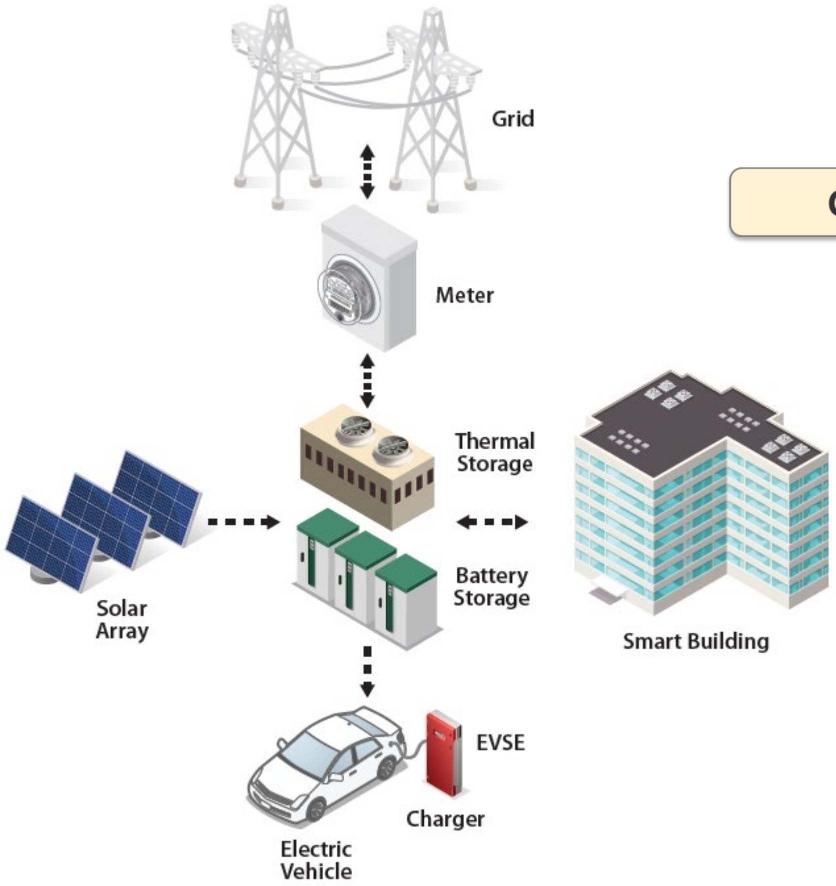
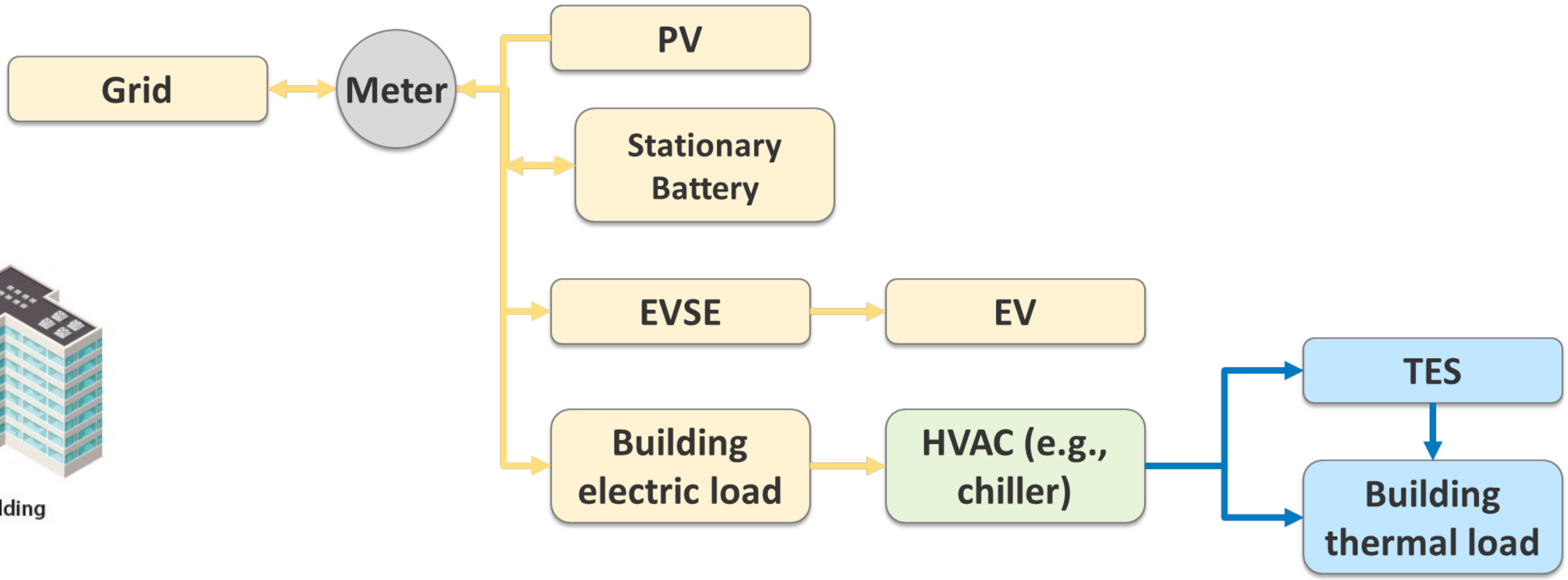
Behind the Meter Storage Analysis





NREL
Margaret Mann, Group Manager
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2021 BTO Peer Review
August 25, 2021 3:30 ET

Project Summary

Timeline:
Start date: 10/1/2019
Planned end date: 9/30/2022

Key Milestones

1. Working EnStore model, incorporating existing models, and draft results – Sept 2020
2. Summary of EnStore results from incorporation data from the BTO-funded research project on thermal energy storage (TES) – June 2021
3. Interactive visualization tools for scenario exploration by audiences outside of project team such as DOE and industry advisors – Sept 2021

Collaboration & Coordination:

- A joint project between VTO, BTO, OE, and SETO
- BTMS Research Project on Thermal Energy Storage and Battery Lifetime Five Laboratory Team lead by NREL: Sandia National Laboratory, Argonne National Laboratory, Idaho National Laboratory, Pacific Northwest National Laboratory
- Receiving inquiries from utilities, charging companies, and building owners – will pursue in FY22

Budget: Total Project Funding to Date:

- BTO: $500k in FY20 + $7500k in FY21
- SETO: $500k in FY20
- VTO: $350k in FY21

Project Outcome:

- *Key Question: What are the optimal system designs and energy flows for thermal and electrochemical behind-the-meter-storage with on-site PV generation enabling fast EV charging for various climates, building types, and utility rate structures?*
- *The EnStore Model is being developed to identify the most efficient means of deploying BTMS across the U.S. for fast-EV charging at different buildings, in different climates, with PV generation*
- *Detailed physics-based modeling and predictive controls provide required fast response to "spiky" EV charging demands and dynamic utility rate structures.*

A Talented Team for a Complex Challenge

Margaret Mann, PI

Tony Burrell, R&D Fearless Leader

Eric Bonnema, E+ & Buildings Guru

Brennan Borlaug, EV Charging Oracle

Madeline Gilleran, Code, Results, & Visualization Prodigy

Darice Guittet, Battery, SAM & Controls Programmer Extraordinaire

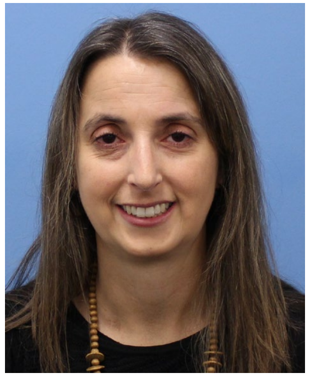
Chad Hunter, Finance Authority

Monte Lunaceck, Simulation Tamer

Andrew Meintz, EV Charging Master

Matt Mitchell, HPC Tamer & TES Expert

Partha Mishra, EVI-EnSite Creator



Kristi Potter, Visualization Whiz

Challenge

- **Several fundamental and watershed changes in the transportation, electrical, and buildings sectors are happening simultaneously. Understanding the intersection of these changes is essential for optimizing the economic, social, and climate benefits.**
  - Buildings are going to be required to serve a lot more needs than before, e.g., grid services, EV charging, electric generation, space conditioning, energy storage, resiliency….
  - Rapid EV adoption could have a significant, and potentially negative effects on grid infrastructure and buildings operations
  - Large penetration of solar photovoltaic (PV) generation installed on buildings is leading to new challenges for building interactions with the electric grid
  - New wind and solar installations are market competitive, creating new challenges for utilities
  - Energy storage energy costs are rapidly declining, enabling greater use of clean energy

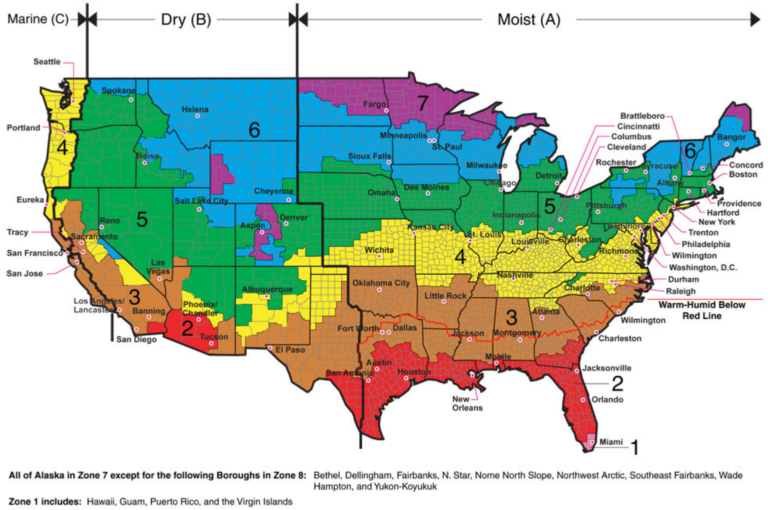
- **Individual components behave differently when integrated into systems.**

- ***The EnStore Model dynamically evaluates, at the physics-based level, how batteries and thermal energy storage can reduce costs for fast EV charging at multiple buildings in different locations***

- **EnStore seeks to evaluate how *integrated systems* can unlock additional value for building owners, utilities, and EV drivers – at the same time, across the U.S.**

Approach: Use Detailed Physics-based Modeling and Predictive Controls to Evaluate the Potential for Behind the Meter Energy Storage (BTMS) to Mitigate Costs and Grid Impacts of Fast EV Charging

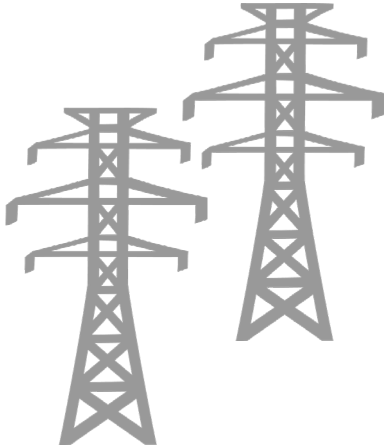
Key Question: What are the ***optimal*** **system designs** and **energy flows** for **thermal** and **electrochemical** behind-the-meter-storage with on-site **PV** generation enabling **fast EV charging** for various climates, building types, and utility rate structures?



6 ASHRAE Climate Zones

5 Building Types with Varying EV Charging Demand

Corner charging station, Retail big-box grocery store, Fleet vehicle depot, Commercial office building, Multi-family residential



Thousands of Utility Rate Structures Across U.S. (and changes very likely)

Approach: Other Important Questions

1. What is the sensitivity of analysis results to the variability of location, building loads, EV charging demands, and component costs, and combinations of each case within those categories?

2. What research achievements (e.g., material characteristics for thermal energy storage, battery material costs and lifetime, PV deployment) would increase the economic viability of the various configurations of BTMS at multiple locations?

3. What level of improved iterative feedback modeling (controls), informed by BTO research on TES and VTO research on battery degradation, would be necessary to optimize sizing and designs for subsystem components (PV, battery size and operation, thermal storage)?

4. What is the potential energy savings, GHG emissions reduction, PV energy generation, and EV demand coverage in different locations across the U.S., as a function of technical and cost improvements?

Approach: The EnStore Model - High-Level Architecture

Utilize existing models where appropriate and update them to evaluate the interaction between components at physics-based resolution

EnStore

Pre-Process

- Generate the baseline building load profile using **EnergyPlus**
- Generate the electric vehicle charging station load profile using **EVI-EnSite**
- Specify component costs, weather data, utility rate tariffs.

Seed

- Use **REopt** to limit the initial parameter space with simplified models and idealized controls.
- Suggest initial sizes for stationary battery and solar PV.

Explore

- Perform battery simulations in **SAM**
- Use **EnergyPlus** for building loads and thermal energy storage.
- Co-optimize storage dispatch in **SAM** and **EnergyPlus** with supervisory predictive controls
- Run sensitivities across parameters

Model Report

- Store key system characteristics, e.g., stationary battery, solar PV, and thermal storage sizes for each run.
- Provide time-series outputs for post-processing.
- Use **SAM** to calculate financial metrics.
- Report results for all cases to visualization

Post-Process

Use data analytics and advanced visualizations

- Analyze which parameter variations yield the lowest LCOC.
- Analyze sensitivity of results to key input parameter values.
- With each set of insights, refine & define new scenarios

Approach – Sensitivity Analysis is Critical for Understanding Important Cost Levers and Optimal Configurations

The design and configuration of a BTMS system depends on many factors:

- Climate: building energy use, battery conditioning, battery lifetime, efficiency of EVs
- Utility rate structures: demand and time-of-use charges, cost of energy
- Connection to the grid: infrastructure improvement costs (and can BTMS help reduce or defer these costs)
- Building type energy demand profiles, space limitations, population served
- Capital costs – batteries, thermal energy storage (TES), EVSEs, PV, power electronics
- Controls algorithm – when to dispatch stationary battery and TES; EnStore now uses supervisory model predictive controls (MPC)
- Storage operation - battery and TES state-of-charge, discharge/charge rate, temperature

Parameters are varied separately and in combination, leading to tens-of-thousands of simulations, necessitating high-performance-supercomputing and advanced visualization techniques

Approach: Improve Representation of Thermal Energy Storage Using Data From Companion Lab Research Project

EnStore

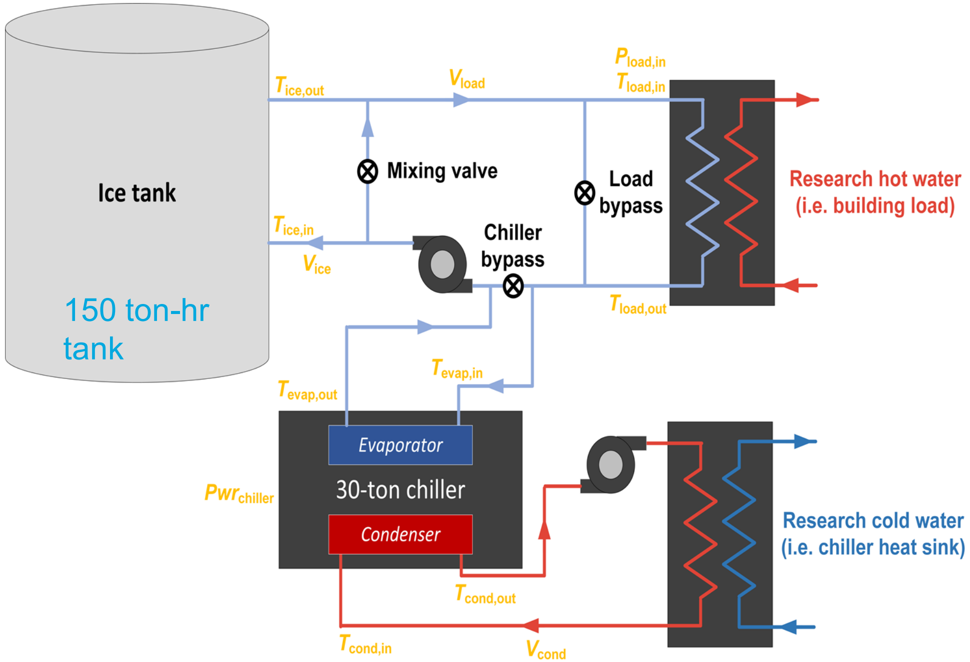
Pre-Process
- Generate the baseline building load profile.
- Generate the electric vehicle charging station load profile.
- Specify system costs, weather data, utility rate tariff, etc.

Seed
- Use **REopt** to limit the initial parameter space with simplified models and idealized controls.
- Suggest initial sizes for stationary battery and solar PV.

Explore
- Model system and component variations with greater fidelity.
- Use **OpenStudio/ EnergyPlus** for building loads, thermal storage, and supervisory controls; **SAM** for stationary batteries.
- Vary selected parameters to explore impact on LCOC.

Report
- Store key system characteristics, e.g., stationary battery, solar PV, and thermal storage sizes and corresponding LCOC.
- Provide time-series outputs for post-processing.

