Synergies between Building-Sited Batteries and Thermal Energy Storage

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Seminar 30 - The Solar Panel: Enabling Renewables' Grid Integration with Thermal Energy Storage Systems

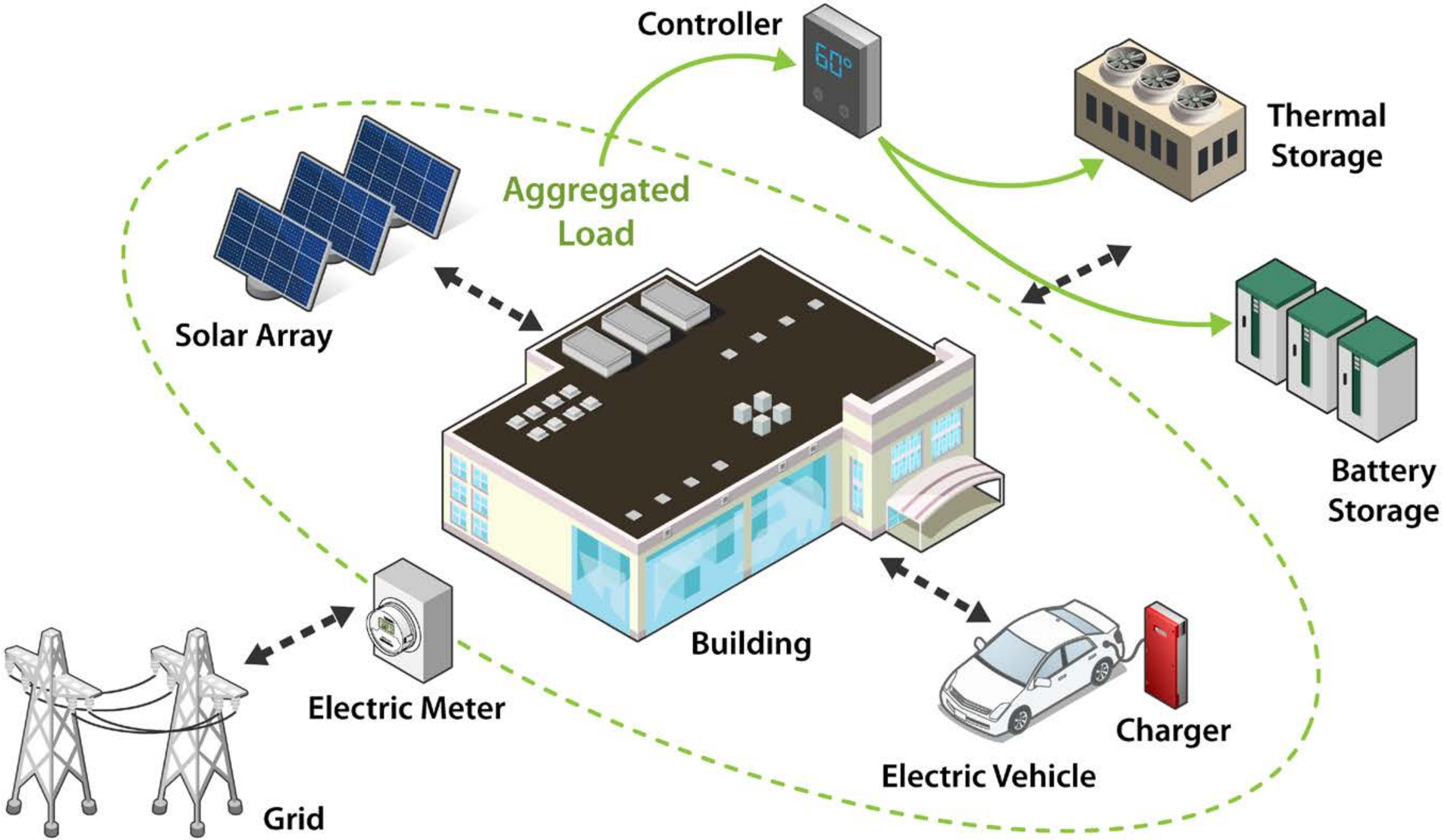
Learning Objectives

1. Explain how water heaters can provide demand side management to the grid.
2. Identify effects of load shifting on end-user electricity bills and the use of solar-self consumption.
3. Describe how a phase-change-material-based cool thermal energy storage system can be used to enable renewables on the electric grid.
4. **Describe the pros and cons of behind-the-meter battery and thermal energy storage, and how to select the appropriate combination depending on the building load profile.**

Pros/Cons of Energy Storage Systems

- Batteries
    - (+) More flexible—directly meets total electric load
    - (-) More costly—capital expense is typically higher
    - (-) More sensitive to cycling

- Thermal energy storage
    - (-) Less flexible—can only meet thermal loads
    - (+) Less costly
    - (+) Less sensitive to cycling


Controller
60°
Thermal Storage
Aggregated Load
Solar Array
Battery Storage
Building
Electric Meter
Charger
Electric Vehicle
Grid

Outline

- Simulations
  - Methods
  - Results – optimal sizing of thermal and battery storage
- Experiments
  - Hardware-in-the-loop setup
  - Results – supervisory control and additional efficiency benefits

Simulation

Analyzed case

A big-box retail building in Phoenix, AZ with a 600-kW PV array, and six 150-kW EV chargers with assumed load profiles from EVI-EnSite[1,2]

- Independent variables:
  - Thermal energy storage size
  - Battery energy storage size
- Dependent variables:
  - Utility cost savings
  - Battery cycles per year
  - Annualized cost savings

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[1] M. Gilleran et al., “Impact of electric vehicle charging on the power demand of retail buildings,” Advances in Applied Energy, vol. 4, p. 100062, Nov. 2021, doi: 10.1016/j.adapen.2021.100062.

[2] P. Mishra et al., “A Framework to Analyze the Requirements of a Multi-Port, Megawatt-Level Charging Station for Heavy-Duty Electric Vehicle,” presented at the 99th Transportation Research Board Annual Meeting, Washington D.C., Jan. 2020.

