Urban Combined Heat and Power with Integrated Renewables and Energy Storage

U.S. DOE EERE Award Number DE-EE00009140
Project Dates: 5/15/2020 to 12/31/2022

Program Review Meeting

June 06, 2022

THE GEORGE WASHINGTON UNIVERSITY
WASHINGTON, DC

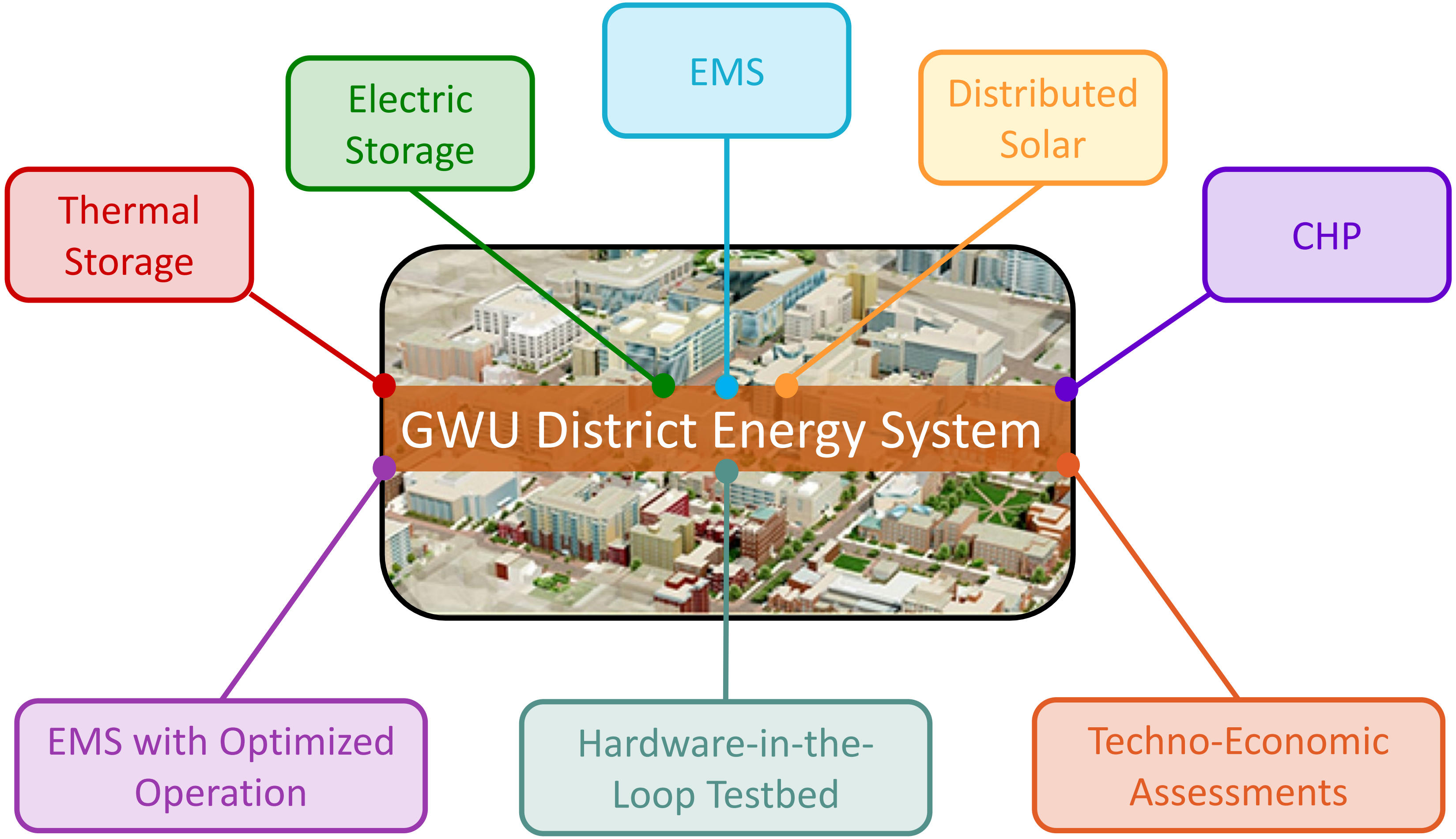
U.S. DEPARTMENT OF ENERGY

Agenda

- **Overview**
- **Participants**
- **District Energy System Cases**
- **Energy Management System**
- **Techno-economic Framework**
- **Hardware-in-the-Loop Testbed**
- **Next Steps**

Project Overview

Project Goal: Determine how to effectively integrate and enhance electricity generation and energy storage components of an urban district energy system (DES) to impact resilience, reliability, vulnerability, and return on investment - using the GWU DES as a case study.



- ✓ Design & apply Energy Management System
- ✓ Create specifications for energy storage technologies
- ✓ Create testbed demonstration
- ✓ Develop technoeconomic framework

Project Participants

Research Team

Ekundayo Shittu
(Systems Engineering)
- Microgrid systems design & analysis
- Energy system techno-economic models

Saniya LeBlanc: Project Lead & Manager
(Mechanical Engineering)
- Energy systems design & analysis
- Power generation technology
- Waste heat recovery technology

Payman Dehghanian
(Electrical Engineering)
- Power systems
- Grid reliability & resilience

Tripp Griffith
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Eliot Hunter
Research Assistant

Rachel Gray
Research Assistant

Ben Vergara
Research Assistant

Amanda Long
Research Assistant

Advisory Board

Dongbo Zhao
(Energy System Scientist, Argonne National Lab)

Adam Rickey, Timothy Reynolds, Wayne Martin
(KCI Technologies)

Daron Coates, Paul Orentas
(ThinkBox)

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(Senior Advisor for Energy Law Programs, GWU)

Kate Johnson & Edward Yim
(DC Dep. of Energy and Environment, ACEE)

Derek Supple
(Johnson Controls Inc.)

GWU Division of Operations

Josh Laskey
(Director, Office of Sustainability)
- GWU-wide sustainability solution implementation

Mansi Talwar
(Executive Director, Engineering, Utilities & Energy)

Mikel Solupe
(Energy Manager)

Pete Carrino
(CHP plant manager)