Post-Process
- Analyze which parameter variations yield the lowest LCOC.
- Analyze sensitivity of results to key input parameter values.
- **Answer research questions.**



Lab data from TES research was used to develop a novel TES model to update EnergyPlus to better reflect outlet temperature and ensure more accurate integration of TES in BTMS

Laboratory research project on TES, project #34667, Jason Woods PI

Approach: Start with Representative Buildings, Climates, Utility Rate Structures, and EV Charging Profiles

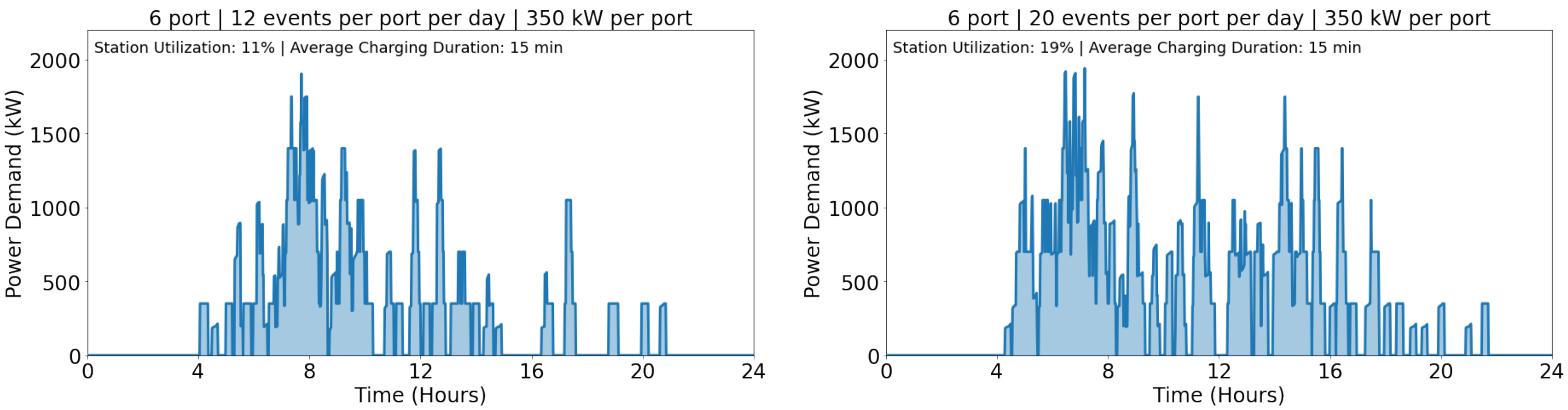
These scenarios were chosen as **examples** to demonstrate BTMS response to different building and EV electricity demands

Specific Locations in Several Climate Regions

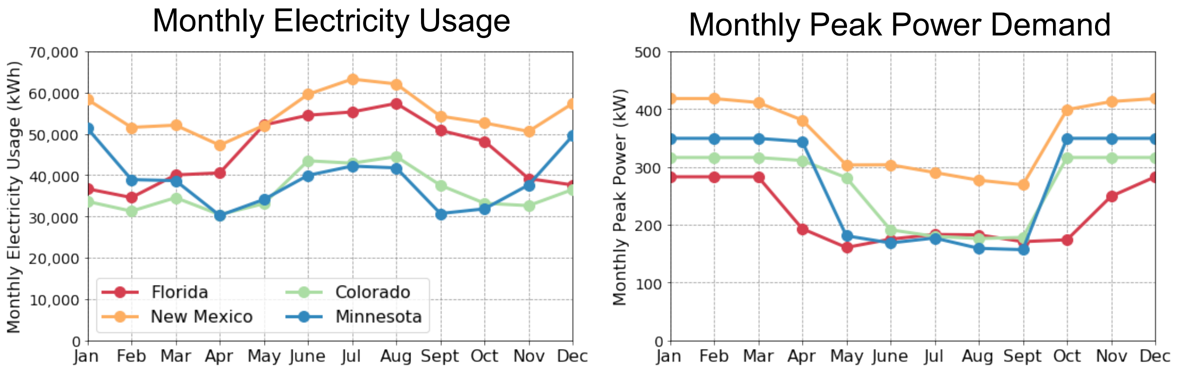
Climate Zone	Climate	Location
2a	Hot & Humid	Tampa, Florida
4b	Mixed Dry	Albuquerque, New Mexico
5b	Cool & Dry	Aurora, Colorado
7	Very cold	International Falls, Minnesota

*Utility rate scenarios shown on next slide

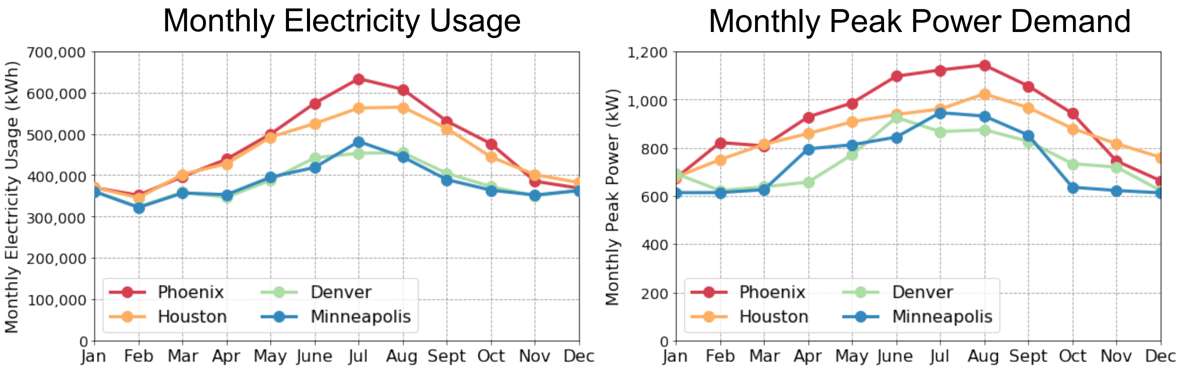
EV Fast Charging Demand Profiles



Commercial Medium Office Building



Big Box Grocery Store – MUCH greater demand



Approach: Evaluate the Impact of Utility Rate Tariffs

There are over 7,000 utility rate tariffs in the U.S. These rates were chosen as **examples** to represent various types of tariffs and demonstrate BTMS response to differing time of use (TOU)/demand charges and electricity prices

CONED

Consolidated Edison: monthly demand charges that range **5.36 - 16.7 $/kW** and TOU demand charges up to **23.89 $/kW**; flat energy rates

Demand Charge Schedule

Weekday Schedule

	12 am	1 am	2 am	3 am	4 am	5 am	6 am	7 am	8 am	9 am	10 am	11 am	12 pm	1 pm	2 pm	3 pm	4 pm	5 pm	6 pm	7 pm	8 pm	9 pm	10 pm	11 pm
Jan	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
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Dec	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

PGE

Pacific Gas & Electric: flat demand charges of **15.97 $/kW** and TOU demand charges up to **20.62$/kW;** TOU energy charges

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XCEL

Xcel Energy: constant demand charges at **5.63 $/kW**, but energy charges vary much more than those of CONED

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Results preview: Utility rate schedules have a significant impact on LCOC and system configuration.

Progress: Results for Big Box Grocery Store

4 Climates, 3 Utility Rate Structures,
2 Charging Demands

Utility rate structure has a big impact on LCOC, PV size, and battery size

Location (climate), while important, has a smaller impact because EV charging demand dominates costs. With less EV demand, climate results in different building energy use

Battery Cost = $120/kWh |$ 540/kW
PV Cost: $1600/kW
EVSE cost per port: $185,000

NOTE: Results are for a specific scenario; do not generalize to other cases

Medium Station Utilization

6 PORT 12 EVENT 350 KW STATION

Minimum LCOC (¢/kWh)

Climate	CONED	PGE	XCEL
Very Cold	22.7	26.6	19.2
Mixed Dry	21.9	21.7	19.2
Hot & Humid	22.2	22.5	18.8
Cool & Dry	21.3	22.4	19.1

Recommended PV Size (kW)

Climate	CONED	PGE	XCEL
Very Cold	0	1,200	2
Mixed Dry	290	1,200	129
Hot & Humid	0	1,200	2
Cool & Dry	0	1,200	2

Recommended Battery Size (kWh)

Climate	CONED	PGE	XCEL
Very Cold	24,730	9,460	0
Mixed Dry	22,330	10,350	0
Hot & Humid	24,670	8,650	0
Cool & Dry	23,320	9,000	0

High Station Utilization

6 PORT 20 EVENT 350 KW STATION

Minimum LCOC (¢/kWh)

Climate	CONED	PGE	XCEL
Very Cold	15.6	22.9	14.0
Mixed Dry	15.1	19.7	14.0
Hot & Humid	15.9	20.5	13.9
Cool & Dry	15.5	21.0	14.0

Recommended PV Size (kW)

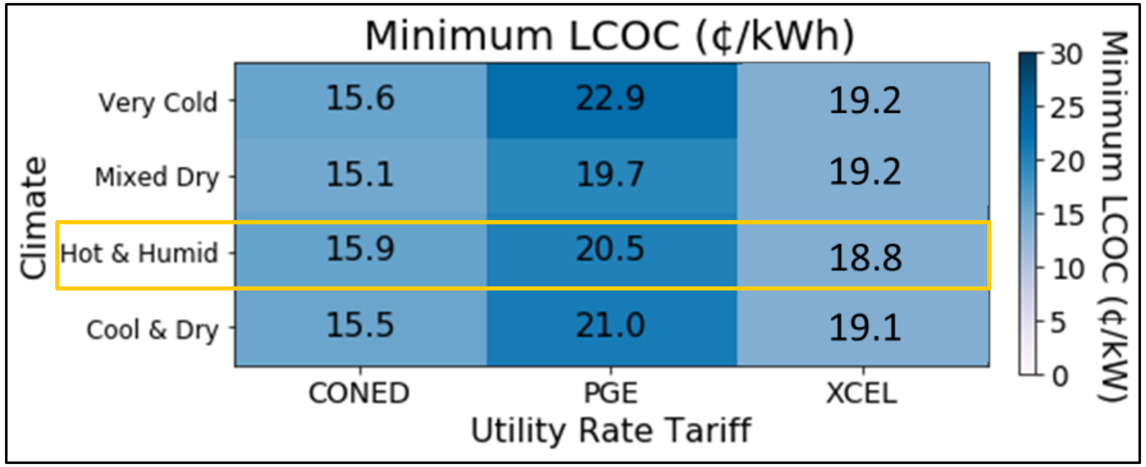
Climate	CONED	PGE	XCEL
Very Cold	2	1,200	2
Mixed Dry	0	1,200	129
Hot & Humid	0	1,200	2
Cool & Dry	0	1,200	2

Recommended Battery Size (kWh)

Climate	CONED	PGE	XCEL
Very Cold	23,670	10,660	0
Mixed Dry	24,010	10,530	0
Hot & Humid	26,390	9,560	0
Cool & Dry	22,240	10,460	0

Progress: Optimal Design of BTMS for a Big Box Grocery Store

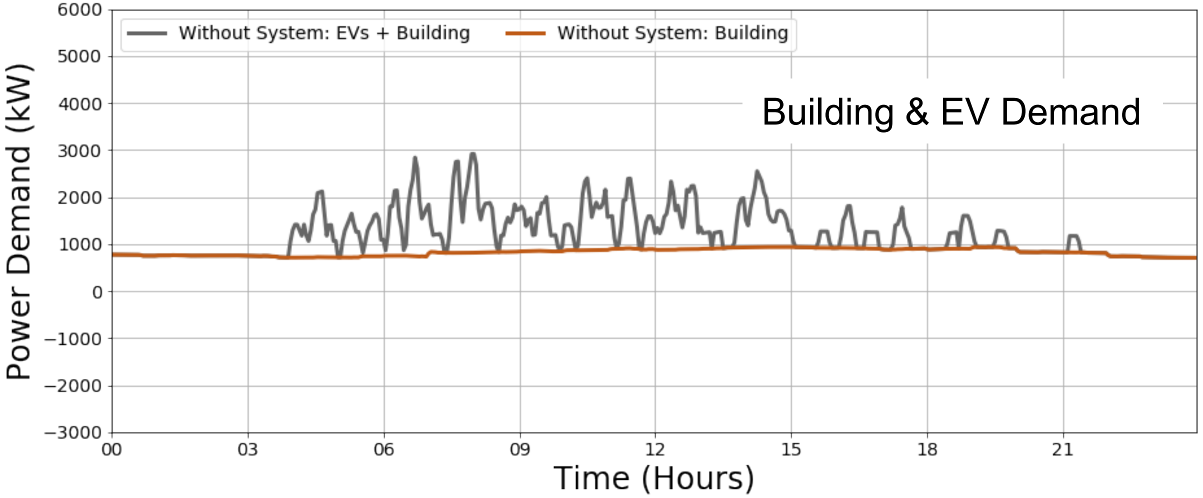
- **The next three slides show the following results for a big box grocery store:**
  - Energy flows for one day of operations
  - *Optimum* levelized cost of charging (LCOC) (¢/kWh) for each scenario
  - LCOC as a function of PV and battery sizes
  - LCOC without PV and stationary batteries (no BTMS)
- **For the following conditions:**
  - Big box grocery store with 6 ports, 20-events per port per day (medium facility utilization)
  - 350 kW fast EV charging
  - 4 example climates
  - 3 example utility rate structures



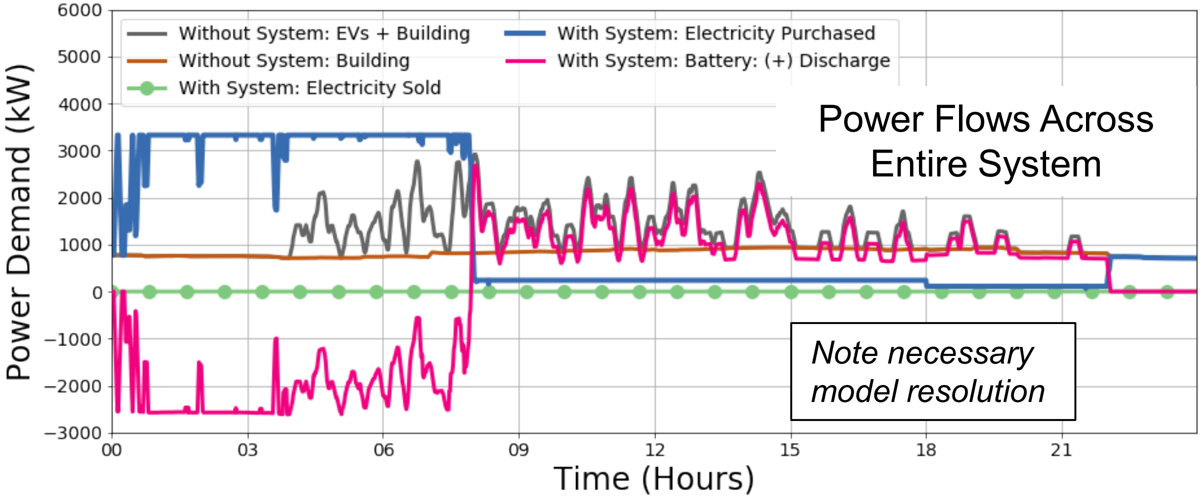
EVSE Cost = $185,000/port
Battery Cost = 120 $/kWh, 540 $/kW
PV Cost: $1600/kW

Big Box Grocery Store with CONED Rate Structure

42% Reduction in LCOC with BTMS



The battery mostly follows EV charging demand, but some electricity is purchased from the grid to supplement. For this scenario, it's cheaper to buy electricity than to install PV.