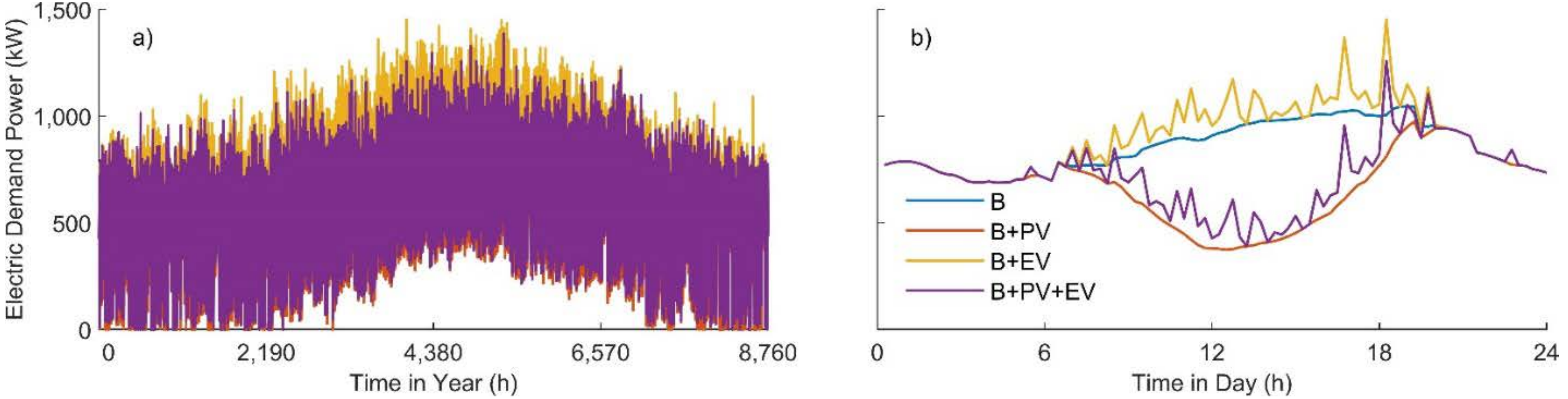
Model parameters

Parameter	**Low**	**Nominal**	**High**
BES Capital Cost ($/kWh$_e$)	300	600	900
BES Lifetime (yr)	10	15	20
Demand Charge ($/kW)[a]	7.5	15	22.5
Discount Rate (%)	4	8	12
Energy Rate ($/kWh)	0.08	0.12	0.16
TES Capital Cost ($/kWh$_e$)[b]	50	100	150
TES Lifetime (yr)	10	15	20

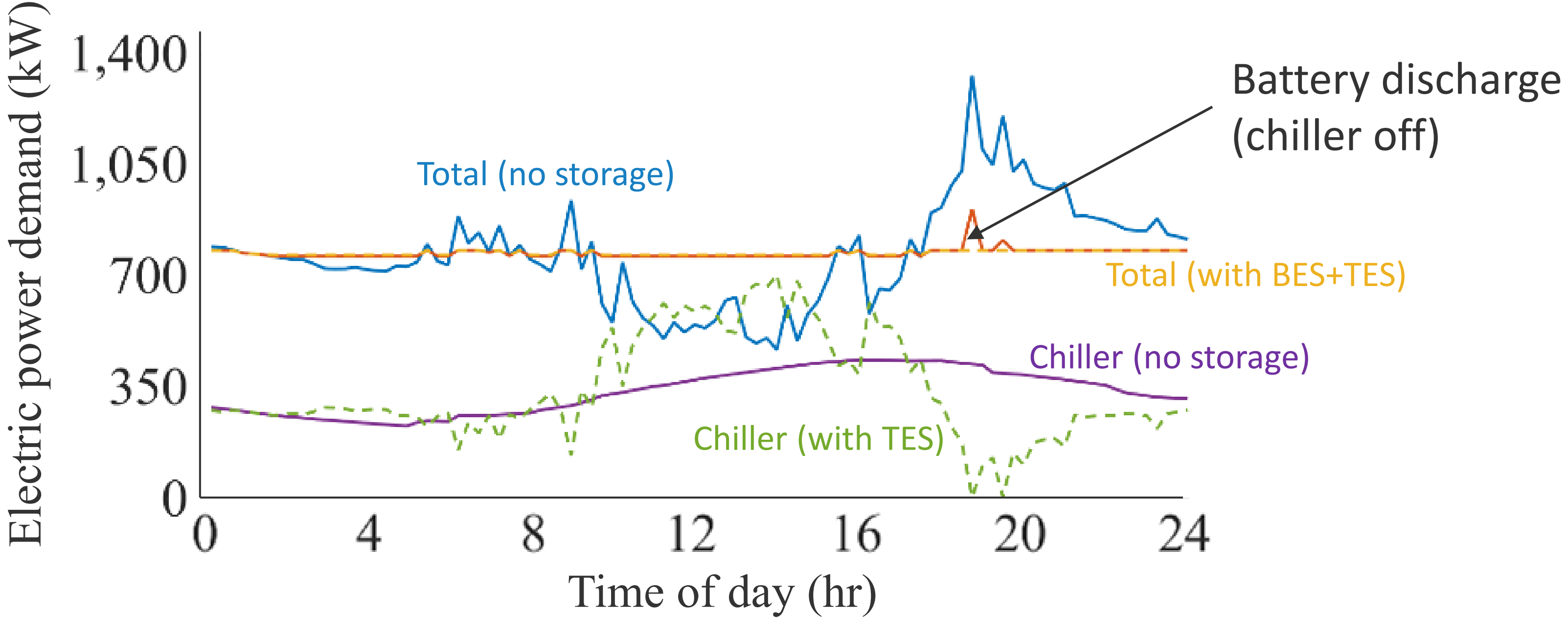
[a] We consider cases where the demand charge is assessed all year or only in summer months

[b] We also consider a case where the TES capital cost equals the BES capital cost ($600/kWh$_e$)