Research Team

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Eliot Hunter
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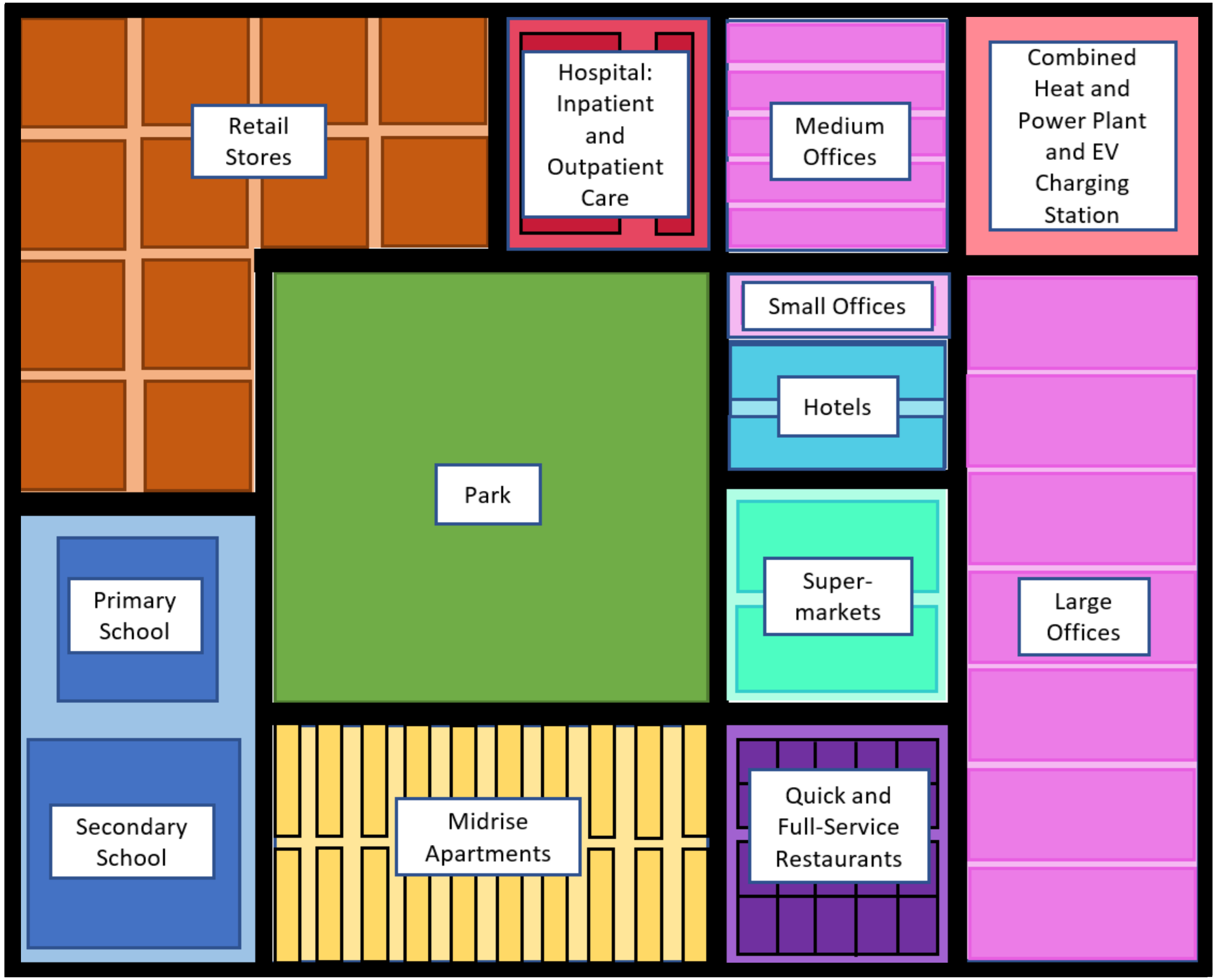
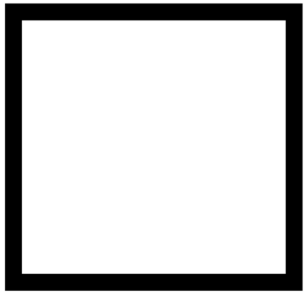
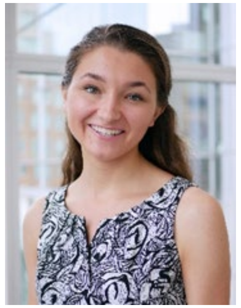
DES Synthetic Case: Comprehensive Urban DES





= One City Block (100,000 square feet)

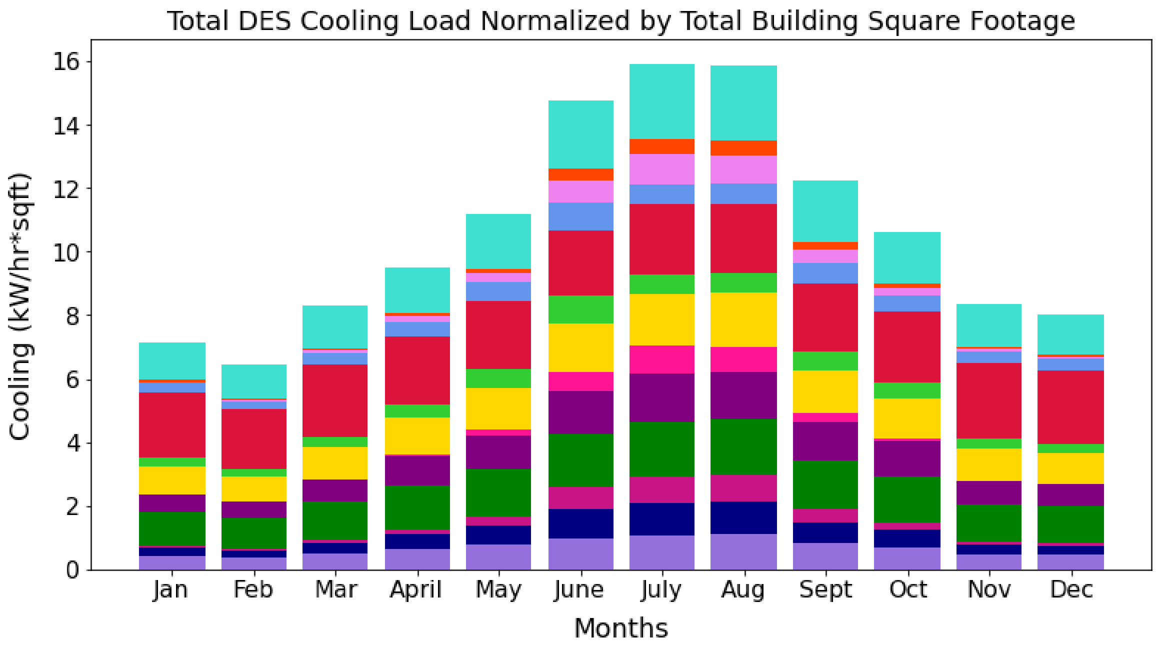
- 1 Primary and 1 Secondary School
- 20 Midrise Apartments
- 10 Quick Service and 10 Full-Service Restaurants
- 7 Large, 5 Medium, and 4 Small Office Buildings
- 2 Supermarkets
- 2 Hotels
- 1 Combined Heat and Power Plant, and 1 EV Charging Station
- 1 Hospital with Inpatient and Outpatient Care
- 12 Retail Stores