Note necessary model resolution

Minimum LCOC (¢/kWh)

Climate	CONED	PGE	XCEL
Very Cold	15.6	22.9	19.2
Mixed Dry	15.1	19.7	19.2
Hot & Humid	15.9	20.5	18.8
Cool & Dry	15.5	21.0	19.1

Utility Rate Tariff

Minimum LCOC (¢/kWh): 0, 5, 10, 15, 20, 25, 30

Min LCOC with System (¢/kWh): 15.9

Size Solar PV (kW) \ Size Battery (kWh)	0	4397	8795	13192	17590	19788	21987	26385	30782	35180	39577	43975	48372	52770	57168	61565	65963	70360	74758	79155
241	27.2	27.6	24.2	20.3	18.7	17.8	16.8	16.0	17.8	20.1	22.4	24.7	27.0	29.3	31.7	34.0	36.3	38.6	40.9	43.2
211	27.2	27.5	24.2	20.2	18.6	17.7	16.8	16.0	17.7	20.0	22.3	24.6	26.9	29.3	31.6	33.9	36.2	38.5	40.8	43.1
181	27.2	27.4	24.1	20.1	18.6	17.7	16.8	16.0	17.6	19.9	22.3	24.6	26.9	29.2	31.5	33.8	36.1	38.4	40.7	43.0
150	27.2	27.4	24.1	20.1	18.6	17.7	16.7	15.9	17.6	19.9	22.2	24.5	26.8	29.1	31.4	33.7	36.0	38.3	40.6	42.9
120	27.2	27.4	24.2	20.8	18.6	17.6	16.7	15.9	17.5	19.8	22.1	24.4	26.7	29.0	31.3	33.6	35.9	38.2	40.5	42.8
90	27.2	27.4	24.2	20.1	18.6	17.6	16.7	15.9	17.4	19.7	22.0	24.3	26.6	28.9	31.2	33.5	35.8	38.1	40.4	42.8
60	27.3	27.4	24.2	20.2	18.5	17.6	16.7	15.9	17.3	19.6	21.9	24.2	26.5	28.8	31.1	33.4	35.7	38.1	40.4	42.7
30	27.3	27.4	24.2	20.2	18.5	17.6	16.7	15.9	17.2	19.5	21.8	24.1	26.4	28.7	31.1	33.4	35.7	38.0	40.3	42.6
0	$\boxed{27.3}$	27.5	24.2	20.2	18.5	17.6	16.8	15.9	17.1	19.4	21.7	24.0	26.4	28.7	31.0	33.3	35.6	37.9	40.2	42.5

LCOC without BTMS System

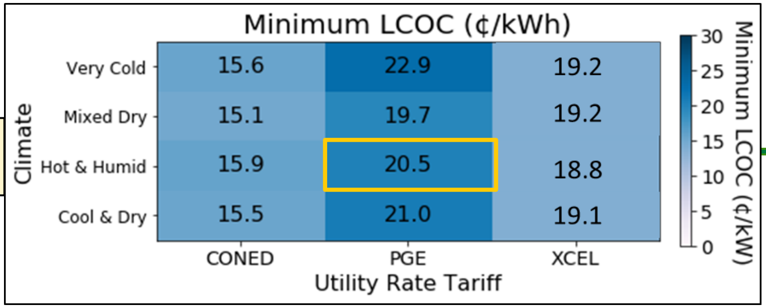
LCOC with BTMS System

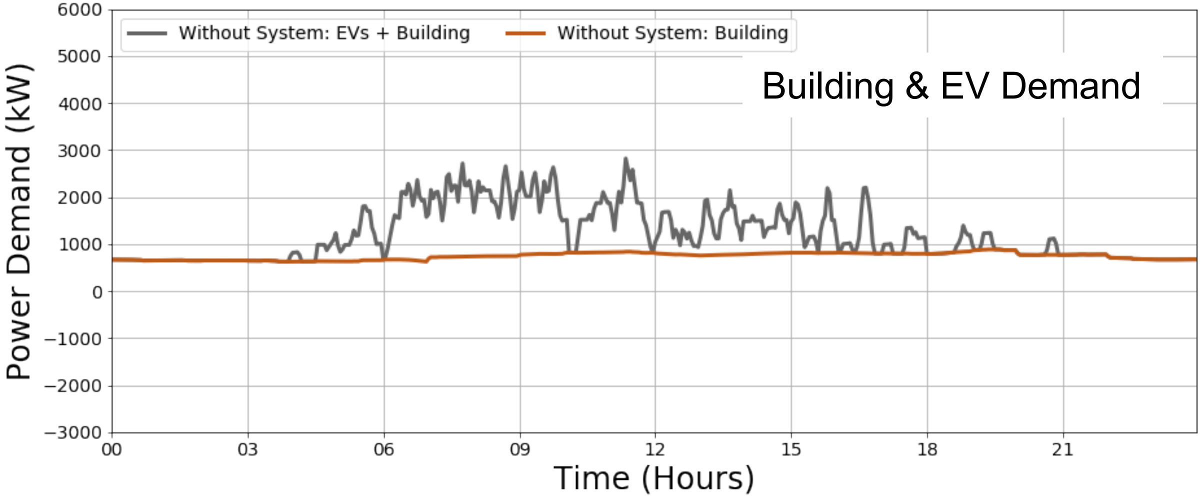
Runs using CONED utility rate recommend a large battery; PV can be installed at essentially no impact on LCOC

NOTE: Results are for a specific scenario; do not generalize to other cases

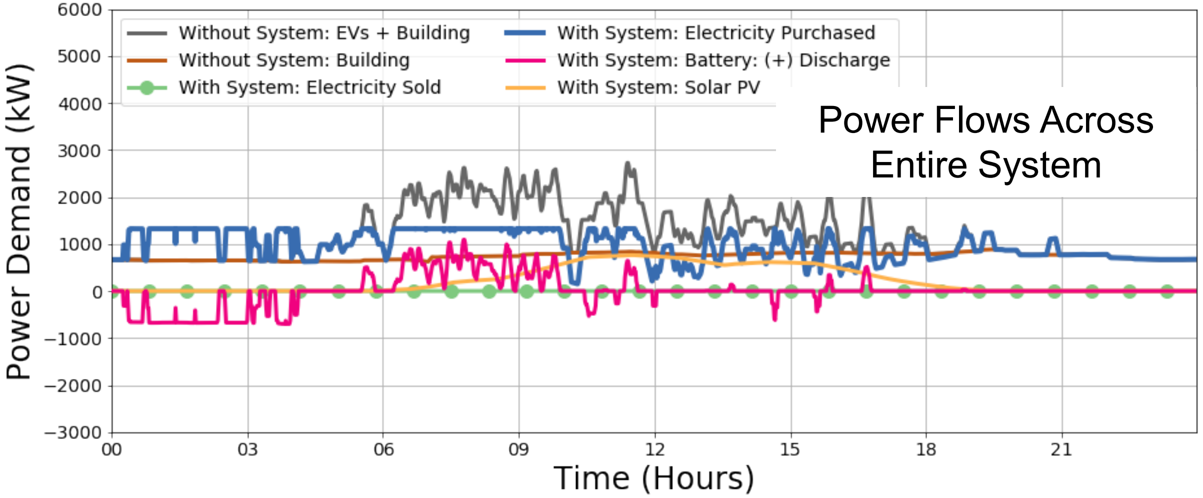
Big Box Grocery Store with PG&E Rate Structure

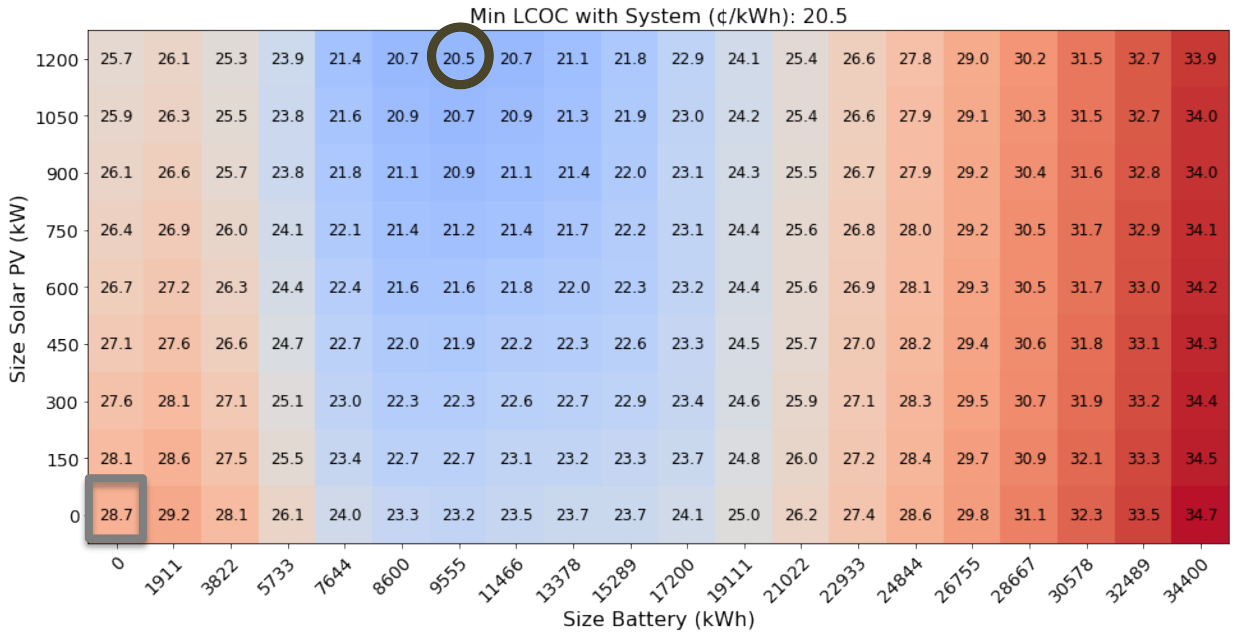
29% Reduction in LCOC with BTMS





The battery mostly follows EV charging demand, but has strong support from PV during the sunny hours and some purchased grid electricity.





29% Reduction in LCOC with BTMS

LCOC without BTMS System

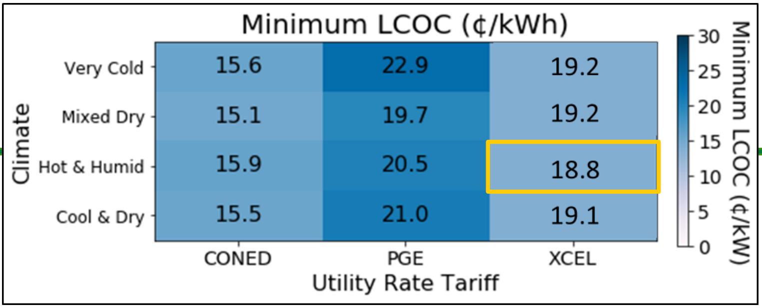
LCOC with BTMS System

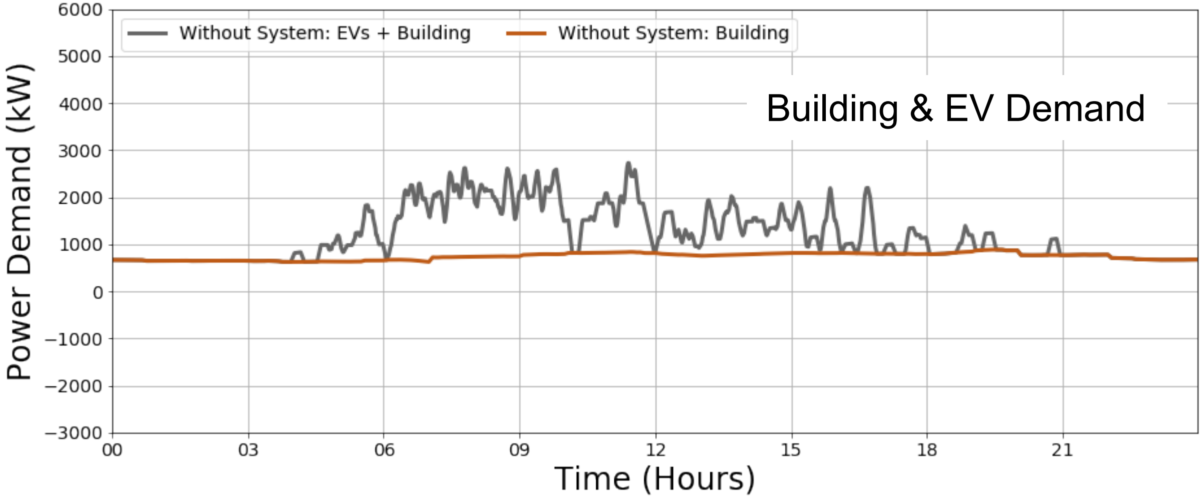
Runs using PG&E utility rate recommend significant PV and battery storage. More PV would be economically favorable if space allows.

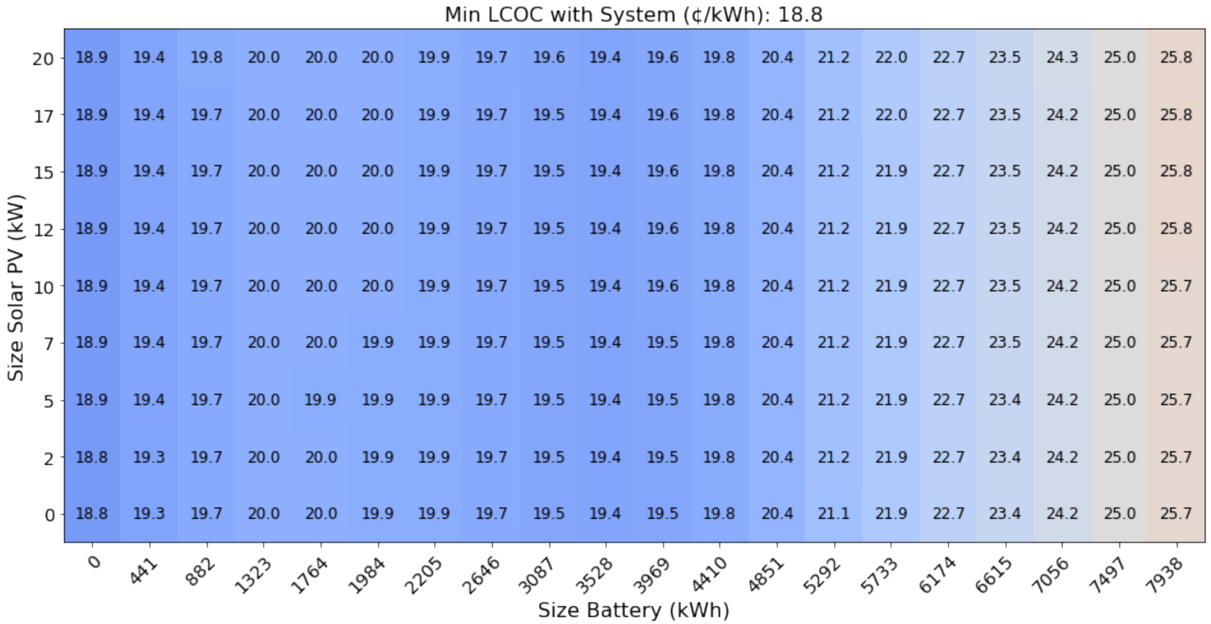
NOTE: Results are for a specific scenario; do not generalize to other cases

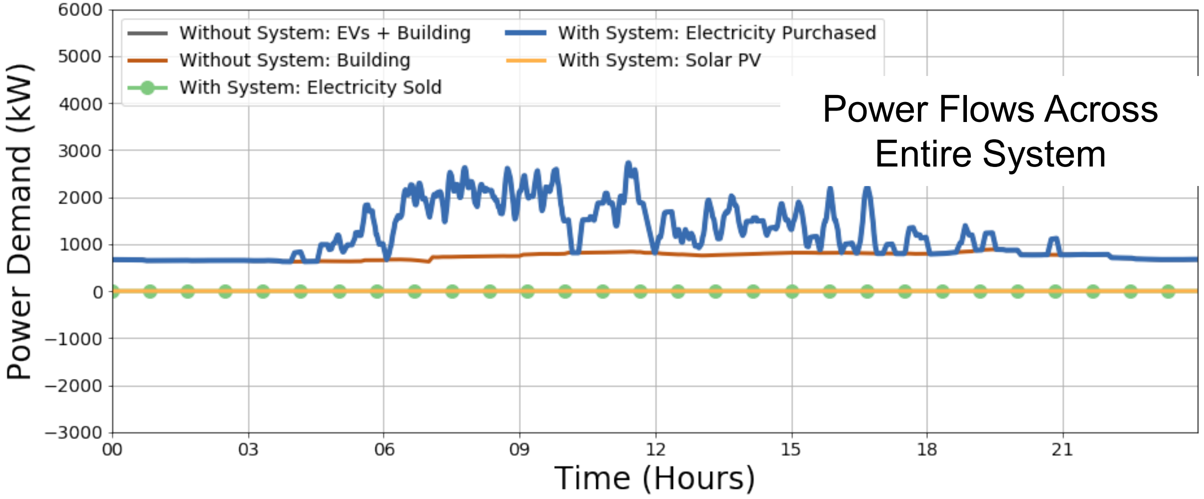
Big Box Grocery Store with XCEL Rate Structure

BTMS Not Economic in This Scenario.
PV is economically neutral.