Annual and daily load profiles

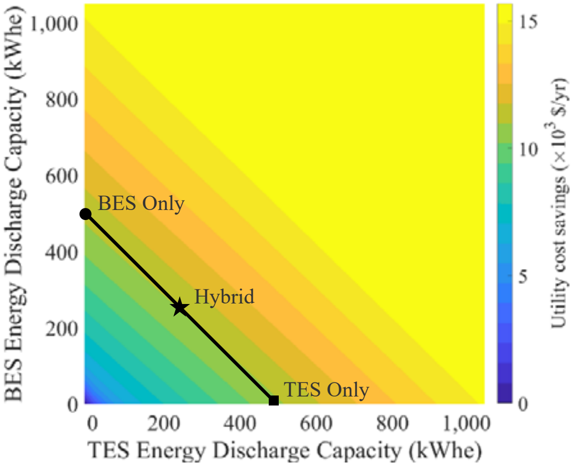


Example day load leveling

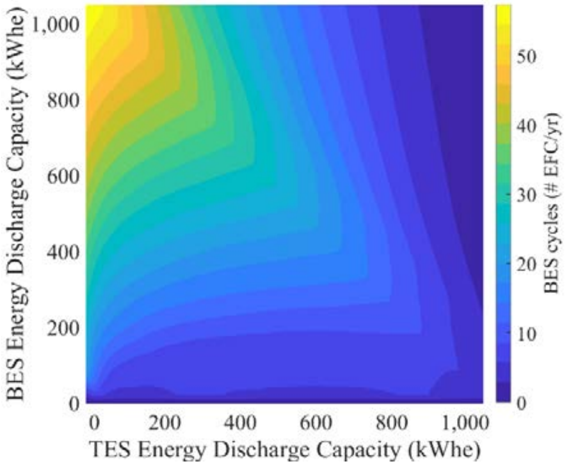


Annual simulation results

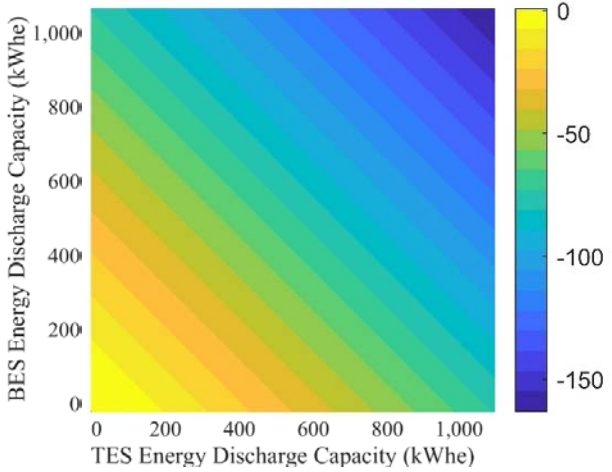
- Building-only scenario
- Demand charges in summer only
- Battery and TES both \$600/kWh$_e$ capital cost



Utility cost savings ($k/yr)



Battery cycles (Eq full cycles / yr)



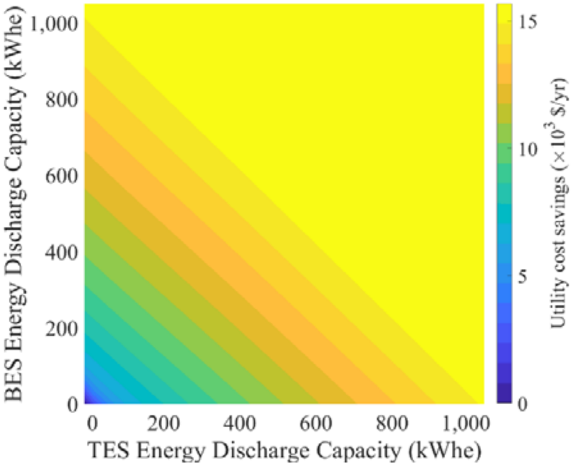
Annualized cost savings ($k/yr)

Brandt, M., J. Woods and P. C. Tabares-Velasco (2022). "An analytical method for identifying synergies between behind-the-meter battery and thermal energy storage." Journal of Energy Storage 50: 104216

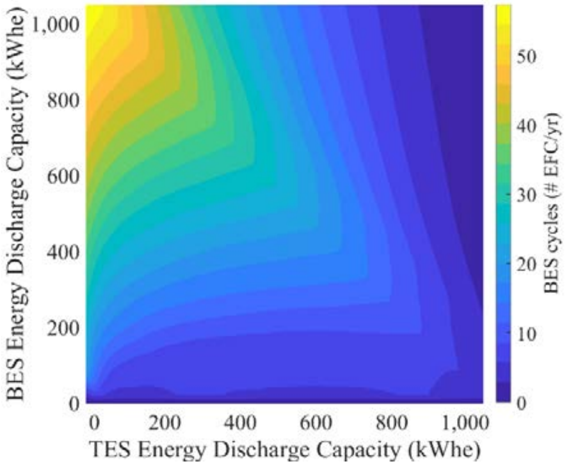
Annual simulation results

- Building-only scenario
- Demand charges in summer only
- **Battery \$600/kWh$_e$ capital cost; thermal storage \$100/kWh$_e$**

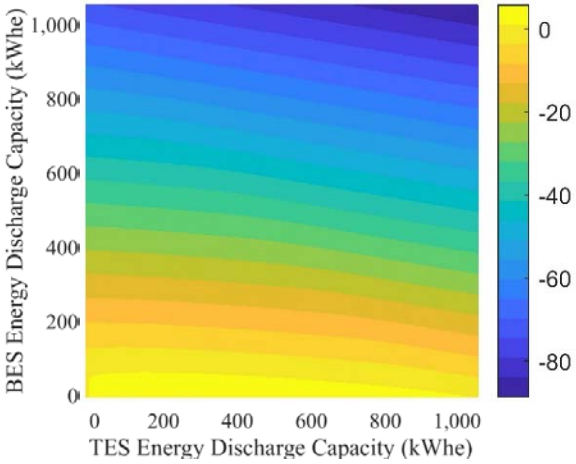
Utility cost savings ($k/yr)



Battery cycles (Eq full cycles / yr)



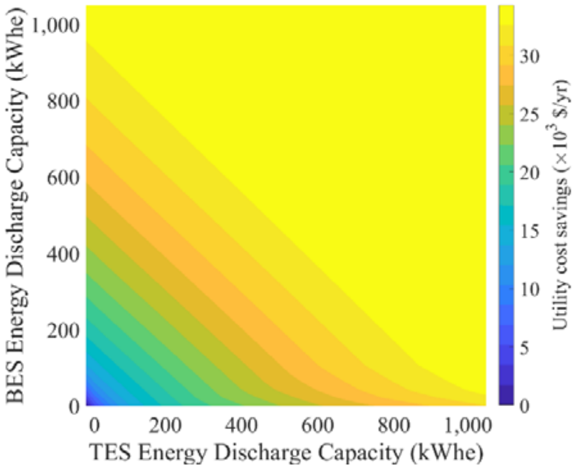
Annualized cost savings ($k/yr)