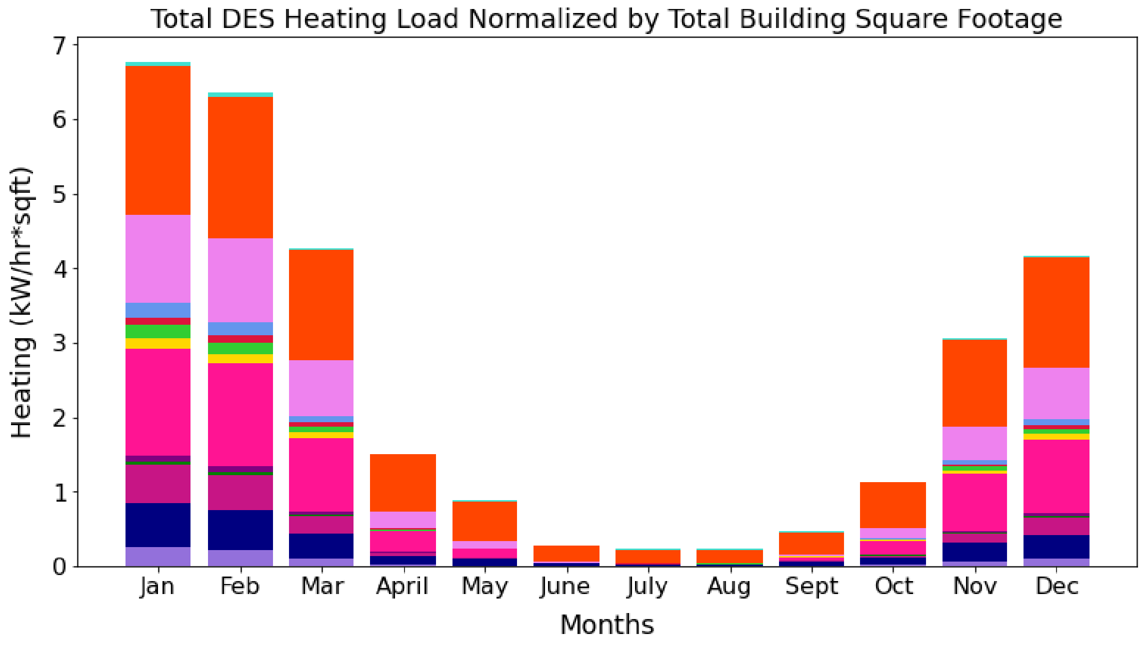


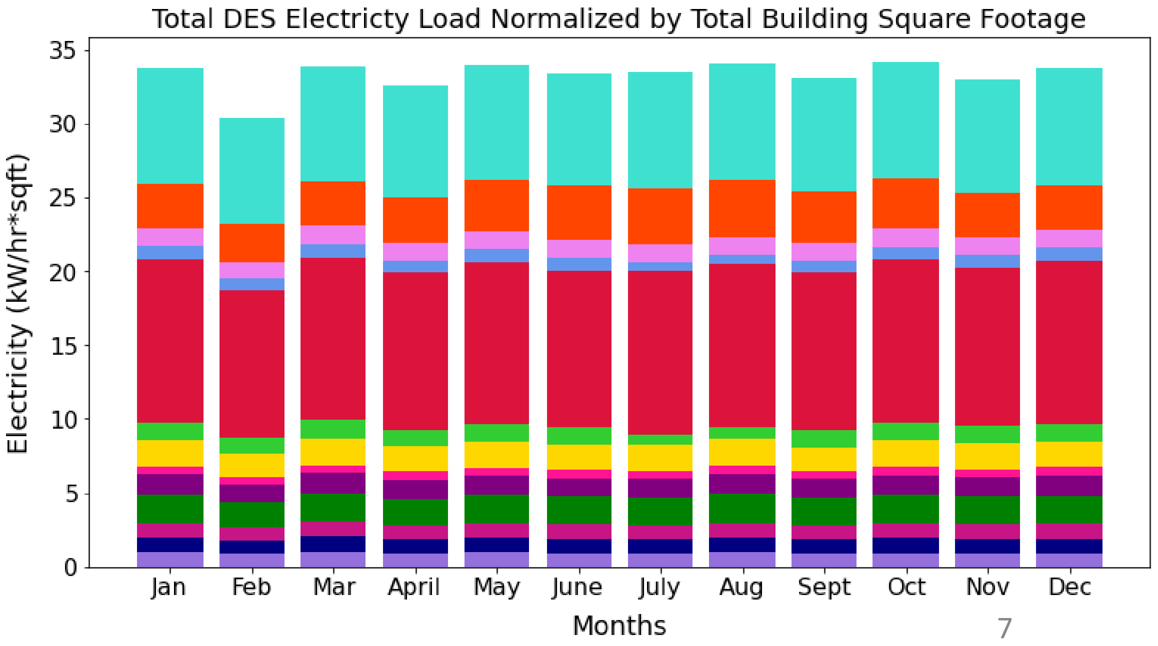
*Load data collected from U.S. DOE Commercial Reference Building Models

Synthetic Case Loads

(normalized by total building square footage)