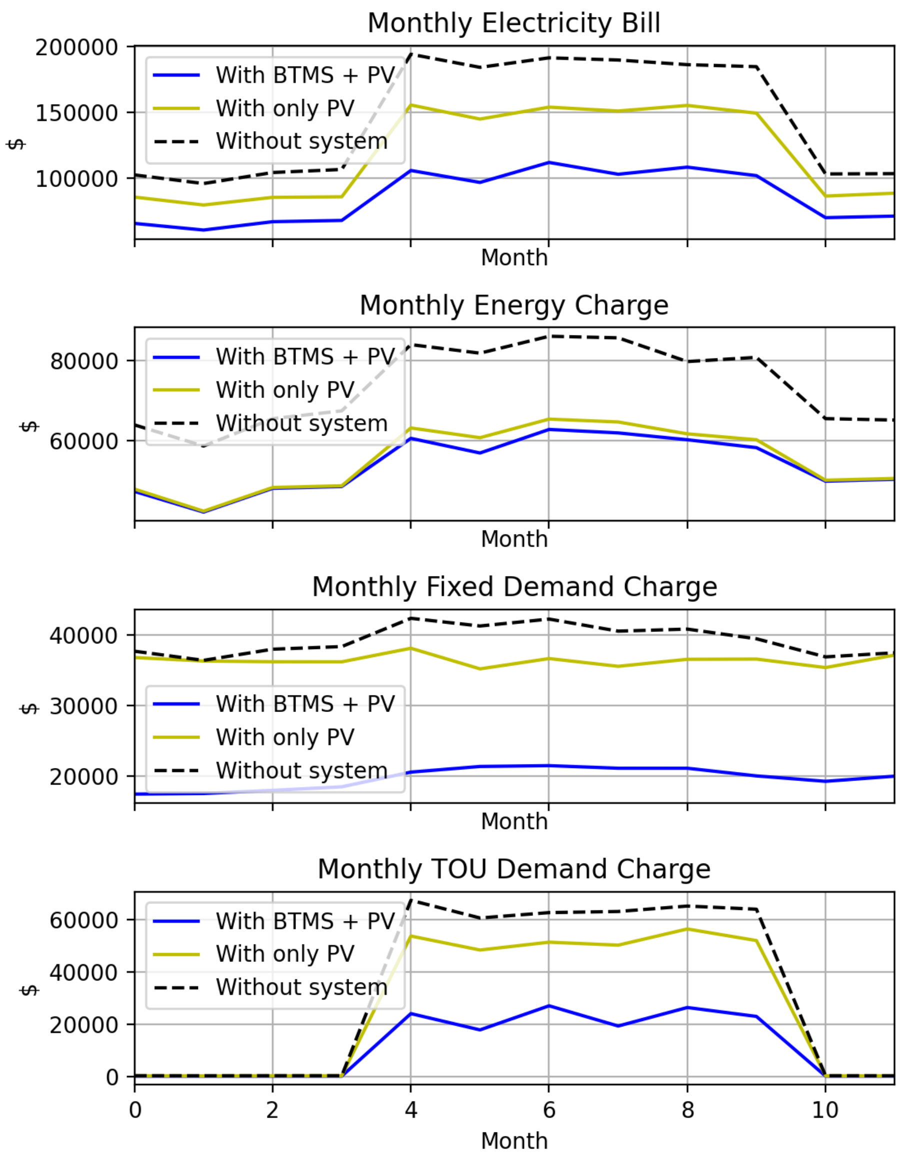


LCOC without BTMS System
LCOC with BTMS System

Runs using XCEL utility rate do not recommend PV or battery.
PV can be installed with essentially no impact on LCOC

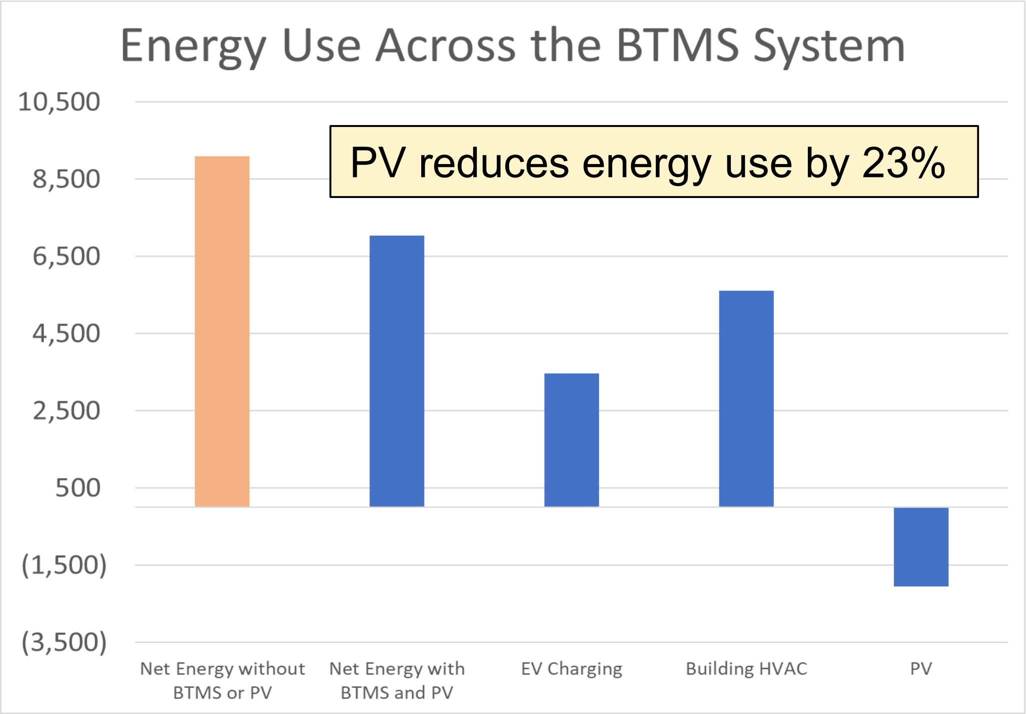
NOTE: Results are for a specific scenario; do not generalize to other cases

Impact: The Energy Use and Energy Cost Benefits of BTMS with PV Can Be Quantified



Big Box Grocery Store with PG&E Rate Structure in a Hot & Humid Climate

Annual Electricity Cost Reduction:
With PV: 19%
With BTMS + PV: 41%

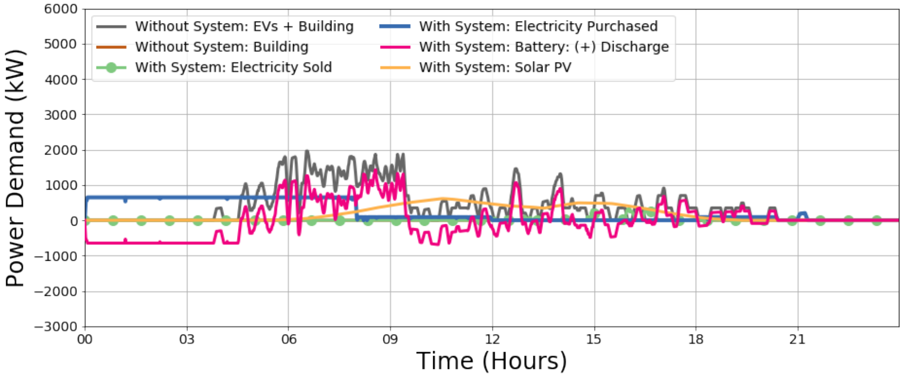


NOTE: Results are for a specific scenario; do not generalize to other cases

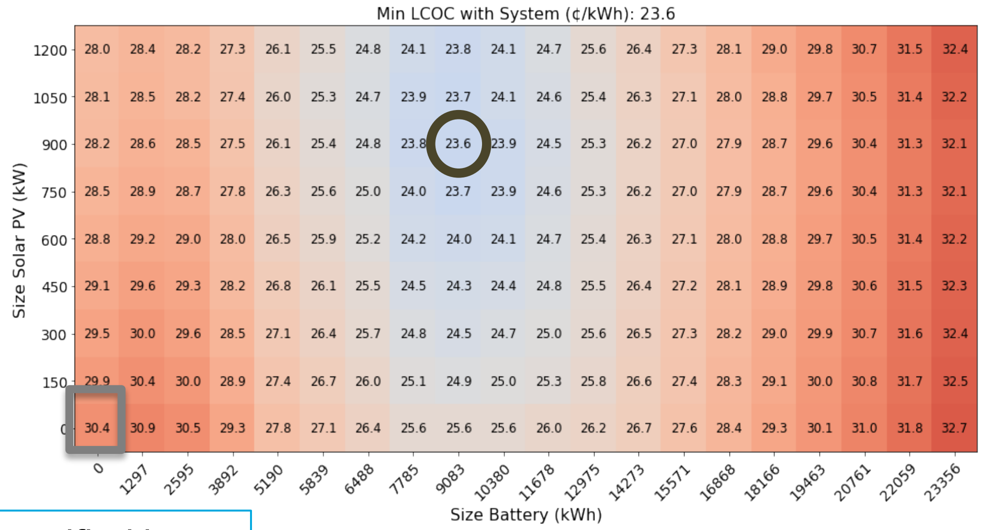
LCOC is Lowered if EV Charging is Behind the Same Meter as Building Because the Battery Can Help with Building Energy Loads

Hot & Humid Climate with PG&E Rate Structure Scenarios

EV charging station alone (separately metered):
Size solar PV: 1200 kW | Size battery: 9083 kWh

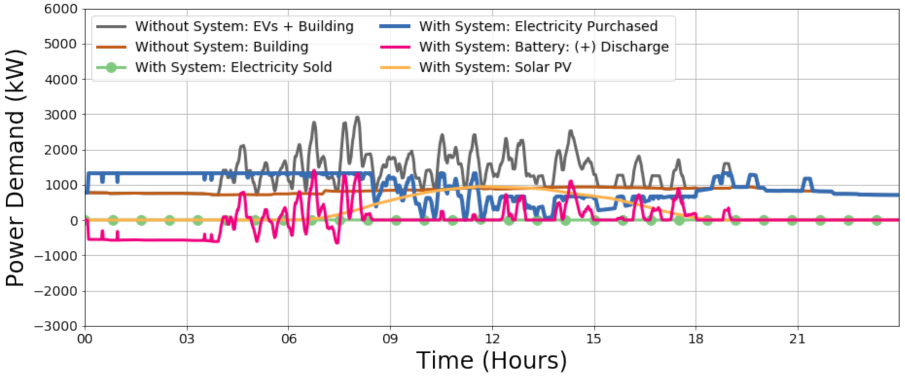


22% Reduction in LCOC with BTMS

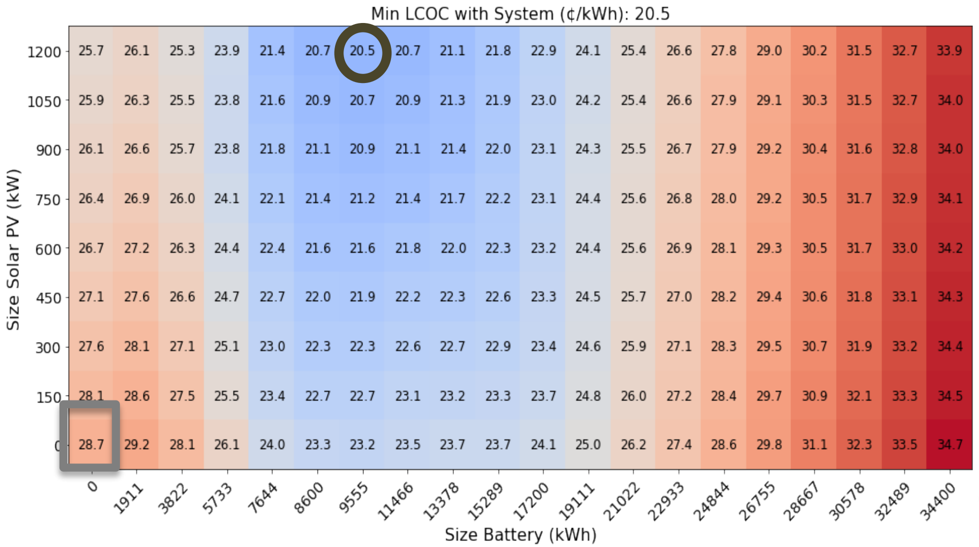


Additional savings due to shared facilities are also likely but were not quantified here

Big Box + EV charging station behind the same meter:
Size solar PV: 1200 kW | Size battery: 9556 kWh



29% Reduction in LCOC with BTMS



13% Reduction in LCOC if BTMS is integrated with building

Impact: EnStore is Ready for Evaluation of BTMS Across the U.S.

- **EnStore can now evaluate more than half-a-billion scenarios (but that's not helpful)**
  - 21 battery sizes(+/- 150% of REOpt seed value)
  - 1 thermal energy storage size (more coming soon)
  - 9 PV sizes (+/- 150% of REOpt seed value)
  - 6 ASHRAE climate zones (accessed from https://www.ashrae.org)
  - 7,000 utility rate tariffs (accessed from the Utility Rate Database: https://openei.org/wiki/Utility_Rate_Database)
  - 16 EV charging profiles (more to be developed)
- **For FY22, we are planning to run ~1 million scenarios**
  - 153,000 allocation units have been requested on the NREL High Performance Supercomputer (HPC)
- **Automated post-processing and visualization now assist the team with analysis of all these scenarios and will soon allow others to access results**
  - End-of-year FY21 milestone is a web-based interactive visualization tool for scenario exploration by audiences outside of project team such as DOE and industry stakeholders
  - FY22 visualizations will include maps of results and estimations of the total impacts of BTMS across the U.S.

Summary

- BTMS can improve the economics of buildings systems that provide fast-EV charging
- The EnStore Model answers the key question for integrated buildings:
  - *What are the optimal system designs and energy flows for thermal and electrochemical behind-the-meter-storage with on-site PV generation enabling fast EV charging for various climates, building types, and utility rate structures?*
- Without sufficient model resolution and physics-level data, the most effective design and use of energy storage cannot be determined, as EV charging demand and battery response time is "spiky".
- Integrated model predictive controls are required to co-dispatch batteries and thermal energy storage.
- EnStore can identify the most economic means of deploying BTMS across the U.S.

Collaboration and Coordination

- This project is part of the wider BTMS R&D project (# **bat442**)
  - Team of Five National Laboratories: *Sandia National Laboratory, Argonne National Laboratory, Idaho National Laboratory, Pacific Northwest National Laboratory*
- This project is funded by VTO, BTO, and SETO, leading to collaboration with researchers in the vehicles, buildings, and solar energy fields
  - In particular, this project regularly works with building researchers focusing on thermal energy storage for grid-interactive buildings and battery researchers
- These collaborations are ongoing, with weekly, monthly, and quarterly meetings, as well as informal project discussions
- *These collaborations are essential* for the partnership between analysis and R&D research. The research project provides input data and technical context for EnStore scenarios. The EnStore analysis project provides insight into the critical technical levers and research targets needed to meet the objectives of greater electrification of transportation and fast EV charging.

Proposed Future Research

Will be addressed by end of FY21:

- Finalize scenarios and run model across full parameter space.
    - We have run scenarios for 4 of 5 building types, 4 of 6 climate regions, battery costs, PV costs, battery lifetime, and impact of battery chemistry
- Public-facing visual interface for exploring the potential of BTMS under different changing scenarios
- On Thermal Energy Storage Model for Evaluation in EnStore
    - Run with multiple tanks
    - Develop model predictive controls for TES (When to start charge/discharge, chiller power trimming)
    - Optimize day-ahead chiller setpoints and ice discharge rates to meet load and objective (e.g., utility cost) given fixed tank size
    - Implement model predictive controls for entire facility to co-dispatch of battery and TES

To be addressed in FY22*:

- Financial impact of deferred upgrades to electric distribution on financial viability
- Exploration of the benefits on cost and building energy with additional grid-integrated-building services (e.g., resiliency, grid storage)
- More detailed visualization of results

Other proposed research*:

- Greenhouse gas emissions savings compared to no BTMS at locations across U.S. and at different levels of EV deployment
- Validate EnStore energy-flow results on charging systems at ARIES scale; improve model predictive controls algorithms
- Partner with charging & vehicle industries to validate market results
- Evaluate demand management of EV charging and building energy

*Any proposed future work is subject to change based on funding levels.