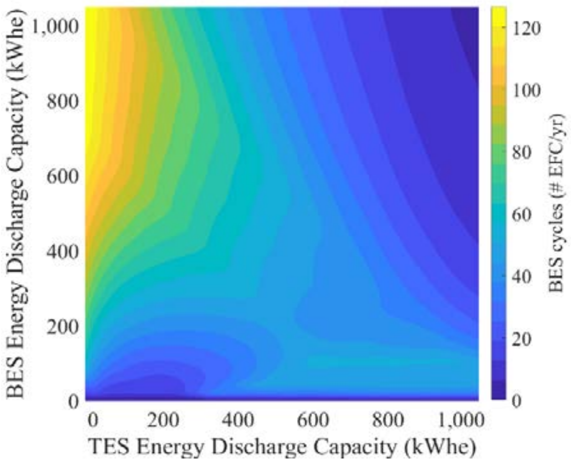
Annual simulation results

- Building-only scenario
- **Demand charges year round**
- Battery \$600/kWh$_e$ capital cost; thermal storage \$100/kWh$_e$

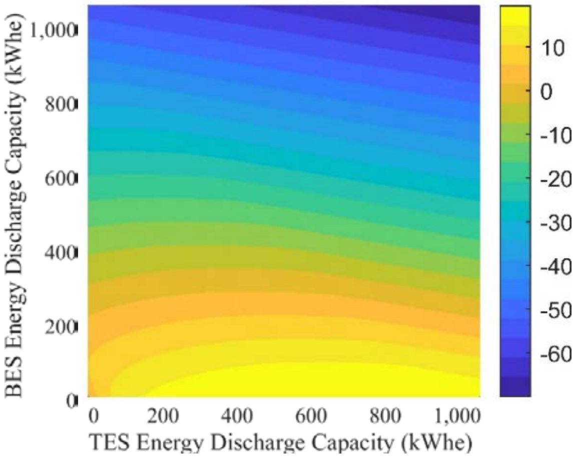
Utility cost savings ($k/yr)



Battery cycles (Eq full cycles / yr)



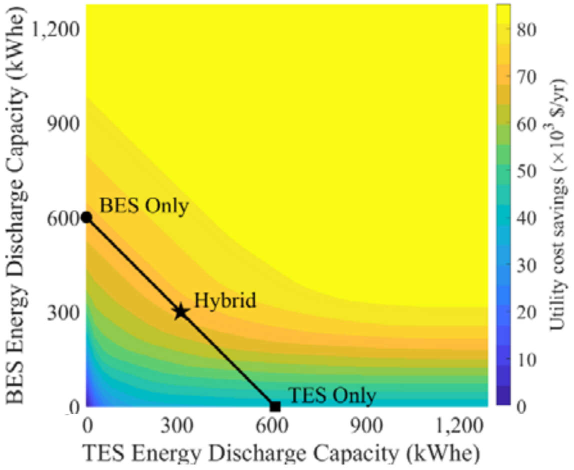
Annualized cost savings ($k/yr)



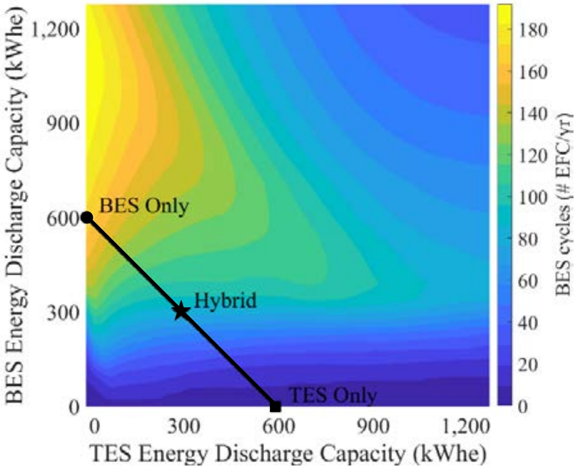
Annual simulation results

- **Building + PV generation + EV charging**
- Demand charges year round
- Battery \$600/kWh$_e$ capital cost; thermal storage \$100/kWh$_e$

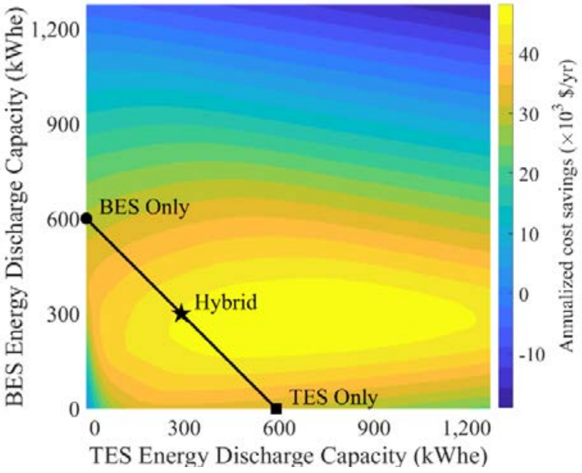
Utility cost savings ($k/yr)



Battery cycles (Eq full cycles / yr)

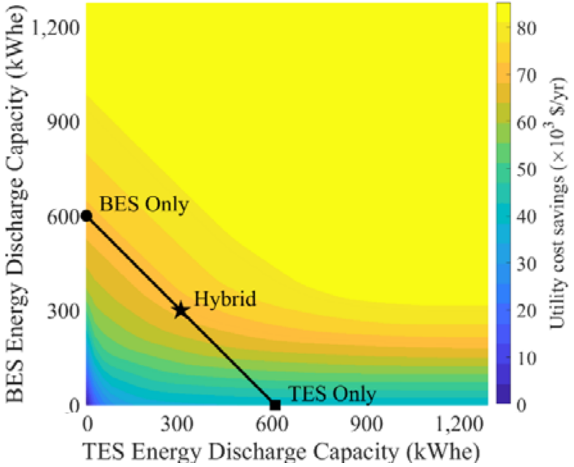


Annualized cost savings ($k/yr)