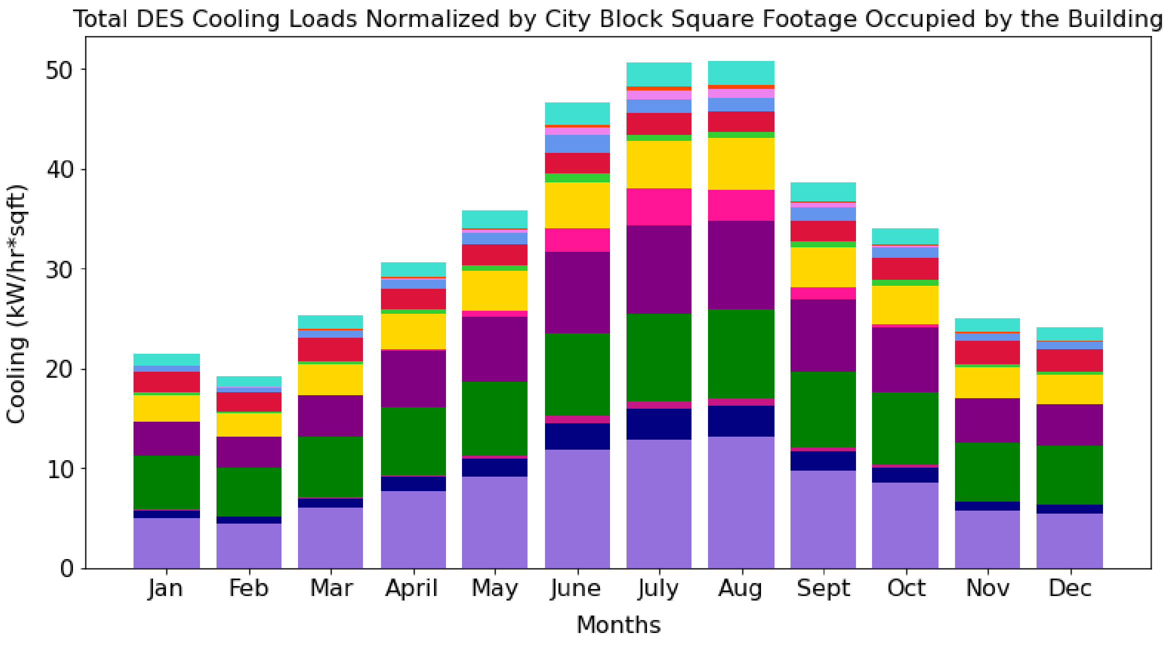


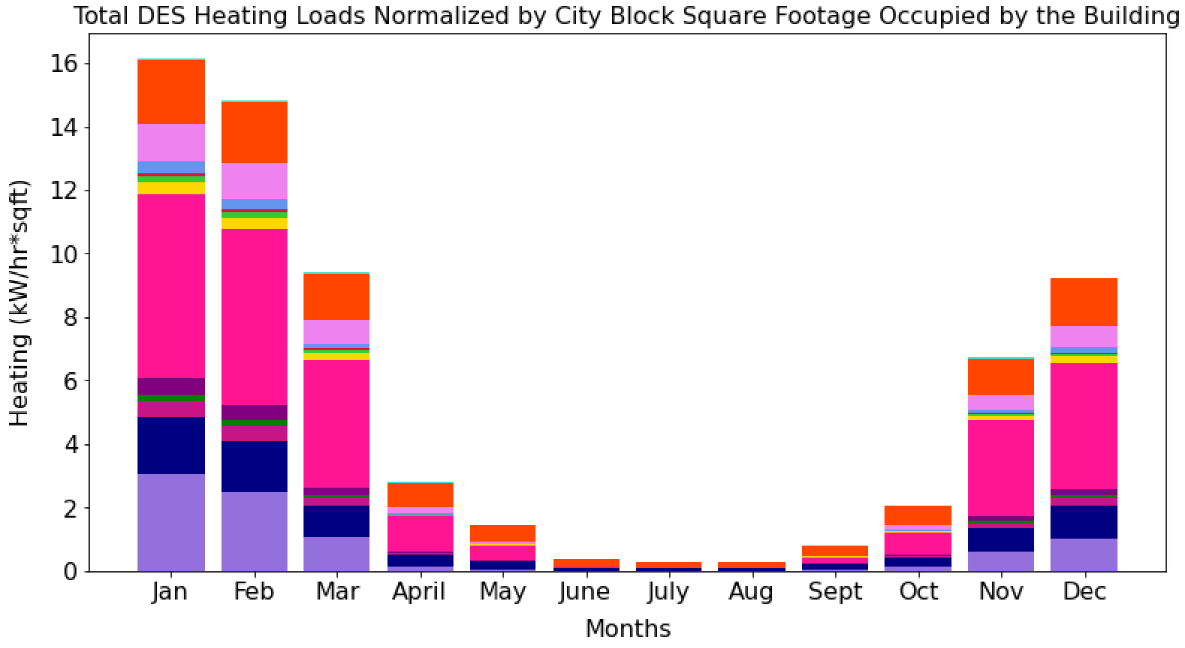


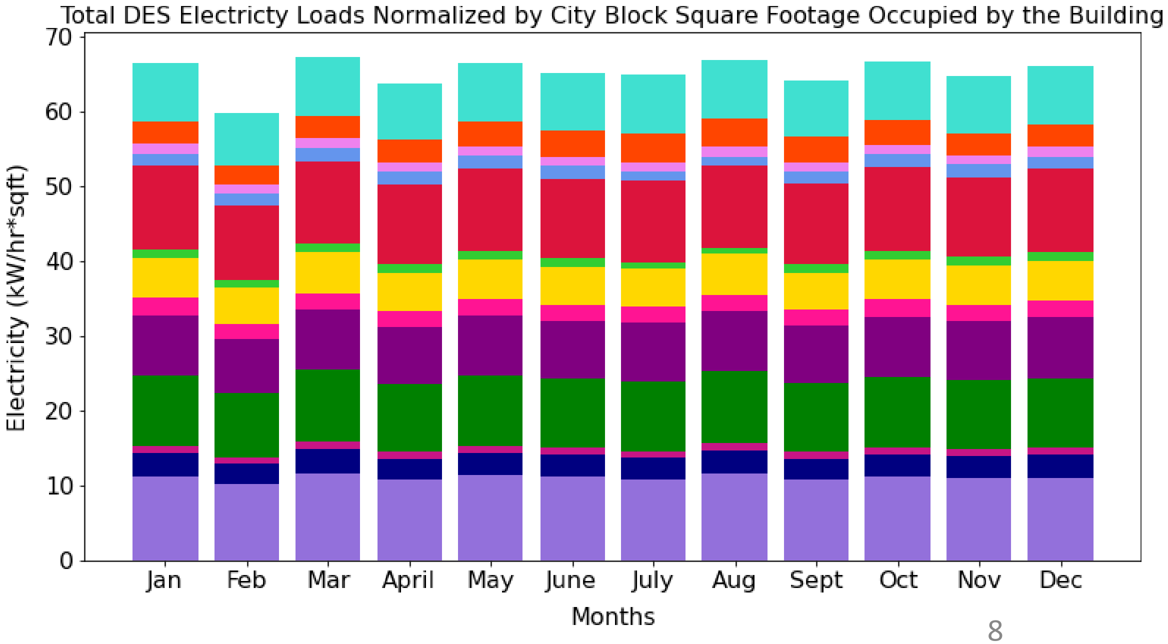


Synthetic Case Loads

(normalized by building footprint)