CONTRIBUTORS AND ACKNOWLEDGMENT

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Thank You

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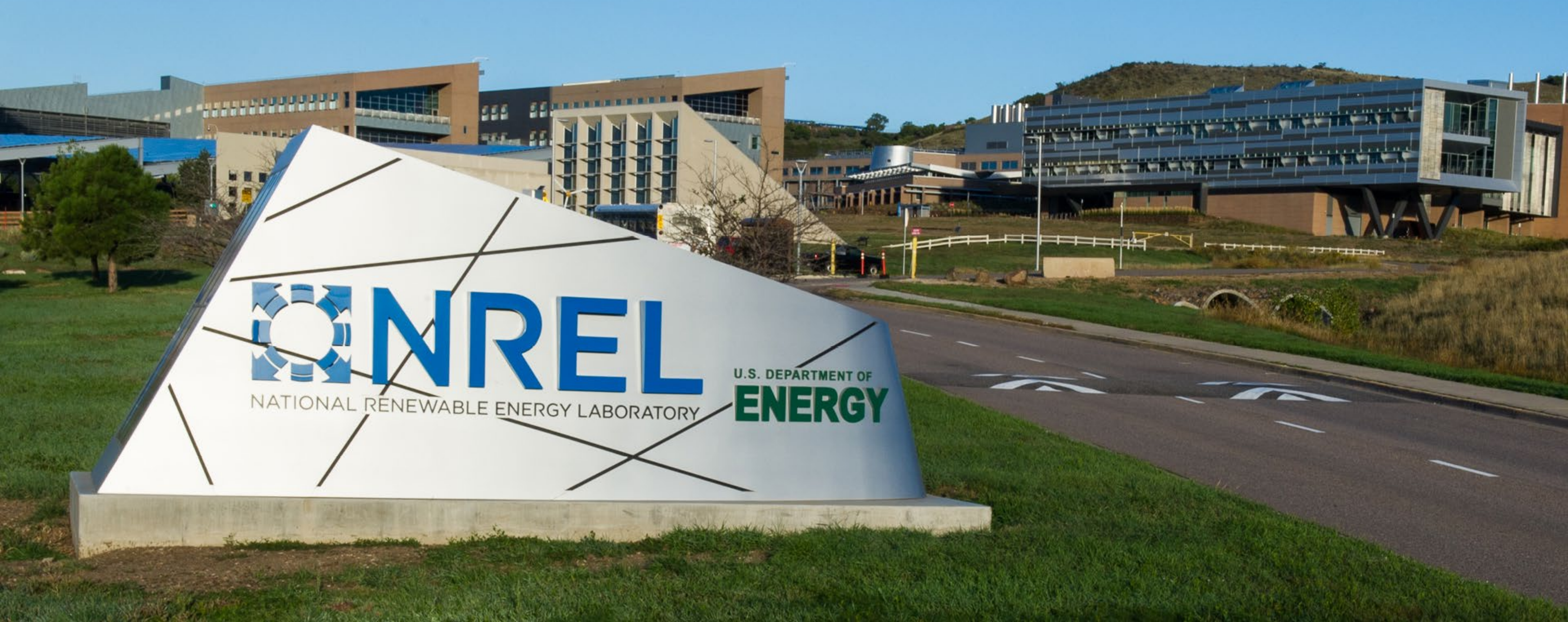


Additional Progress & Reference Slides

AOP Milestones

FY2020 – milestone details

Milestone Description	Due Date	Status
MS 1: Summary of inputs and outputs for models included in the EnStore modeling framework, with accompanying draft functional relationships.	FY21 Q1 12/31/2019	Complete
MS 2: Consult with an industrial advisory committee on research plan. NREL shall hold a webinar presentation to the TAC by the end of Q1. Perspective on assumptions, methodologies, and plan will be collected from all TAC members and shared with DOE.	FY21 Q2 3/30/2020	Complete
MS 3: Summary of range and probability distributions of EV electric load profiles-using EVI-Pro.	FY21 Q3 6/31/2020	Complete
MS 4: Summary of thermal and electric load profiles from the building types described in the Project Summary, as inputs to the EnStore Model.	FY21 Q4 9/30/2020	Complete

FY2021 – milestone details

Milestone Description	Due Date	Status
Summary of results and insights from EnStore runs of initial scenarios, focusing on the sensitivity of analysis results to the variability of location, building loads, EV charging demands, and component costs, and combinations of each within these categories.	FY21 Q1 12/31/2020	Complete
Summary of the incorporation of different controls strategies and the effects on results and insights.	FY21 Q2 3/30/2021	Complete
Summary of EnStore results of incorporation of data from the VTO-funded BTMS research project on battery testing and validation and data from the BTO-funded research project on thermal energy storage (TES).	FY21 Q3 6/31/2021	Complete
Interactive visualization tools for scenario exploration by audiences outside of project team such as DOE and industry advisors.	FY21 Q4 9/30/2021	In-progress; on-track

Project Budget

Budget History								Planned	
FY 2020 (past)		FY 2021 (current)		% of Budget Received Spent-to-Date				FY 2022 – (planned)	
DOE	Cost-share	DOE	Cost-share	DOE BTO	DOE SETO	DOE VTO	Total	DOE	Cost-share
$1M	N/A	$1.1M	N/A	71%	100%	54%	68%	$1M	N/A

Variances From Plan: None
Additional Funding: None

Approach: Assess Optimal Design with Financial Metrics

EnStore uses the standard financial approach known as discounted cash flow (DCF), which takes into account the time value of money throughout the project lifetime. EnStore uses a base discount rate of 8.6% (real).

- **Levelized Cost of Charging (LCOC) - ¢/kWh to vehicle owner**
  - The minimum levelized revenue per unit of electricity sold in the **EV charging station** required to recover the costs of the BTMS equipment over its financial life
  - *Research Question: What is the minimum cost of electricity that needs to be charged to EV owners in order to pay back all of the capital and operating costs over the lifetime of the operation. How does this compare with the cost of charging without BTMS or elsewhere?*

- **Levelized Cost of Electricity (LCOE) - ¢/kWh to building owner**
  - The average revenue per unit of electricity generated in the **building** that would be required to recover the costs of the BTMS equipment over its financial life
  - *Research Question: If we installed the BTMS assets, what would the relative (energy-cost) impact to the building owner be?*

- **Net Present Cost (NPC) - $**
  - The present value of all the costs the system incurs over its project lifetime
  - *Research Question: What will it cost (in today's dollars) to install and operate a BTMS system?*

** Future EnStore assessments can include the ability to assess the lowest carbon-emitting configuration*

Calculation of LCOC

The levelized cost of charging (LCOC) is the minimum selling price that the station owner must charge in order to pay back all capital and operating costs over the lifetime of the facility.

Important note: LCOC is not the market cost of charging a vehicle. Higher market costs will mean that the BTMS station is more profitable. Lower market costs will mean that the BTMS station owner is unable to recover all investment costs.

$$LCOC_{baseline} = \left(\frac{\boldsymbol{C'}_{EVSE+building} - \boldsymbol{C'}_{baseline\ building\ only}}{\boldsymbol{E'}_{BEV}} \right)$$

$$LCOC_{BTMS} = \left(\frac{\boldsymbol{C'}_{EVSE+building+\boldsymbol{BTMS}} - \boldsymbol{C'}_{baseline\ building\ only}}{\boldsymbol{E'}_{BEV}} \right)$$

$\boldsymbol{C'}_i = vector\ of\ discounted\ cash\ flows\ (costs)\ for\ system$
$\boldsymbol{E'}_i = vector\ of\ discounted\ energy\ flows\ going\ to\ item\ i$
$BEV\ =\ battery\ electric\ vehicle$

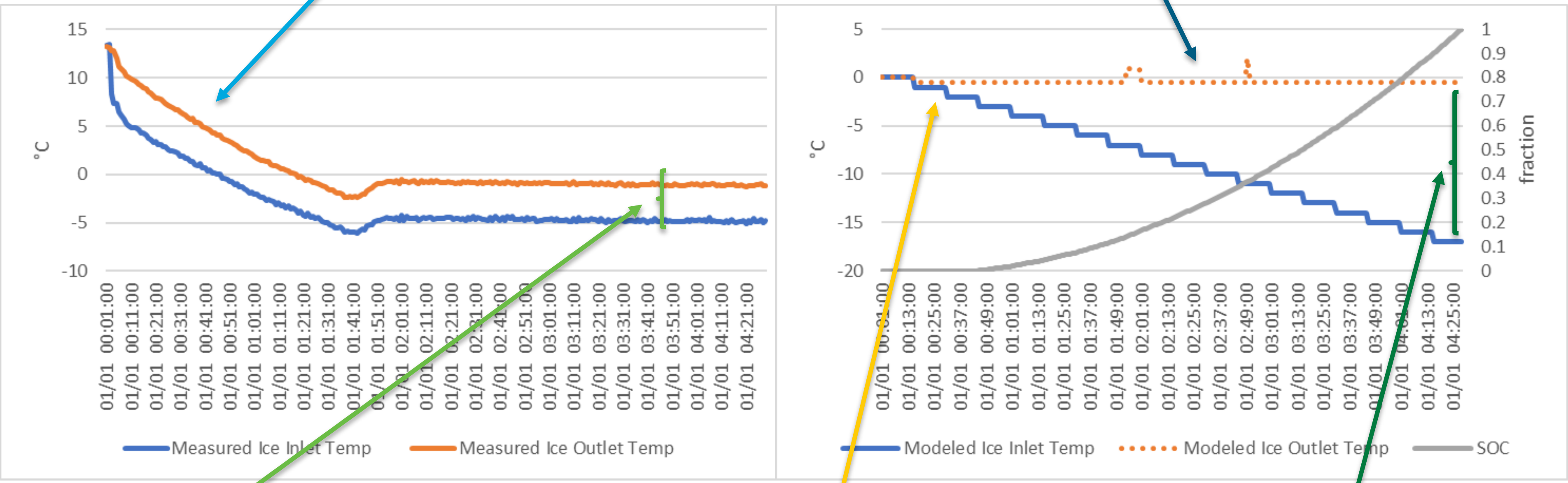
Research Question: How does the LCOC compare with the cost of charging without BTMS or elsewhere?

E+ Built-In Model Lacks Specific Details

EnergyPlus has been updated to better estimate behavior of TES. Examples of simplified, hard-coded values, and absent parameters are shown here.

Use of sensible energy between freezing point of water and leaving tank absent

Tank discharge hardcoded to 0.5° C



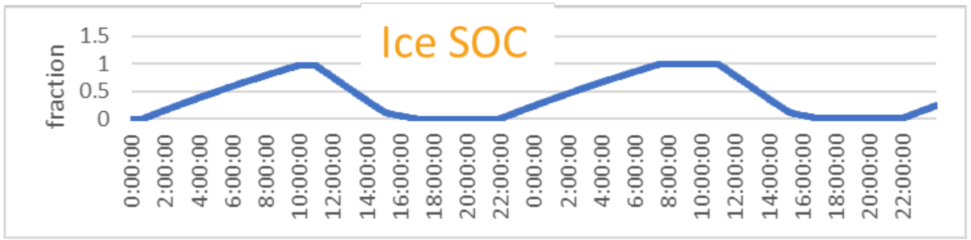
Measured data has constant ΔT

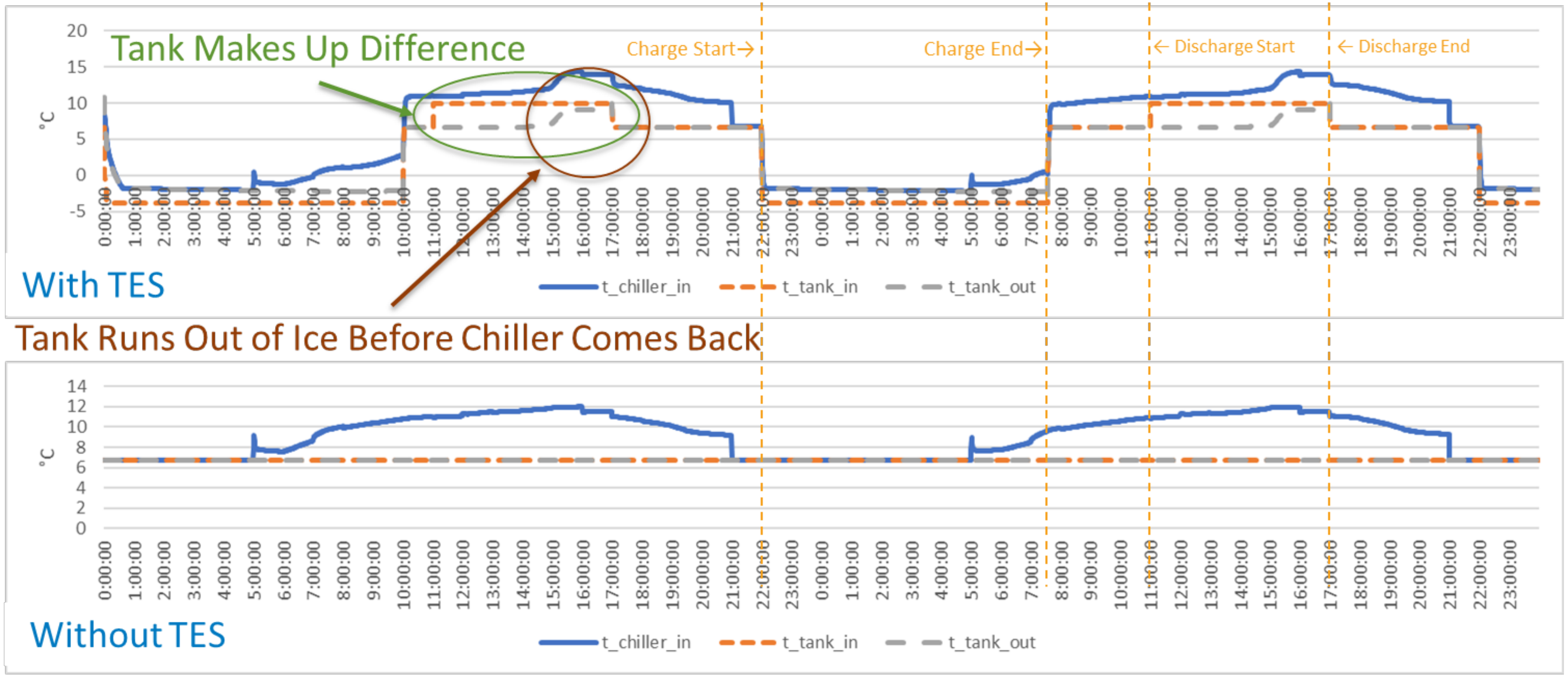
Tank charge starts only when T_{in} < -1° C (hardcoded)

Tank charges to unrealistic capacity

TES Impacts with New Model Chiller Trimming

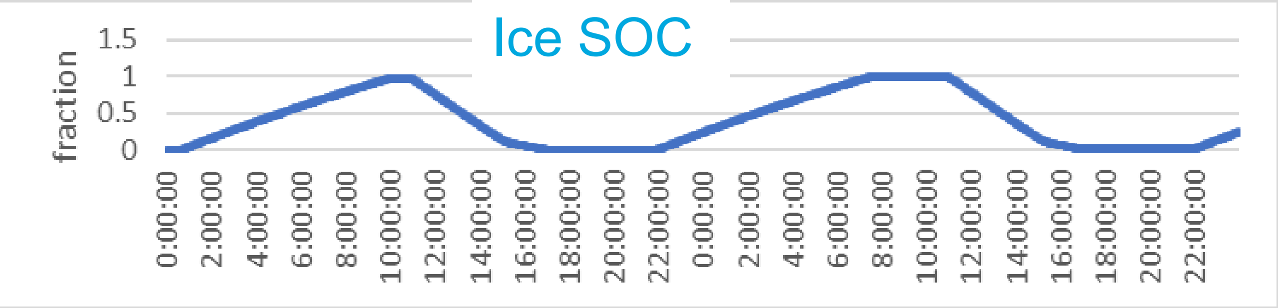
(Tank Size and Controls Not Optimized)





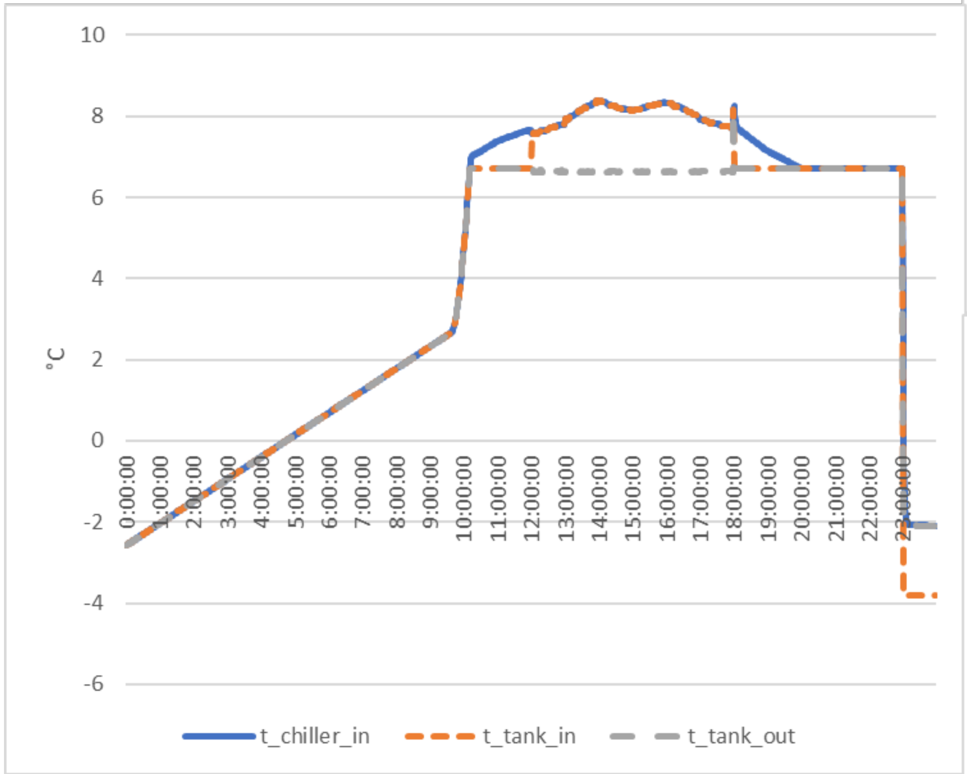
TES Impacts in EnergyPlus with New Model

(Tank Size and Controls Not Optimized)