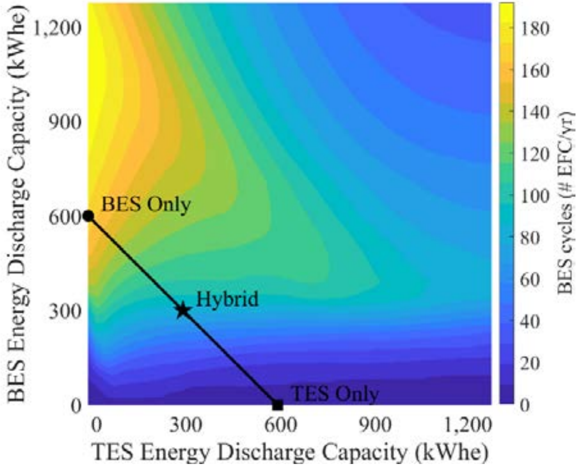


Annual simulation results

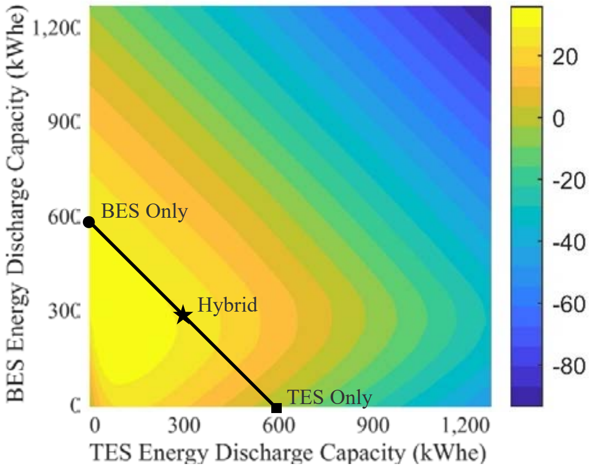
- Building + PV generation + EV charging
- Demand charges year round
- **Battery and TES same $/kWh$_e$ capital cost**



Utility cost savings ($k/yr)



Battery cycles (Eq full cycles / yr)

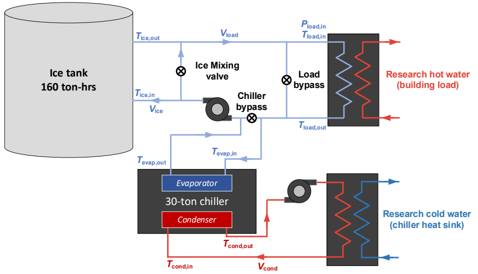


Annualized cost savings ($k/yr)

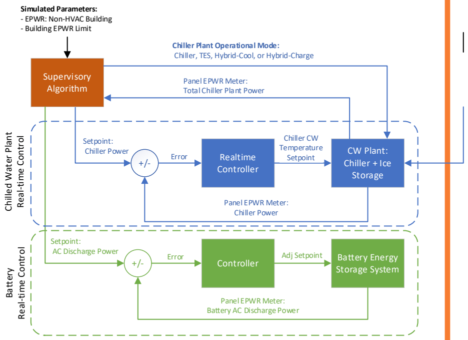
Experiments

Laboratory hardware and controller

Chiller plant + thermal storage



Controller



Simulated Parameters:
- EPWR: Non-HVAC Building
- Building EPWR Limit

Chiller Plant Operational Mode:
Chiller, TES, Hybrid-Cool, or Hybrid-Charge

Supervisory Algorithm

Panel EPWR Meter:
Total Chiller Plant Power

Chilled Water Plant
Real-time Control

Setpoint:
Chiller Power

+/-

Error

Realtime Controller

Chiller CW
Temperature
Setpoint

CW Plant:
Chiller + Ice
Storage

Panel EPWR Meter:
Chiller Power

Battery
Real-time Control

Setpoint:
AC Discharge Power

+/-

Error

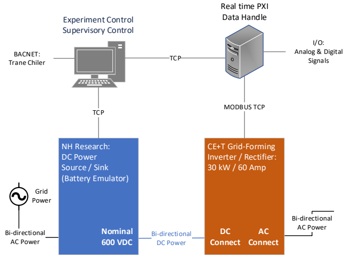
Controller

Adj Setpoint

Battery Energy Storage System

Panel EPWR Meter:
Battery AC Discharge Power

Battery emulator and inverter



Experiment Control
Supervisory Control

Real time PXI
Data Handle

BACNET:
Trane Chiler

TCP

I/O:
Analog & Digital
Signals

TCP

MODBUS TCP

NH Research:
DC Power
Source / Sink
(Battery Emulator)