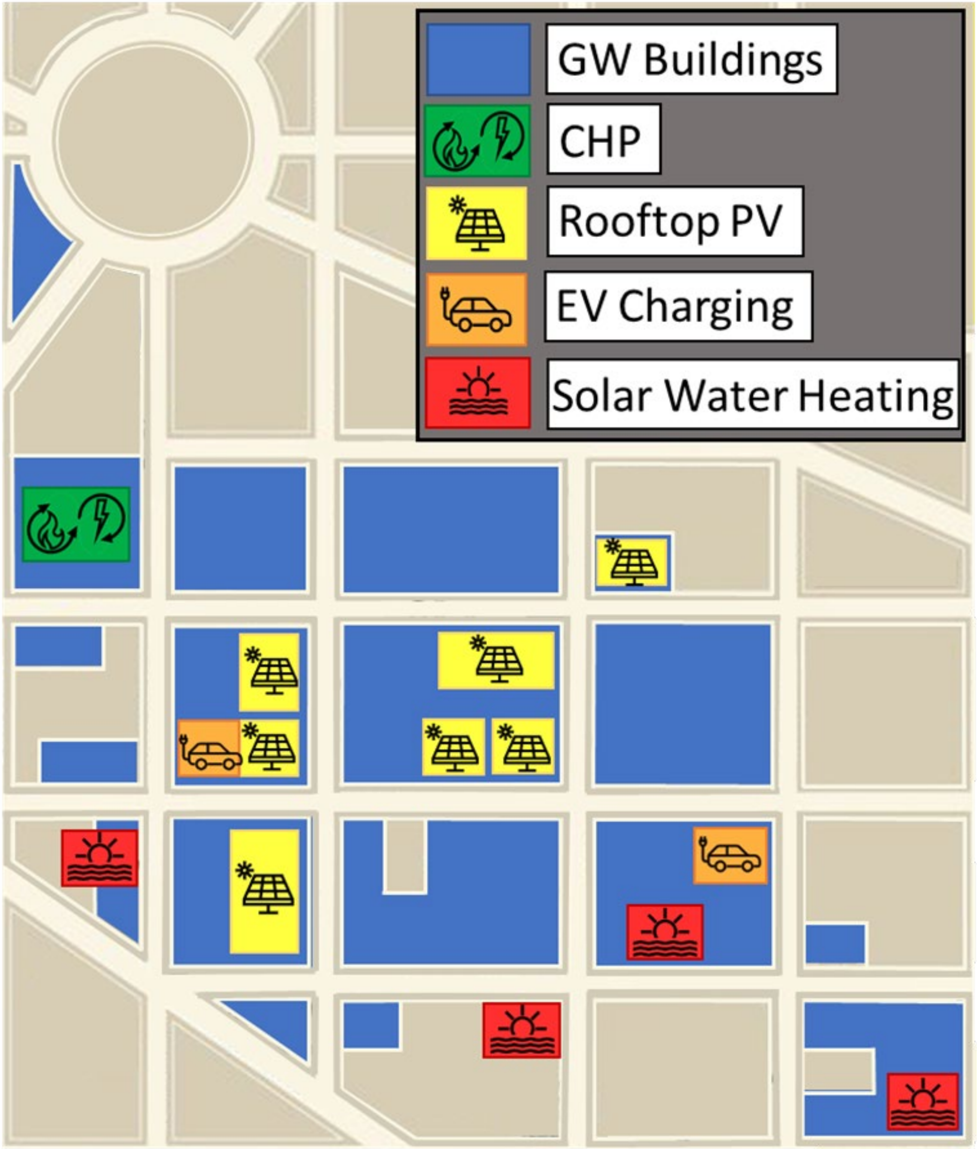




GWU District Energy System

- 7.4 MW Combined Heat and Power Plant
  - Supports 2 academic and 3 residential buildings
- 52 MW solar farm (Capital Partners Solar Project)
  - 50% of GW's Electricity
- 2 electric vehicle charging stations
- 4 solar water heating systems
  - 2/3 of hot water used by 4 residential buildings
- 497 kW campus rooftop solar