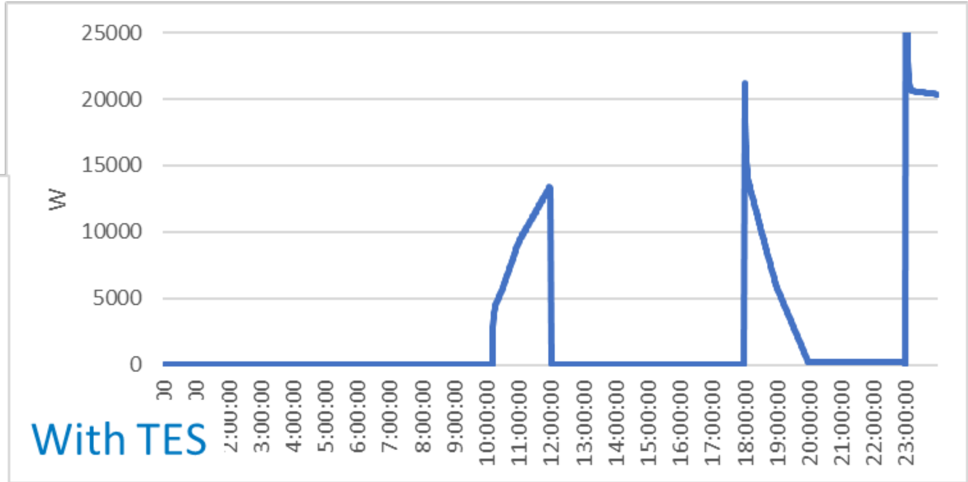


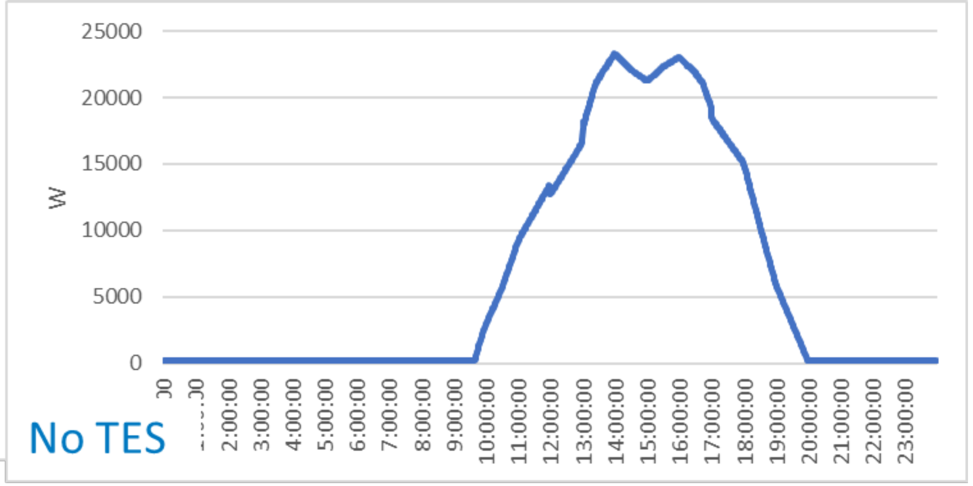
TES Impacts with New Model; Lower-Load Day

(Tank Size and Controls Not Optimized)



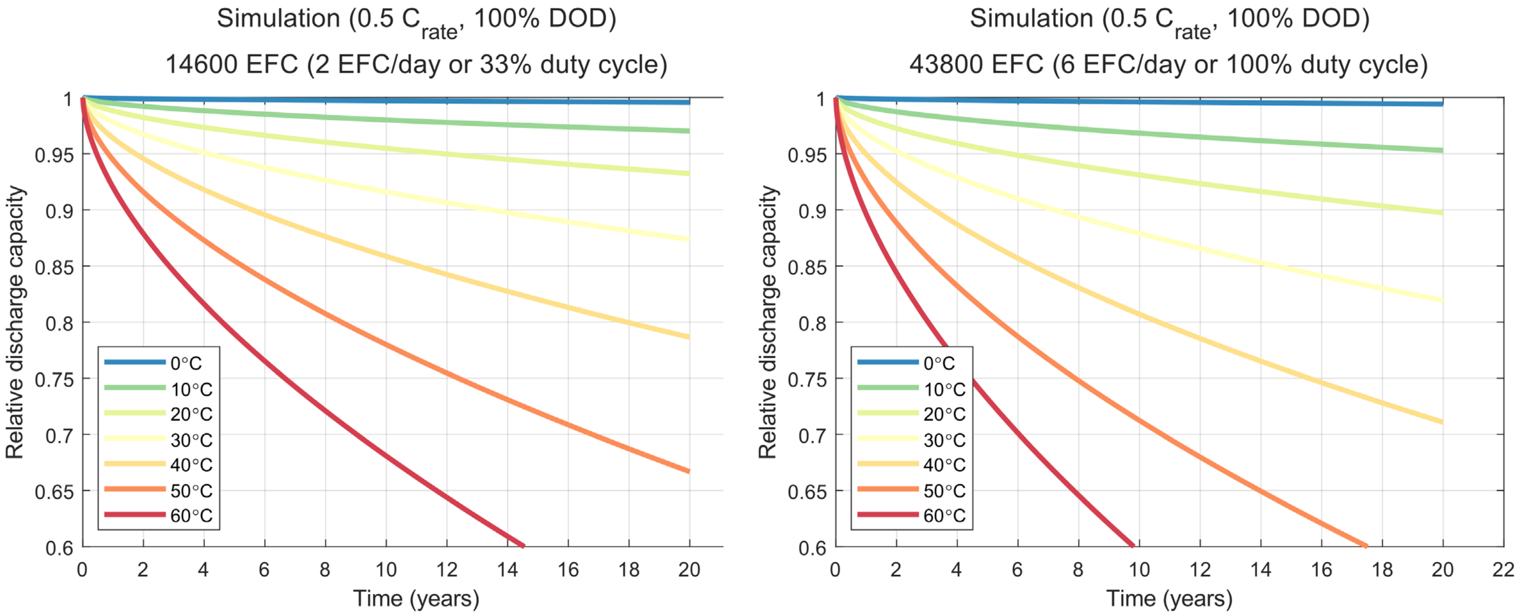
Chiller Turns Off Between 12:00-6:00 PM

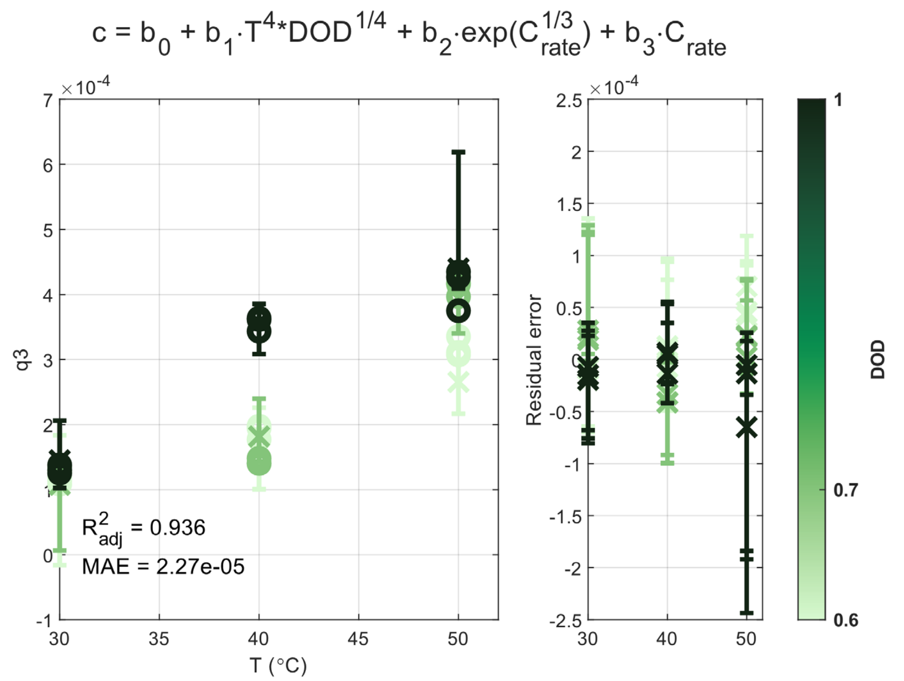




Approach: Include Data-Derived Battery Lifetime Data in EnStore
(FY21 Q3 milestone)

The BTMS R&D Project is developing cobalt-free batteries and evaluating their lifetime characteristics
Curves & equations developed by Matt Shirk (INL), Paul Gasper (NREL), & Kandler Smith (NREL), under VTO project #bat442, for LMO/LTO battery chemistry. EnStore now uses standard lifetime curves for currently commercial batteries.





Model predictions for T < 40 ° C are reasonable, given the convex behavior of the experimentally-observed degradation at those conditions. Above 40 ° C, predictions are very optimistic given mismatch with concave degradation observed at 30 ° C

Cycling degradation rate is predominantly a function of temperature and depth of discharge (DOD). *More data will help to identify a more complex model, capturing both convex and concave fade behaviors.*

Sensitivity Analysis of Battery Cost

One climate zone & one utility rate tariff; *EVSE cost kept constant*

Utility Rate: CONED
Location: TAMPA
EV Load Profile: 2 PORT 16 EVENT 350 KW
EVSE $/port = $185,000 per port
Battery $/kWh = 120 | 270 | 470
Battery $/kW = 540

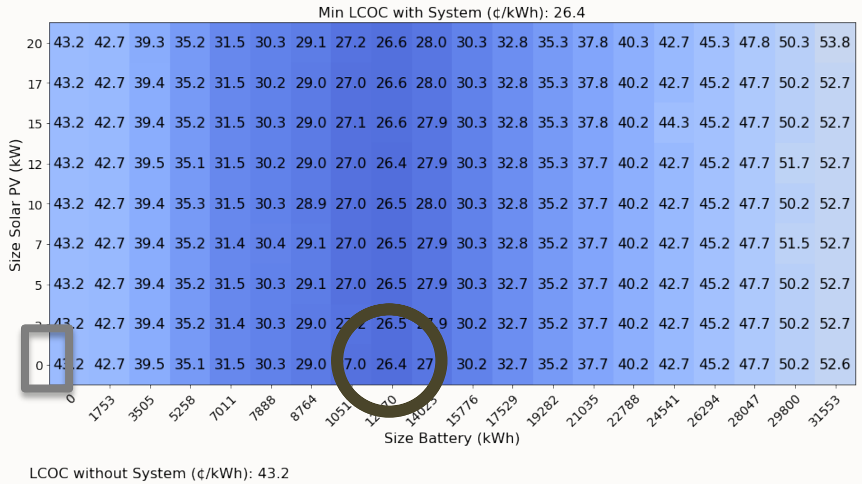
Here, optimal battery size varies drastically (from 12,271 kWh to 10,518 kWh to 7,012 kWh), based on input battery price

The “LCOC without System” or LCOC without any PV or battery stays constant at 43.2 ¢/kWh

The battery cost assumption has an important impact on optimal LCOC & design

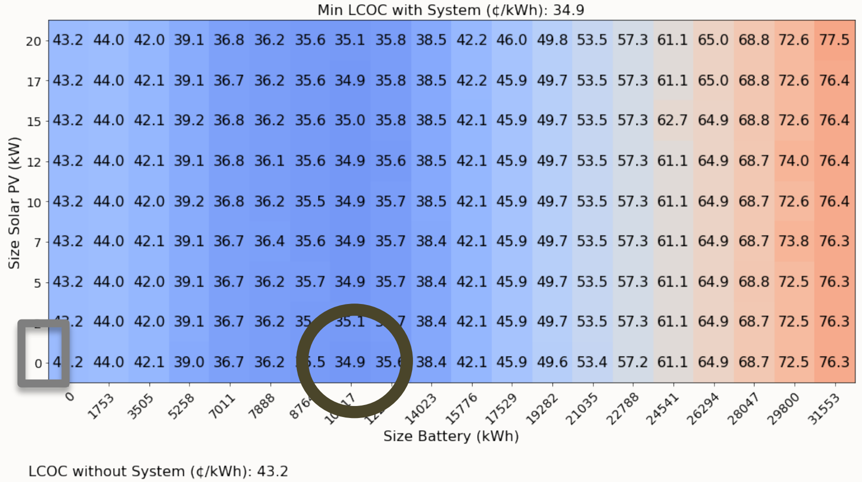
Battery Cost: $120/kWh
Min LCOC: 51.9 ¢/kWh

Battery size: 12,271 kWh



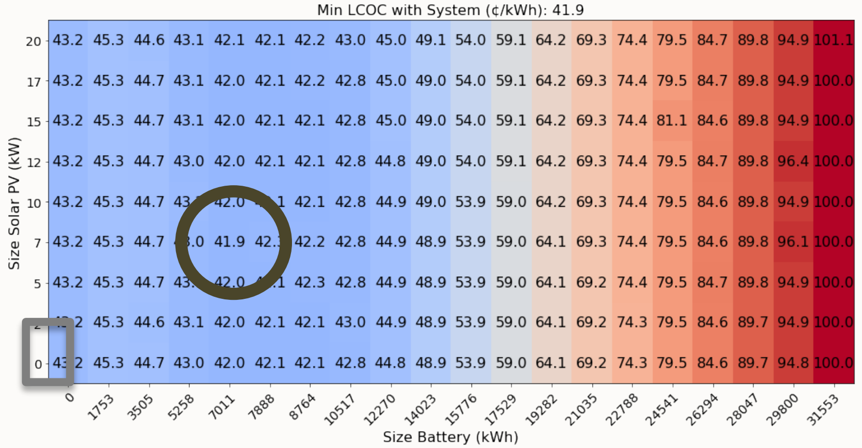
Battery Cost: $270/kWh
Min LCOC: 34.9 ¢/kWh

Battery size: 10,518 kWh



Battery Cost: $470/kWh
Min LCOC: 41.9 ¢/kWh

Battery size: 7,012 kWh



Sensitivity Analysis of EVSE Cost

One climate zone & one utility rate tariff; *battery cost kept constant*

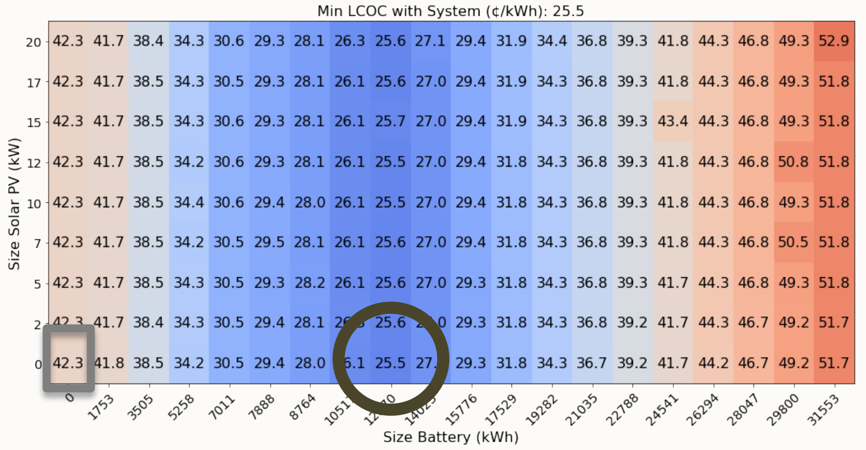
Utility Rate: CONED
Location: TAMPA
EV Load Profile: 6 PORT 12 EVENT 350 KW
EVSE $/port = $154,000 | $185,000 | $216,000 per port
Battery $/kWh = 120
Battery $/kW = 540

Here, optimal battery size stays constant (12,271 kWh) regardless of EVSE input cost

EVSE costs do not have a significant impact on LCOC or design

EVSE Cost: $154,000

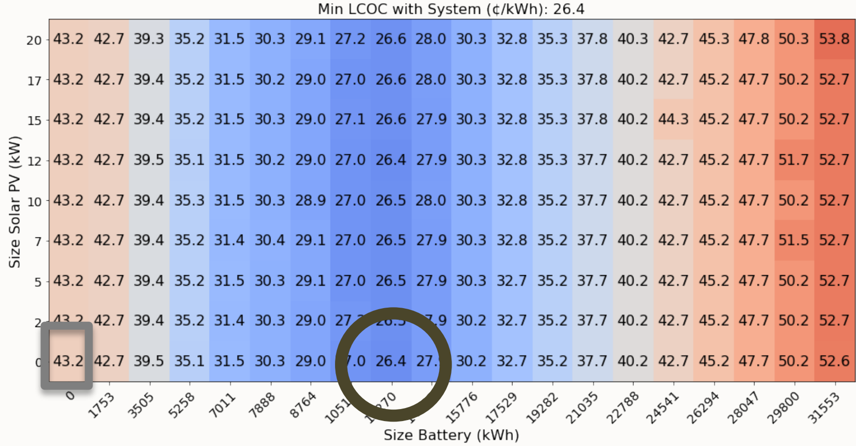
Min LCOC: 25.5 ¢/kWh



LCOC without System (¢/kWh): 42.3

EVSE Cost: $185,000

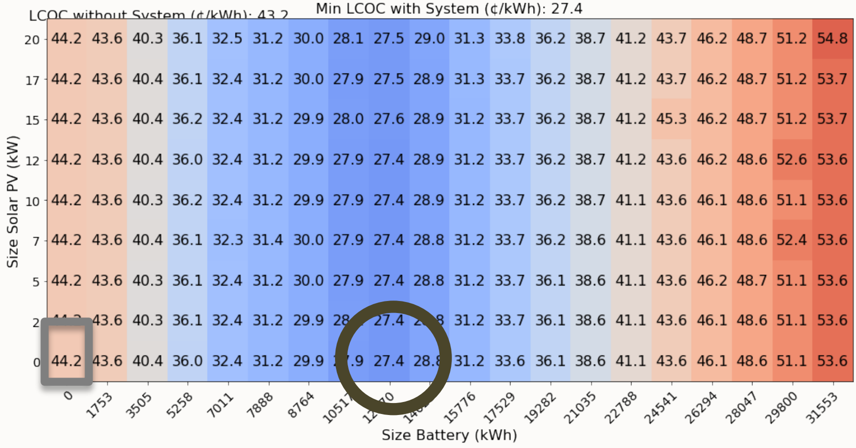
Min LCOC: 26.4 ¢/kWh



LCOC without System (¢/kWh): 43.2

EVSE Cost: $216,000

Min LCOC: 27.4 ¢/kWh



LCOC without System (¢/kWh): 44.2

Example Results for a Corner Charging Station

For a corner charging station, the utility rate structure has a more significant impact on results than climate. This is largely due to the low energy use of the building.