**Nominal
600 VDC**

CE+T Grid-Forming
Inverter / Rectifier:
30 kW / 60 Amp

DC Connect

AC Connect

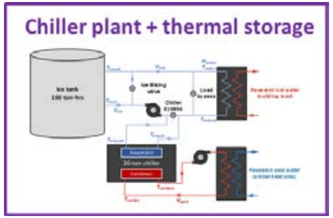
Grid
Power

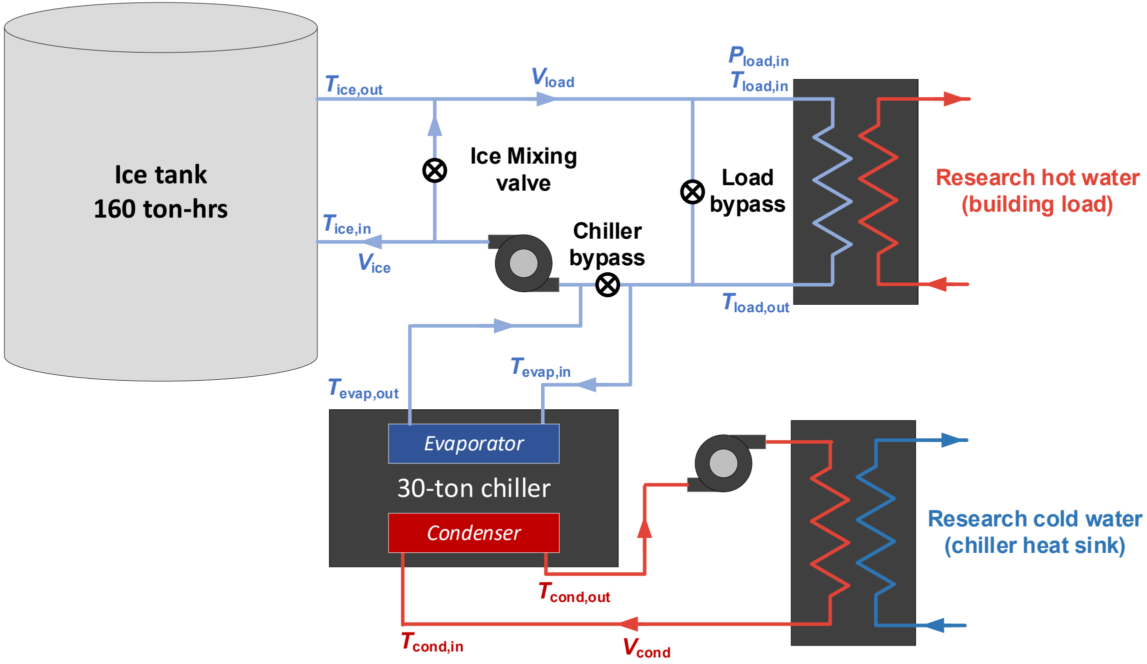
Bi-directional
AC Power

Bi-directional
DC Power

Bi-directional
AC Power

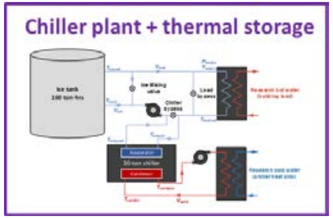
Chiller plant + thermal storage





Chiller is controlled to modulate down with ice tank making up the difference

Chiller plant + thermal storage

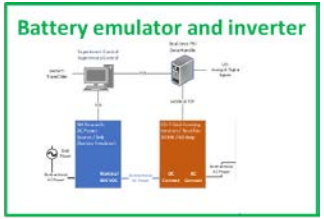


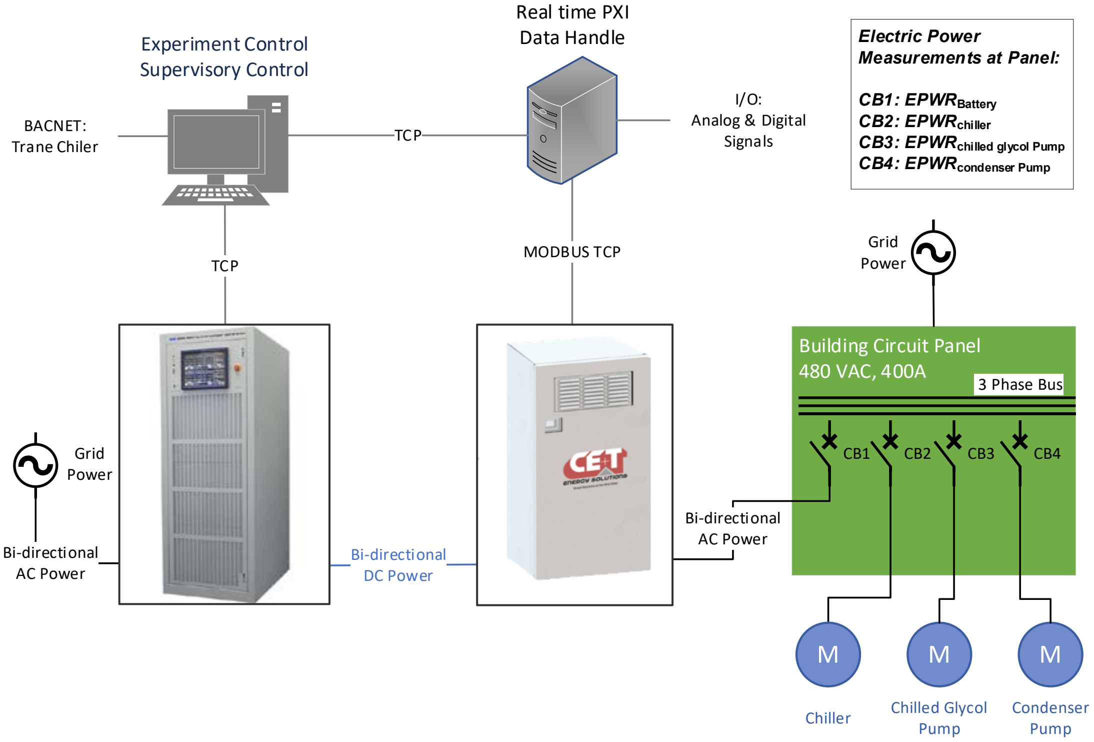
Fluid conditioning module

Ice tank, 162 tonh (570 kWh)

Chiller, 30 ton (105 kW)

Battery emulator with inverter


Battery emulator and inverter


Experiment Control
Supervisory Control

Real time PXI
Data Handle

BACNET:
Trane Chiler

TCP

I/O:
Analog & Digital
Signals

TCP

MODBUS TCP

Electric Power Measurements at Panel:

CB1: $EPWR_{Battery}$
CB2: $EPWR_{chiller}$
CB3: $EPWR_{chilled\ glycol\ Pump}$
CB4: $EPWR_{condenser\ Pump}$