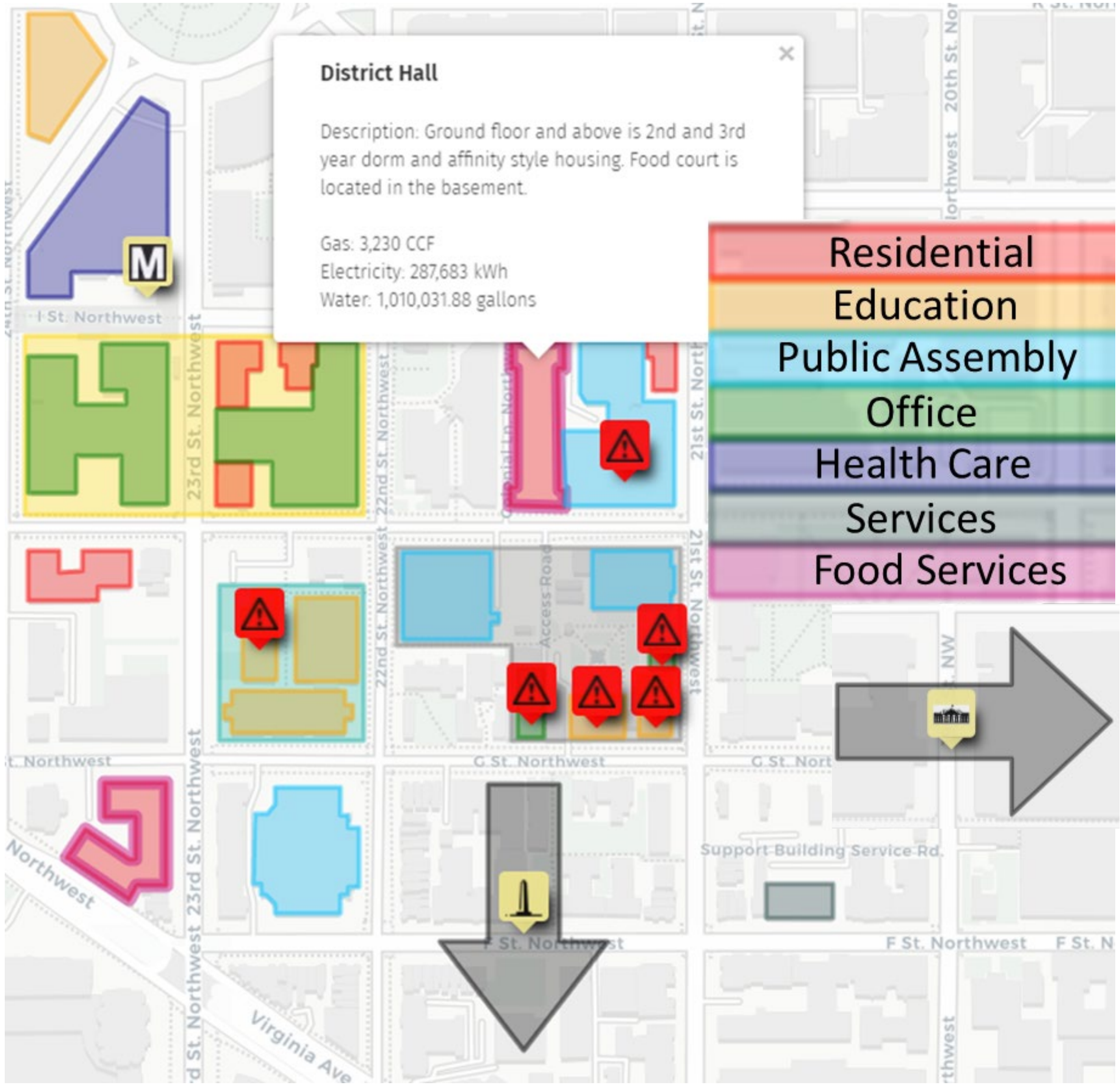




Urban Building Types in Both Cases

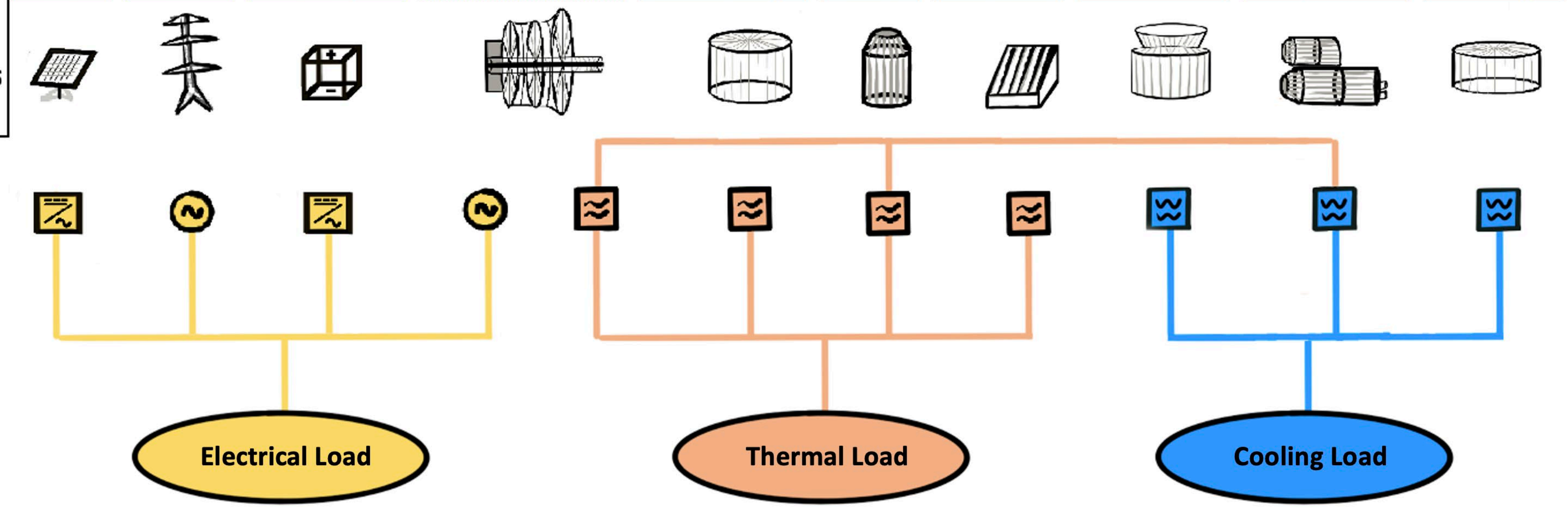
Building Types	DES Synthetic Case	GWU's Energy System
Public Assembly	Park	Lisner Auditorium, Smith Center, Gelman, Marvin
Food Service	10 Quick Service and 10 Full Service Restaurants	The Basements of District and Shenkman
Food Sales	2 Supermarkets	
Public Safety		
Lodging	2 Large Hotels	
Residential	20 Midrise Apartments	JBKO, Munson, Shenkman, Lafayette, District
Transportation	Electric Vehicle Charging Station	
Office	7 Large, 5 Medium, and 4 Small Offices	University Honor's Building, Department of Psychology, SEH, Ross
Mercantile	12 Stand-Alone Retail Stores	
Services		The Support Building
Education	Primary and Secondary School	Hall of Government, Milken, Monroe, Tompkins, Funger, Duques
Health Care	Hospital with Inpatient and Outpatient Care	GWU Hospital, Marvin (Colonial Health Center)

Mapping Tool for GWU DES Data



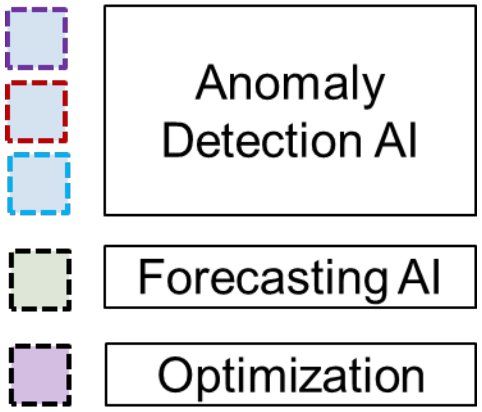
Energy Management System

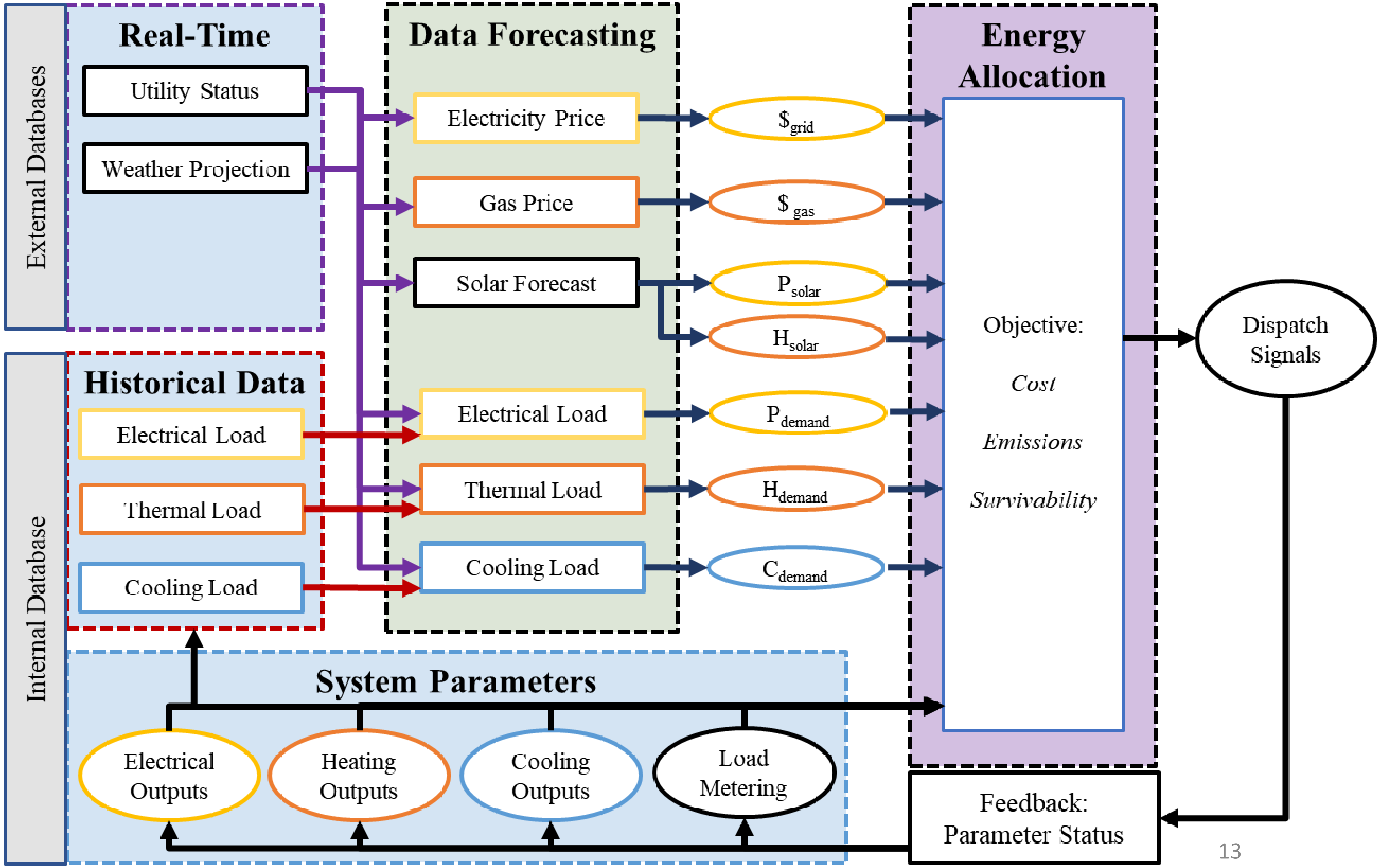
	Solar	Grid	Battery	CHP	Thermal Storage	Boiler	Solar Heater	Towers & Chiller	Absorption Chiller	Ice Storage
Parameter	Power Output	Max In/Out	Capacity	Heat Output	Capacity	Heat Output	Heat Output	Output Max	Output Max	Capacity
	[kW]	[kW]	[kWh]	[kW]	[kWh]	[kW]	[kW]	[gpm]	[gpm]	[gal]
	5491	5000	24071	1538	19569	23503	0	26024	2246	1754995
Sizing	Area	Min In/Out	Critical Load Support	Heat Load Percentile	Critical Load Support	% Peak Heat	Area	% Peak Cooling	% CHP Peak Heat	Critical Load Support
	[m^2]	[kW]	[days]	[%]	[days]	[%]	[m^2]	[%]	[%]	[days]
	49139	0	0.50	75	0.50	125	0	125	100	0.50
Energy Resource	Solar	Grid	Battery	CHP	Thermal Storage	Boiler	Solar Heater	Towers & Chiller	Absorption Chiller	Ice Storage