Other buildings, especially grocery stores, will have greater location impacts.

<u>Related to the figures on this slide:</u>
Utility rate has a big impact on LCOC, battery size, PV size, and battery discharge power
Location (climate), while important, has a smaller impact because EV charging demand dominates costs

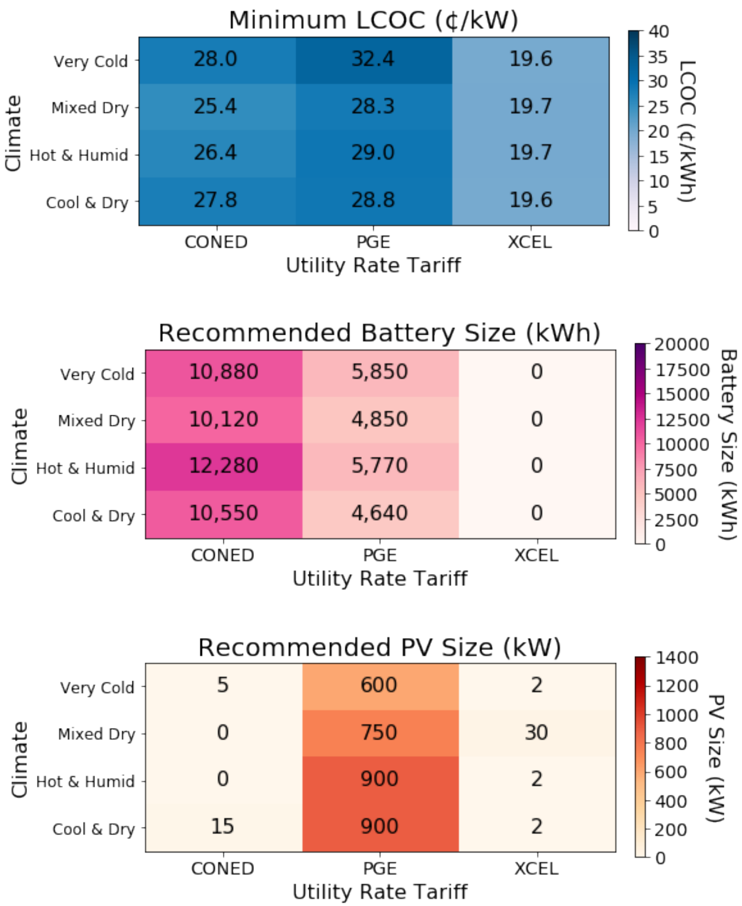
Corner-type Charging Station
Battery Unit Cost = \$120/kWh |\$ 540/kW
PV Unit Cost: \$1600/kW
EVSE cost per port: \$185,000

Medium Station Utilization: 6 ports, 20 events/port/day, 350 kW/port
High Station Utilization: 6 ports, 12 events/port/day, 350 kW/port

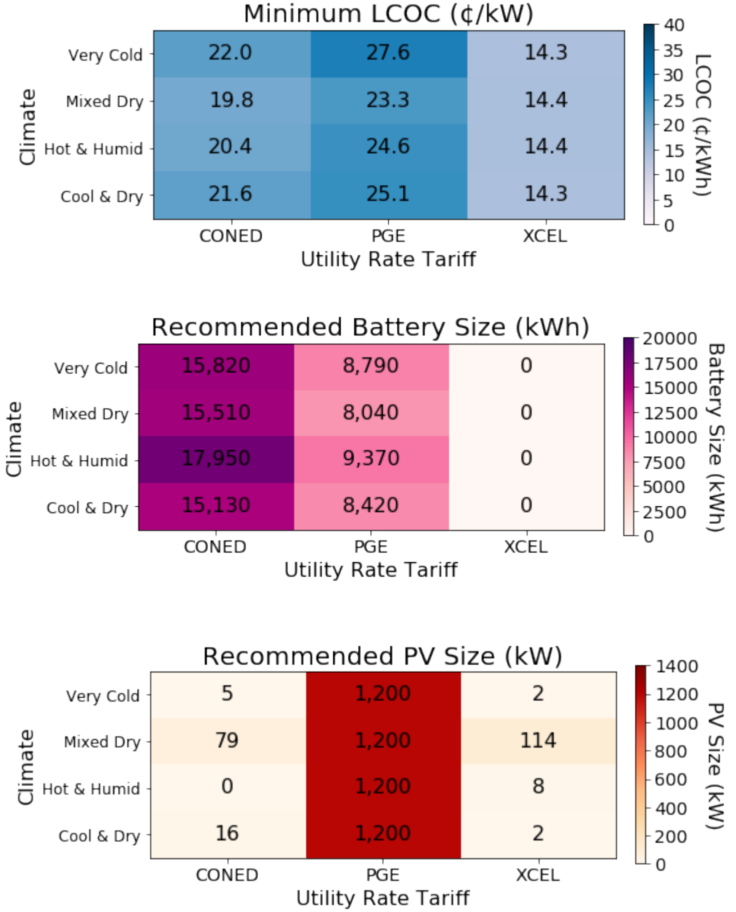
LCOC = levelized cost of charging

NOTE: Results are for specific scenarios; do not generalize to other cases

Medium Station Utilization

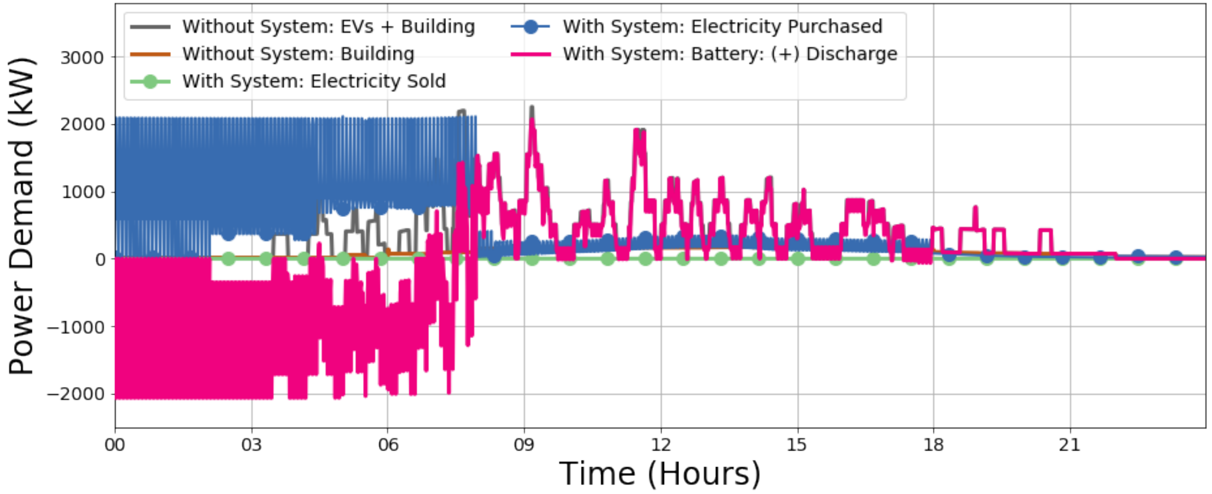


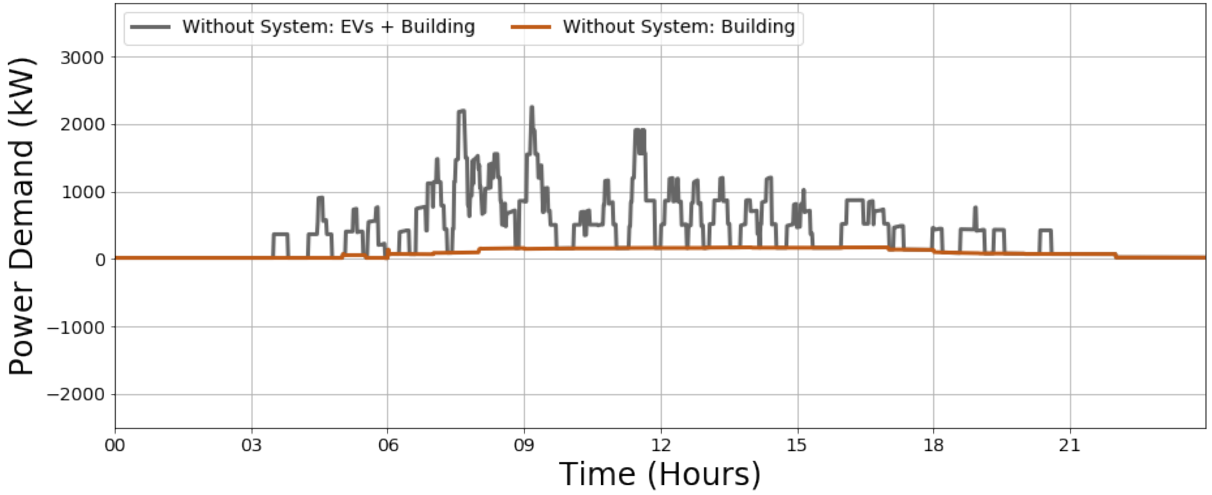
High Station Utilization

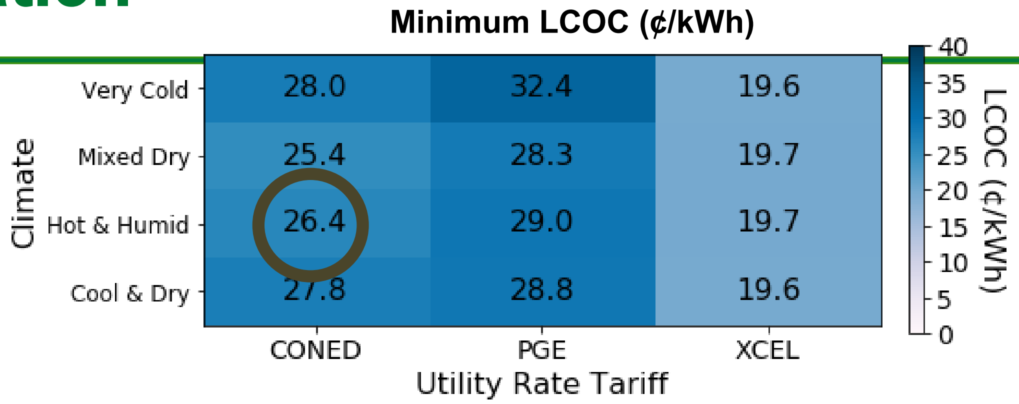


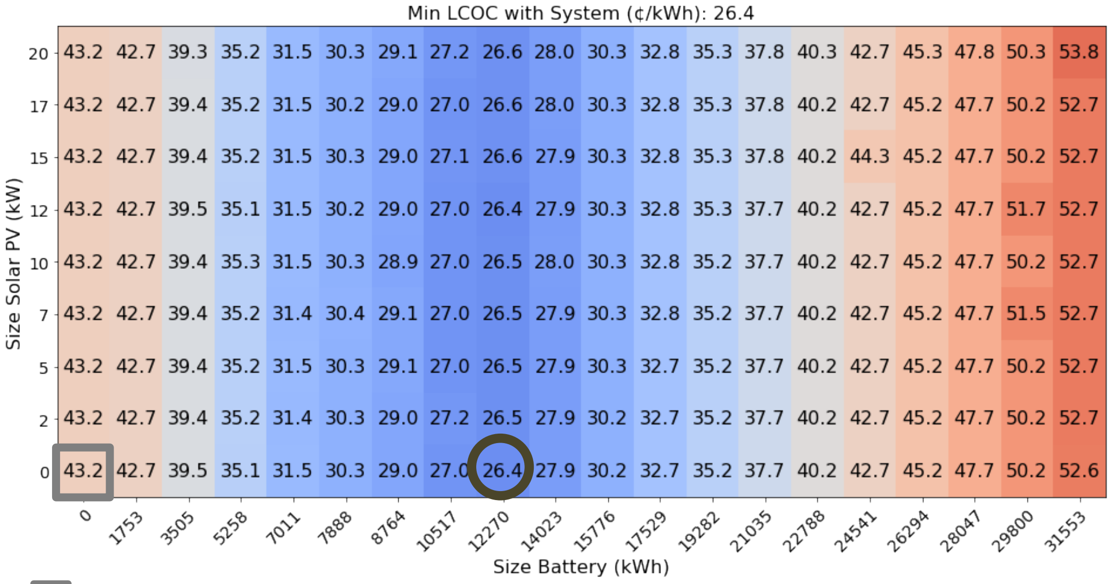
Example Results for a Corner Charging Station

Utility Rate: CONED: HIGH DEMAND CHARGES
Location: TAMPA: HOT & HUMID









LCOC without BTMS System

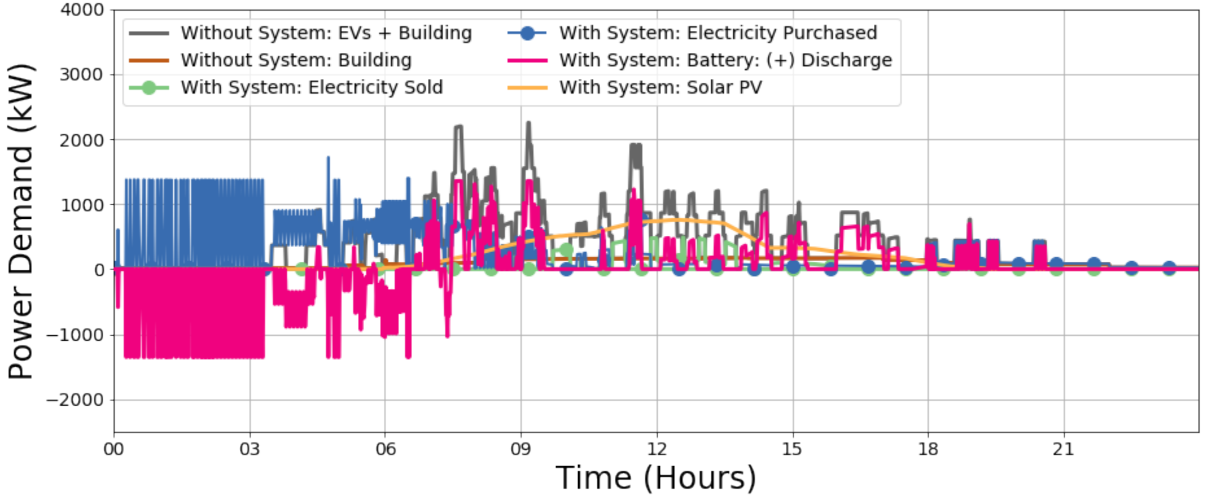
LCOC with BTMS System

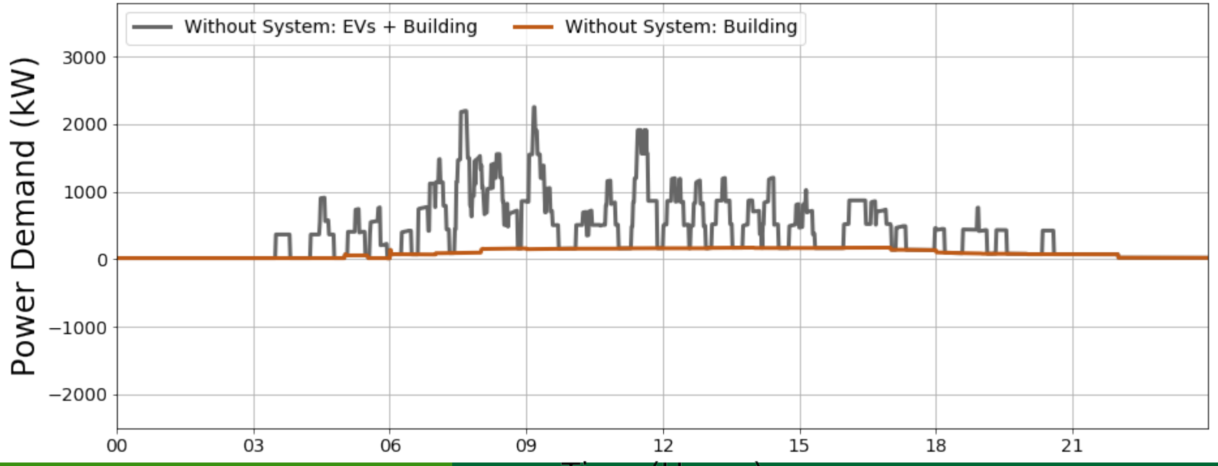
NOTE: Results are for a specific scenario; do not generalize to other cases