Grid
Power

Building Circuit Panel
480 VAC, 400A
3 Phase Bus
CB1
CB2
CB3
CB4

Grid
Power

Bi-directional
AC Power

Bi-directional
DC Power

Bi-directional
AC Power

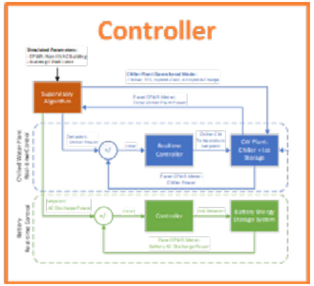
M
Chiller

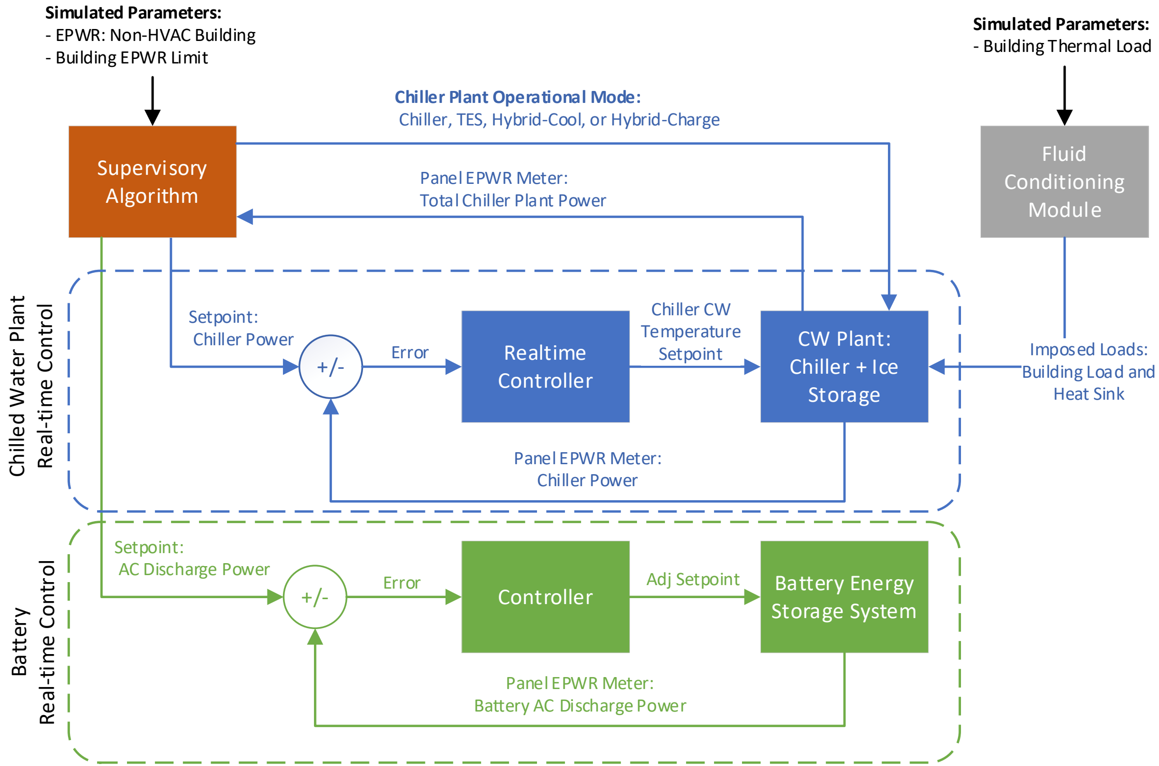
M
Chilled Glycol
Pump

M
Condenser
Pump

Battery charge/discharge is controlled with 30-kW CE+T inverter/rectifier, through MODBUS signal

Supervisory controls

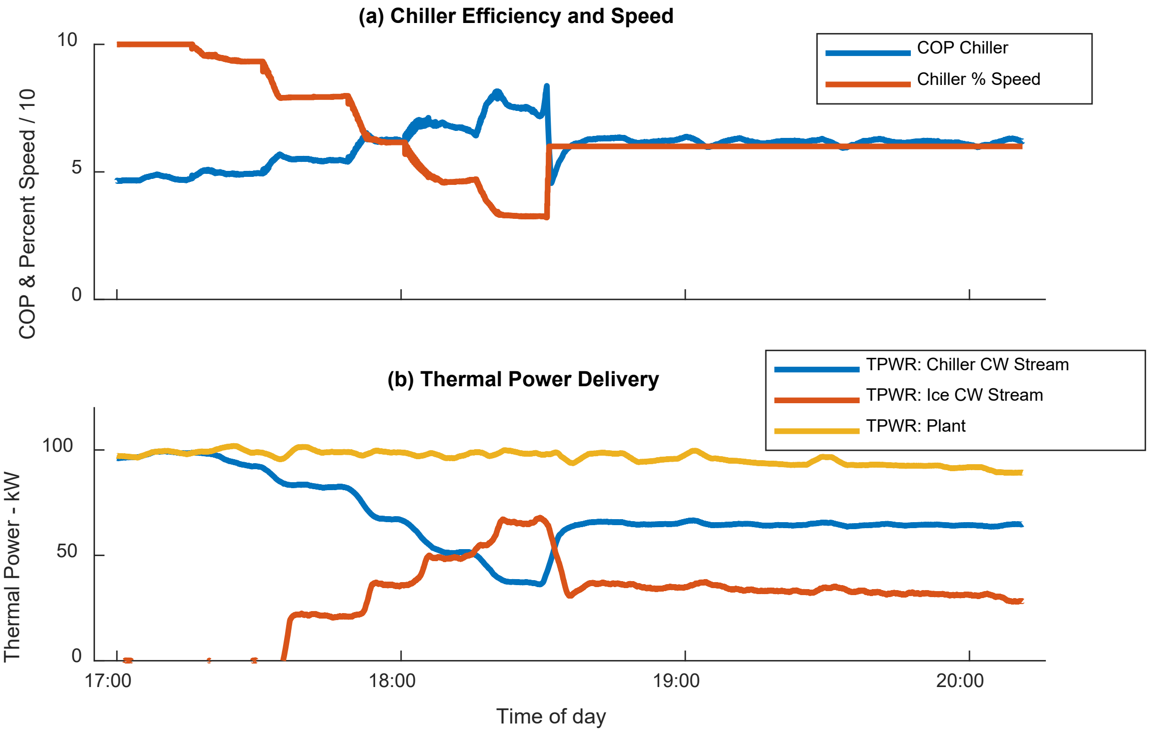




Chiller + TES performance

- Modulation of chiller increases efficiency by ~45%

- Compressor modulation limited to 60-100%, based on an internal Trane software limit.

