evaluate the

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annual operational cost. This analysis does not consider the impact of future load

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growth resulting from the addition of new buildings served by the central plant.

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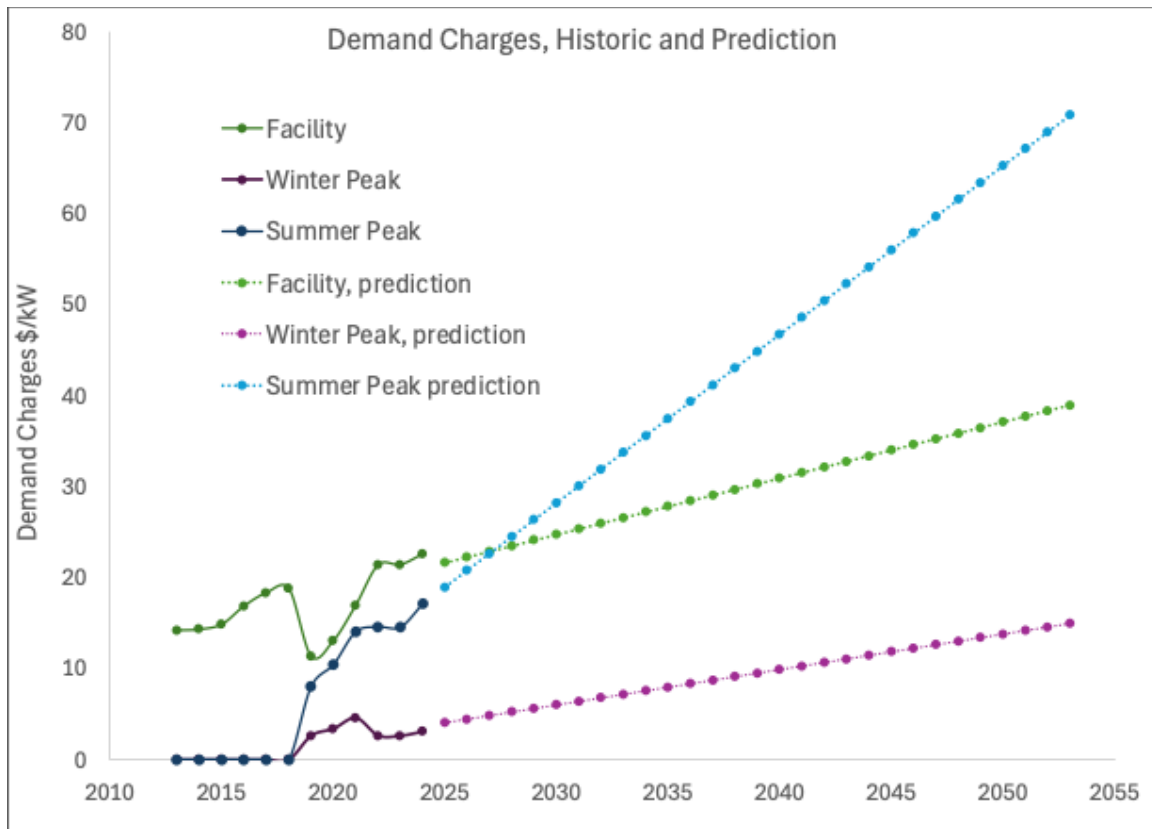
456

457 Table 9. The payback period for various scenarios considering predicted increases in
 458 price over the next 30 years.

Scenario	Tank Size m ³ (Gallons)	Capital Cost (\$)	Payback - Full price - Discount rate 0%	Payback - Full price - Discount rate 3%	Payback - IRA discounted price - Discount rate 0%	Payback - IRA discounted price - Discount rate 3%
Full Storage Chiller Loading 70%	4,258 (1,124,715)	\$2,193,194	>30 years	>30 years	26 years	> 30 years
Load Leveling	1,204 (318,057)	\$620,211	12 years	>30 y	7 years	8 years
Peak Limiting	2,175 (574,688)	\$1,120,641	14 years	>30y	9 years	10 years

459 *Note: Payback has been calculated for the capital costs based on different tank sizes. After-tax credit/rebate prices assume 40% reduction*
 460 *of capital cost. Discount rate (0 and 3 % in this work) indicates how future annual savings are contributing to the net present value and can*
 461 *depend on the type of financing used to provide the capital, in addition to the inflation rate.*
 462

463 To calculate the capital cost for addition of a TES, we assumed \$1.95/gallons [46] for the
 464 concrete water storage tank. Table 9 provides details of the tank size, estimated capital
 465 cost, and payback periods for the three discussed scenarios. Although peak demand
 466 limiting offers the highest annual cost savings, the load leveling method achieves the
 467 shortest payback period. This difference is because the load leveling method requires a
 468 relatively smaller tank size than peak demand limiting, resulting in a lower initial
 469 investment.



470

471

Figure 17. Historic and predicted demand charge rates.

472 6 Conclusions and Recommendations

473 The increasing adoption of TES in commercial buildings is a testament to their growing
 474 importance in addressing the challenges of energy demand management and grid
 475 stability. One of the most significant advantages of TES lies in its ability to significantly
 476 reduce peak demand charges by storing thermal energy during off-peak hours, when
 477 electricity prices are typically lower, and supply cooling during peak periods. This peak-
 478 demand reduction translates to substantial cost savings for businesses and institutions,
 479 as they are often charged higher rates for electricity consumption during peak hours.
 480 Moreover, by leveling out the demand profile, TES systems reduce stress on the
 481 electrical grid.

482 While the benefits of TES are undeniable, the extent of these benefits hinges on careful
483 considerations of system sizing and control approaches. The optimal design and
484 operation of a TES system are highly correlated to the prevailing rate structure and the
485 dynamic nature of the cooling load of the buildings designed to serve. For instance, a
486 system optimized for a rate structure with high peak demand charges might not be as
487 effective in a region with a flat rate structure. Similarly, the system design needs to
488 account for variations in cooling load throughout the year, ensuring efficient storage
489 and thermal energy utilization.

490 This paper investigates the impact of sizing methods and control approaches on
491 infrastructure and operational costs associated with TES. Mathematical models
492 representing key central plant equipment were developed to quantify the response of
493 the system to different control strategies.

494 The results indicate that, for the specific rate structure and campus cooling load
495 analyzed, the load leveling and peak limiting methods outperform full storage. The full
496 storage method incurs both higher operational costs and requires a larger TES size.

497 Although this manuscript outlines general sizing and control strategies for TES systems,
498 it is important to note that the techno-economic feasibility results are based on 2023
499 weather conditions and the corresponding building energy loads. However, similar
500 trends are expected in other years. It is important to note that the presented payback
501 periods do not account for the avoided capital cost of downsizing the chiller plant when
502 TES is integrated during new construction, expansion, or chiller replacement. Factoring
503 in these potential upfront savings could further shorten the payback periods.

504 In addition, the analysis was conducted in Southern California, where both the cooling
505 and heating demands are relatively moderate. In regions with more extreme climates,
506 the energy and economic benefits of TES are likely to be more substantial.

507 The analytical framework presented in this study can be easily adapted to other
508 commercial buildings seeking to leverage TES as a practical solution to shift cooling or
509 heating loads, reduce peak demand, and reduce electricity costs.

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