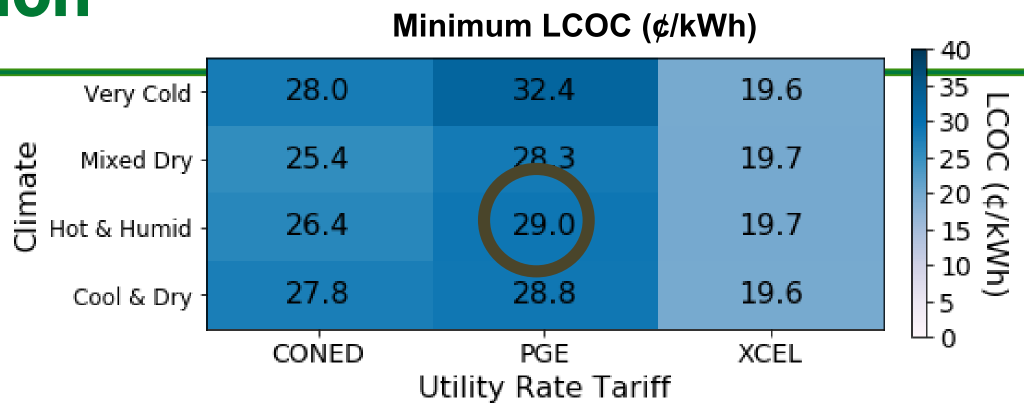
Corner-type Charging Station
EV Load Profile: 6 PORT 12 EVENT 350 KW
EVSE $/port = $185,000
Battery = 120 $/kWh, 540 $/kW
Season of Interest: Summer
PV Cost = $600/kW

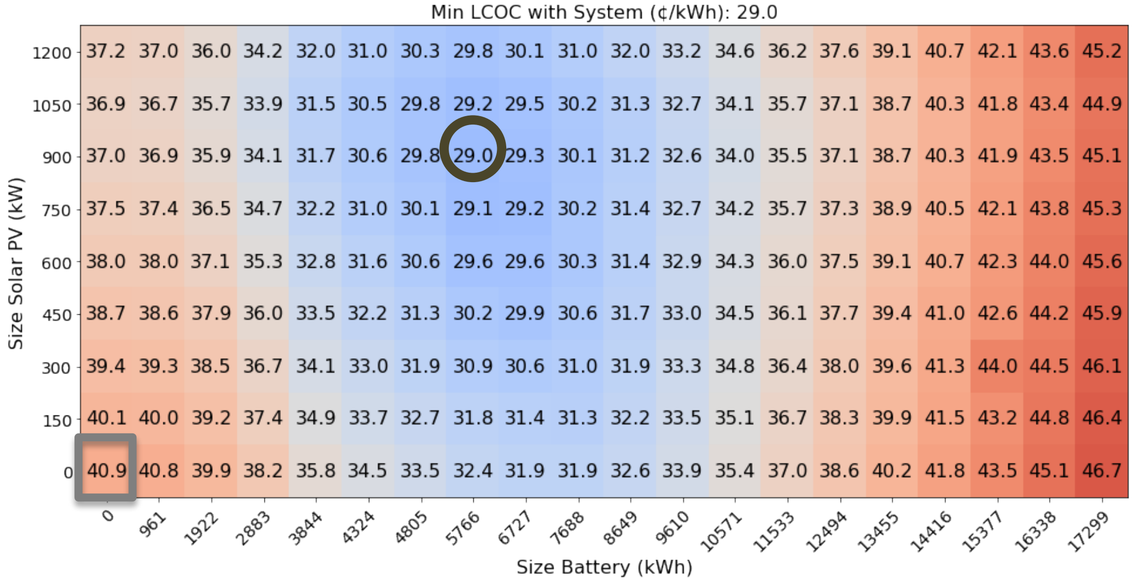
Example Results for a Corner Charging Station

Utility Rate: PG&E: TOU DEMAND & ENERGY CHARGES
Location: TAMPA: HOT & HUMID









LCOC without BTMS System

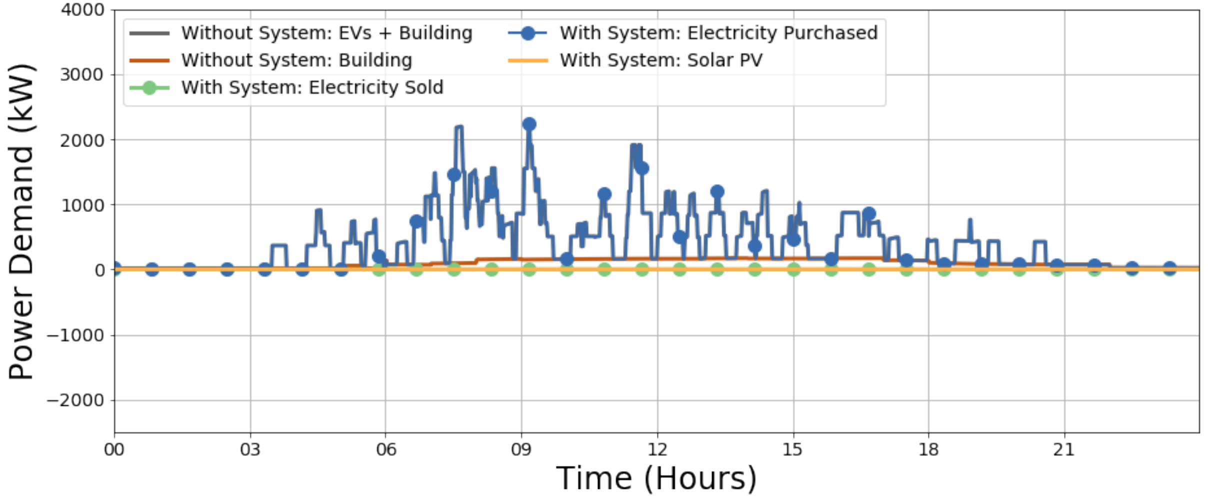
LCOC with BTMS System

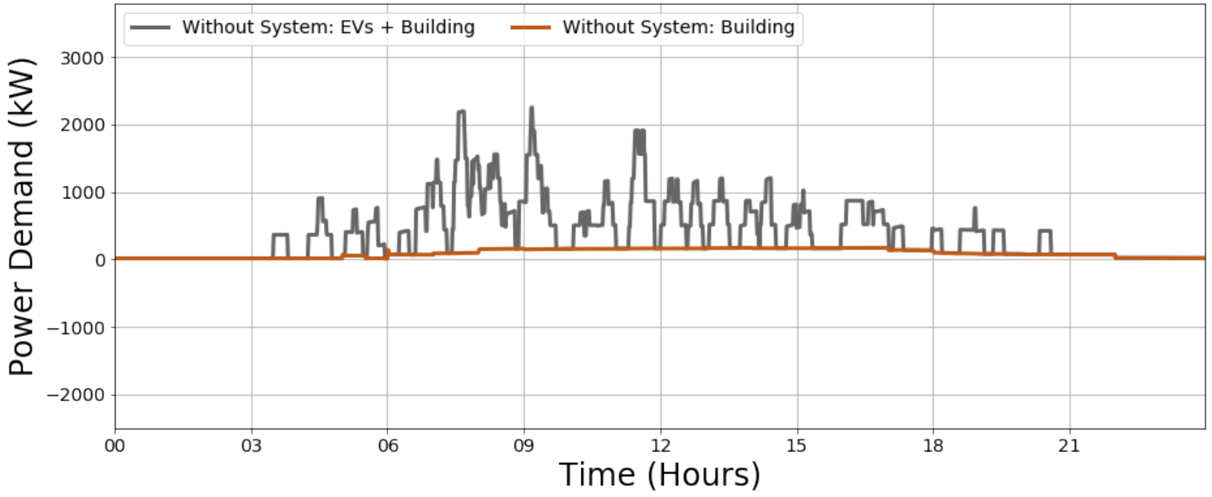
NOTE: Results are for a specific scenario; do not generalize to other cases

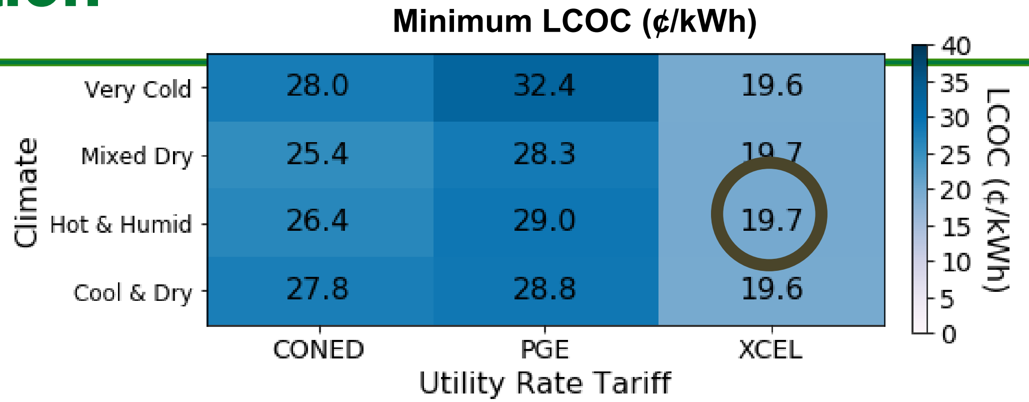
Corner-type Charging Station
EV Load Profile: 6 PORT 12 EVENT 350 KW
EVSE $/port = $185,000
Battery = 120 $/kWh, 540 $/kW
Season of Interest: Summer
PV Cost = $600/kW

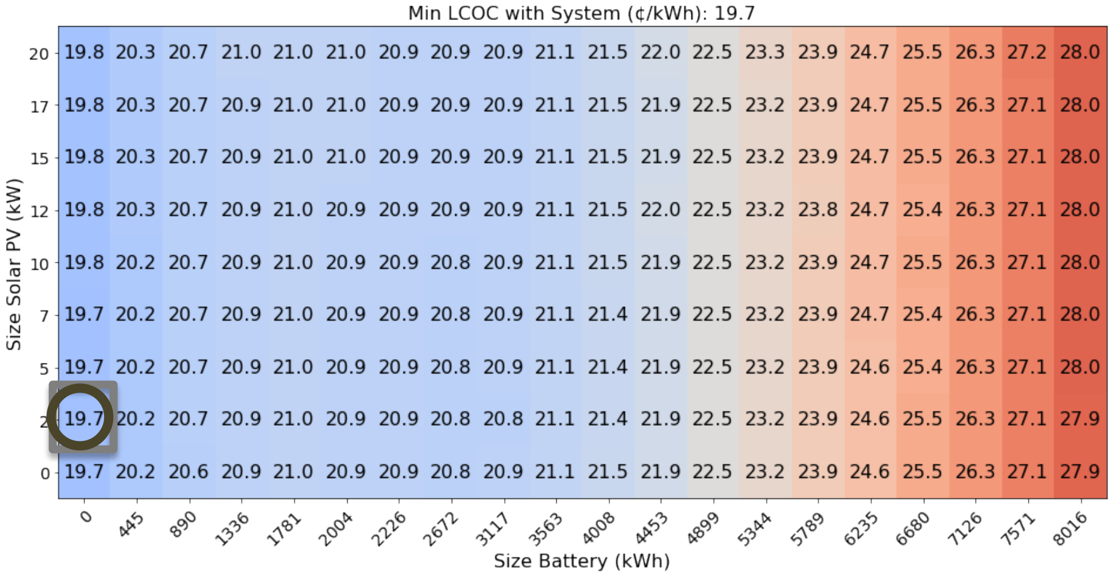
Example Results for a Corner Charging Station

Utility Rate: XCEL: TOU BUT LOW-COST ENERGY
Location: TAMPA: HOT & HUMID









LCOC without BTMS System

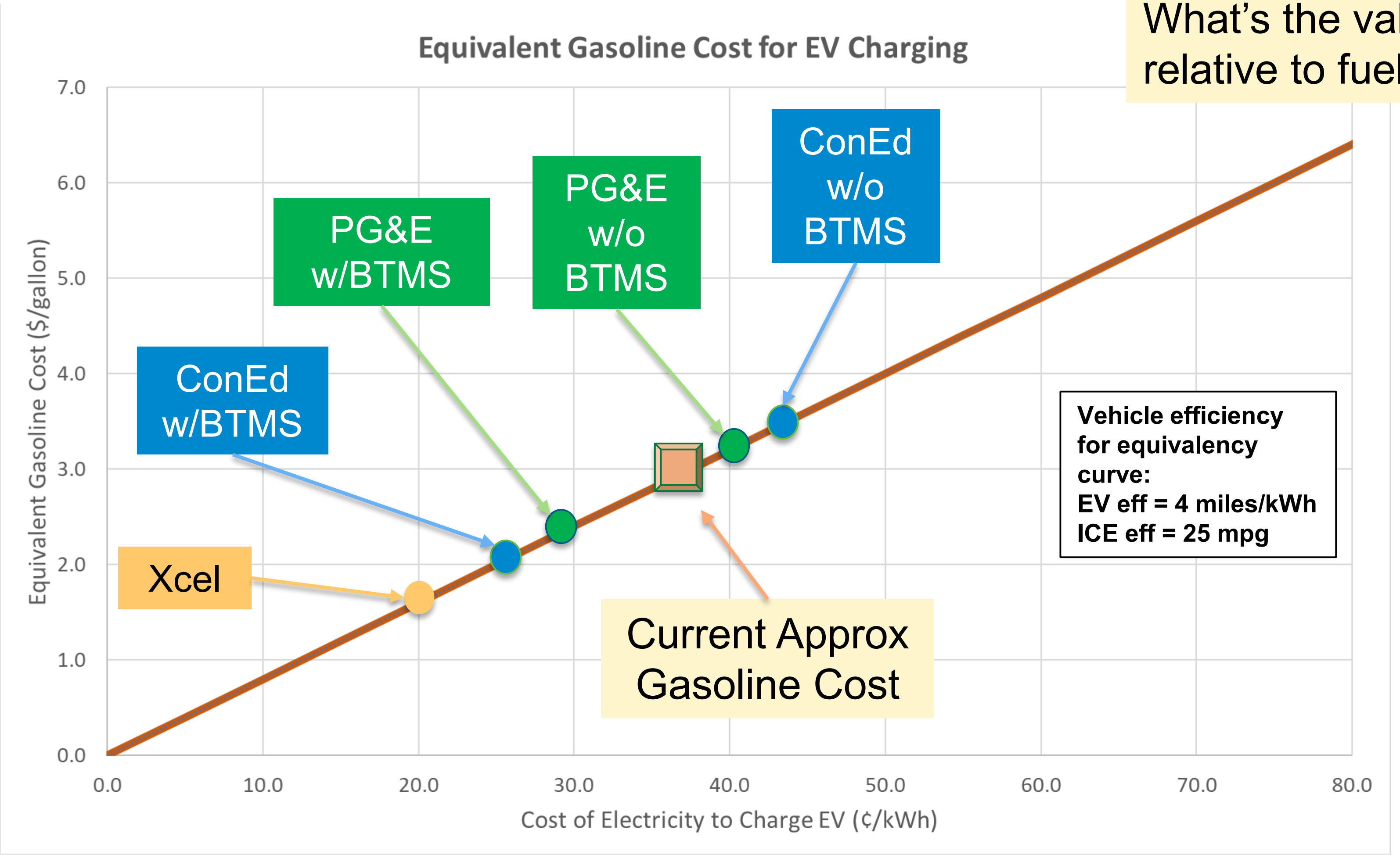
LCOC with BTMS System

NOTE: Results are for a specific scenario; do not generalize to other cases

Corner-type Charging Station
EV Load Profile: 6 PORT 12 EVENT 350 KW
EVSE $/port = $185,000
Battery = 120 $/kWh, 540 $/kW
Season of Interest: Summer
PV Cost = $600/kW

Accomplishments: BTMS Can Reduce the Costs of Fast EV-Charging

Corner Charging Station, Medium Station Utilization



What's the value of these BTMS cases relative to fueling a vehicle with gasoline?

For a corner charging station with 6 ports, 12-events per port per day, with 350 kW fast EV charging:

- *Charging an electric vehicle at "reasonable" electricity rates is cheaper than driving with gasoline*
- *BTMS reduces the cost of fast EV-charging*
- *BTMS can be an economic means of reducing impacts of fast EV-charging*

Important caveats:

- Results are for the specific scenarios shown; may not hold for different building types, utility rates, and capital costs
- Utilities are very likely to change their rate structures as more variable renewables are added to the grid

Stay tuned for the results of more scenarios (being examined now)