Energy Management System Architecture

- Designed for general DESs
- Utilizes AI & optimization techniques to allocate energy resources





Baseline & Emergency Scenarios

EMS Baseline Operation Objective Function:

- Minimizes energy resource operational cost
- Heavy penalty (outage cost) on any load shed, both critical and non-critical load

$$\min \sum_{t\in \mathbf{T}} \Big[C^{GR}(P_t^{GRb}, P_t^{GRs}) + \sum_{i\in \mathbf{I}} C^{HP}(P_{i,t}^{HP}, H_{i,t}^{HP}, x_{i,t}, y_{i,t}, z_{i,t}) + \sum_{k\in \mathbf{K}} C^{BO}(H_{k,t}^{BO}, u_{k,t}) + \sum_{e\in \mathbf{E}} C^{BS}(P_{e,t}^{BSc}, P_{e,t}^{BSd}) + \sum_{s\in \mathbf{S}} C^{TS}(H_{s,t}^{TSc}, H_{s,t}^{TSd})$$
$$+ \sum_{c\in \mathbf{C}} C^{IS}(C_{c,t}^{ISc}, C_{c,t}^{ISd}) + \sum_{a\in \mathbf{A}} C^{CT}(C_a^{CT}, l_a) + \sum_{b\in \mathbf{B}} C^{SC}(j_b) + C^{ls}(P_t^{ls}, H_t^{ls}, C_t^{ls}) + C^{lsc}(P_t^{lsc}, H_t^{lsc}, C_t^{lsc}) \Big]$$

Grid | CHP | Boilers | Battery | Thermal Storage | Grid | Towers & Chillers | Steam Chiller | Load Shed | Critical Load Shed

EMS Emergency Operation Objective Function:

- Minimizes energy resource operational cost
- Heavy penalty (outage cost) for critical load shed
- Mild penalty (lack of storage cost) for not having stored energy

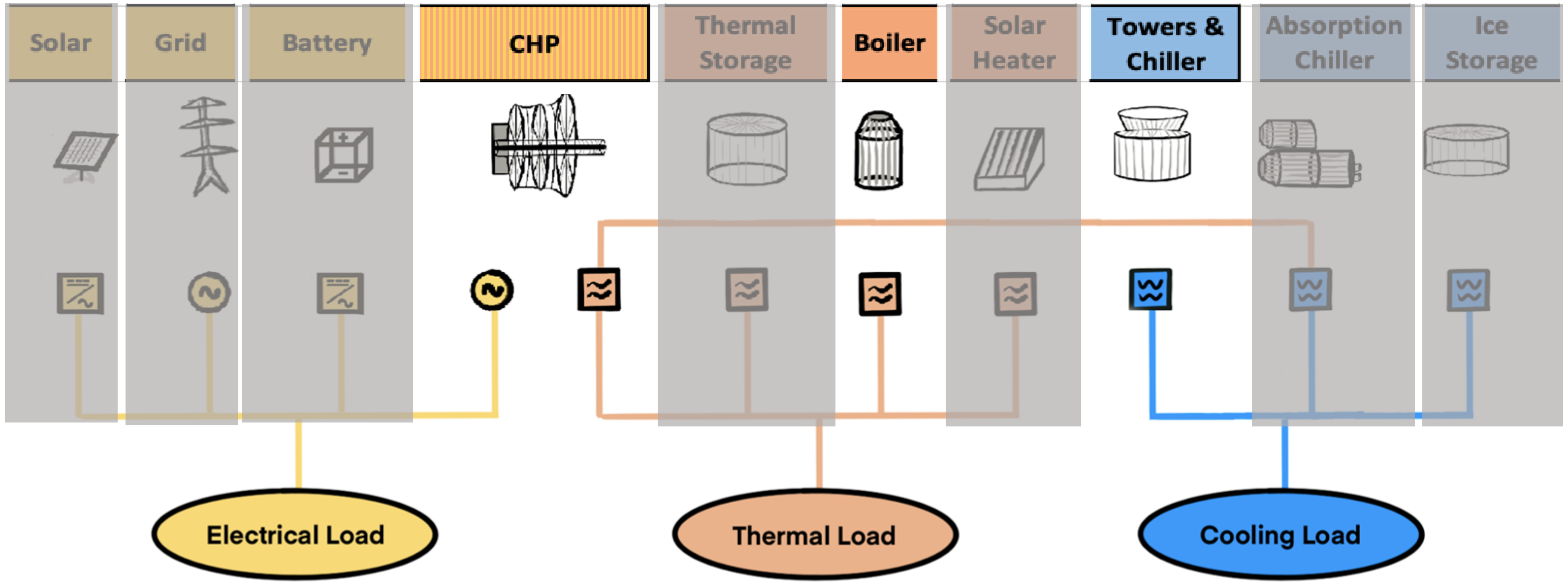
$$\min \sum_{t\in T} \Big[C^{GR}(P_t^{GRb}, P_t^{GRs}) + \sum_{i\in I} C^{HP}(P_{i,t}^{HP}, H_{i,t}^{HP}, x_{i,t}, y_{i,t}, z_{i,t}) + \sum_{k\in K} C^{BO}(H_{k,t}^{BO}, u_{k,t}) + \sum_{e\in E} C^{BS}(P_{e,t}^{BSc}, P_{e,t}^{BSd}) + \sum_{s\in S} C^{TS}(H_{s,t}^{TSc}, H_{s,t}^{TSd})$$
$$+ \sum_{c\in C} C^{IS}(C_{c,t}^{ISc}, C_{c,t}^{ISd}) + \sum_{a\in A} C^{CT}(C_a^{CT}, l_a) + \sum_{b\in B} C^{SC}(j_b) + C^{lsc}(P_t^{lsc}, H_t^{lsc}, C_t^{lsc}) + \sum_{e\in E} \big(C^{BSe}(E_{e,t}^{BS})\big) + \sum_{s\in S} \big(C^{TSe}(E_{s,t}^{TS})\big) + \sum_{c\in C} \big(C^{ISe}(E_{c,t}^{IS})\big) \Big]$$