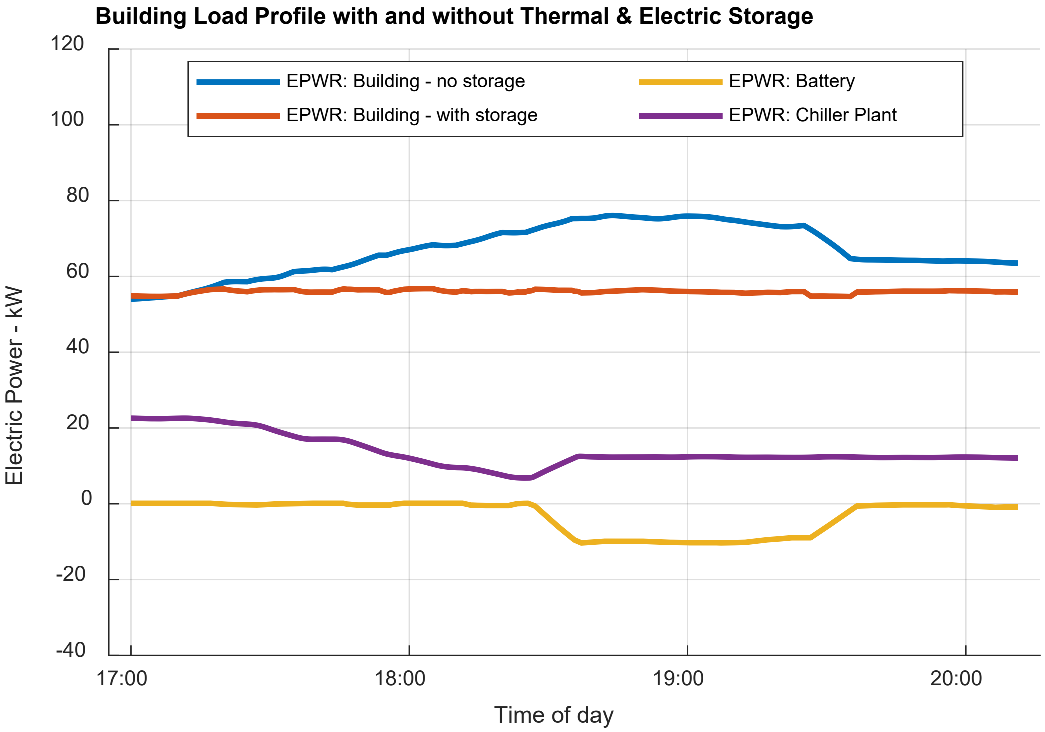


Example experiment: Electric load leveling

- Chiller modulation reduces electric load from 5-6:30pm. Battery provides additional load reduction from 6:30-7:30pm.

- Chiller efficiency improves by ~40% at part load.

- 35.3 kWh of shaved energy
  - 71% from TES
  - 29% from BES



Conclusions

Simulations:

- Adding batteries to a TES system can increase the total system's load shaving potential (and increase TES utilization for peak demand reduction)
- Adding TES to a battery system can improve economics since TES often has a lower capital cost, and because it can significantly lower battery cycling, extending the battery life
- In the climate analyzed in this study, which has a large cooling load, the pseudo-optimal hybrid design is often some combination of thermal and battery storage, and rarely only a battery-only or TES-only system

Experiments:

- Supervisory controllers can communicate with both thermal and battery energy storage systems to optimize controls
- Improved chiller efficiency at part load can increase the load shifting capability for TES (not yet included in above simulations)
- Limitations on chiller turndown ratio and response time can limit what is possible compared to simulations above. This should be considered when selecting a chiller for a thermal storage application

Questions

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Supplemental slides

Modeling approach

Model Inputs

- 2.1 Variable utility rate structures
- 2.2 Energy storage system models
- 2.3 Electric demand from building thermal and nonthermal loads

Processing

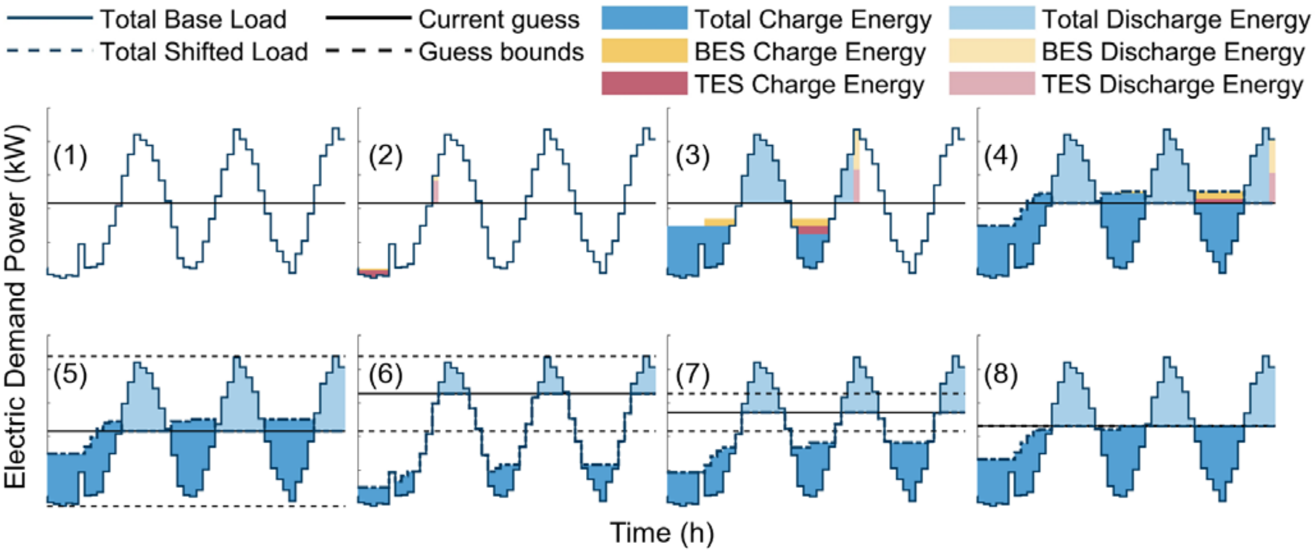
- 2.4.1 Binary search approach
- 2.4.2 Idealized dispatch algorithm
- 2.5 Post-processing
- 2.6 Sensitivity analysis

Results & Discussion

- 3.1 Load profiles and load duration curves
- 3.2 Annual performance and cost savings of hybrid storage systems
- 3.3 Sensitivity to model inputs

Idealized dispatch strategy

Binary search finds peak load reduction by successively guessing the final shaved load shape.



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Sensitivity analysis