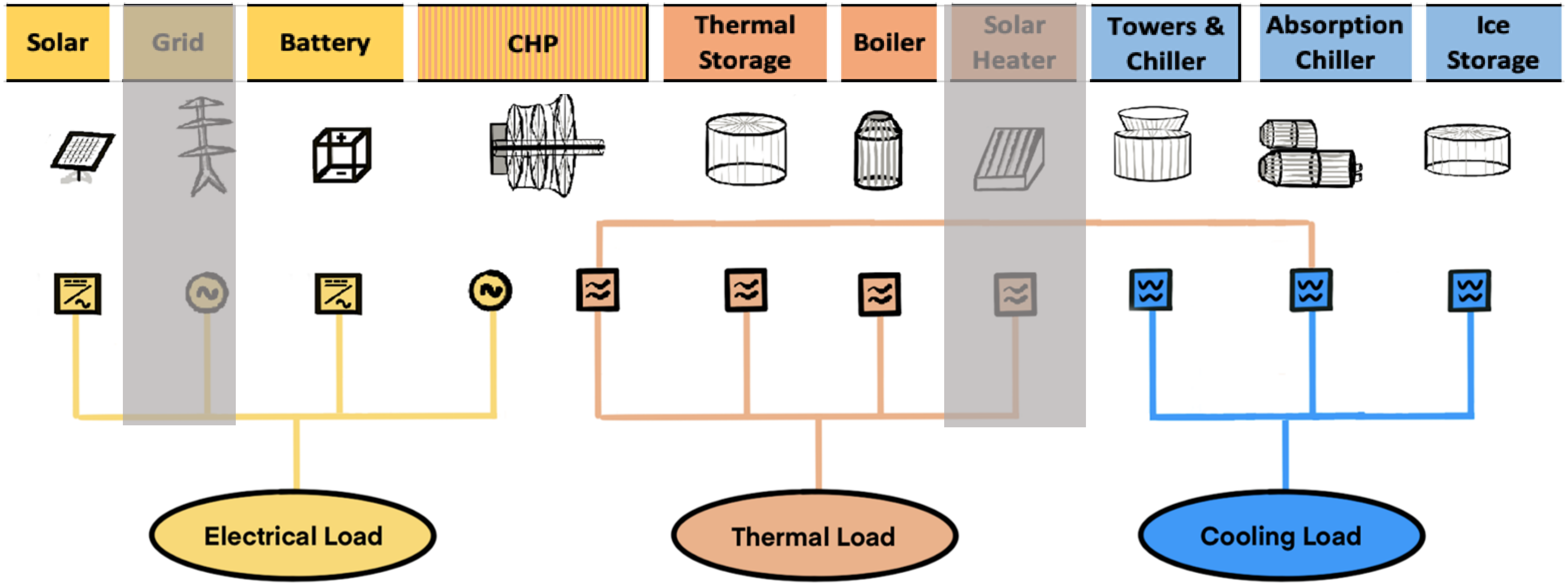
Grid | CHP | Boilers | Battery | Thermal Storage | Grid | Towers & Chillers | Steam Chiller | Critical Load Shed | Electrical Storage Penalty | Thermal Storage Penalty | Cold Storage Penalty

Example Cases

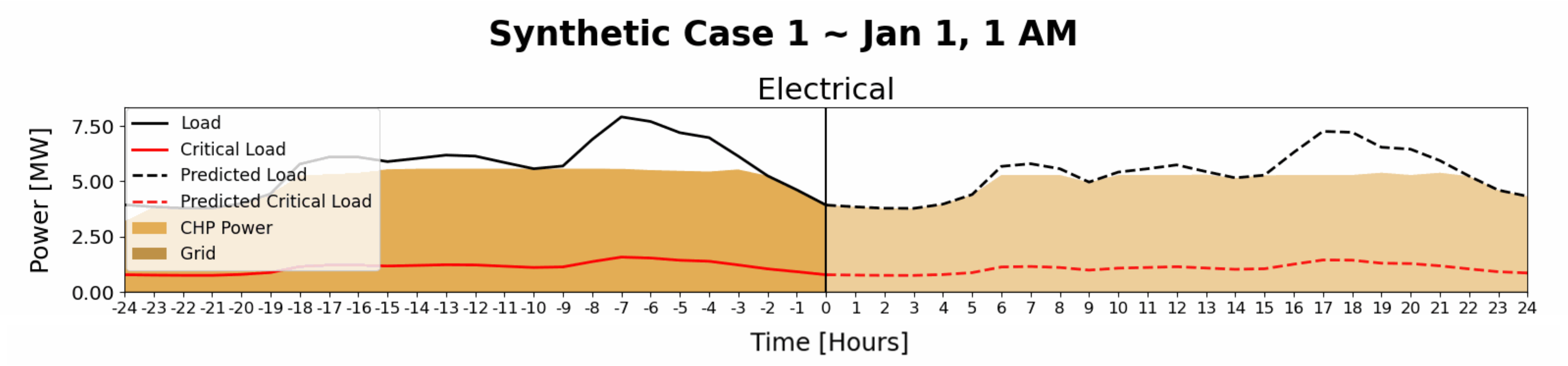
	Case 1	Case 2
Synthetic DES	• CHP, Boiler, Electric chillers/Cooling Towers • Utilities (electricity, natural gas, water) • 76 buildings, previously defined loads • Evaluated for 8760 hours • No grid	• Case 1 • *Solar PV* • *Battery, hot water storage, chilled water storage* • *Absorption chillers* • No grid
GW DES	• CHP, Boiler, Electric chillers/Cooling Towers • Utilities (electricity, natural gas, water) • 5 buildings (supported by CHP) • Evaluated for 24 hours • No grid	• Case 1 • *Solar PV* • *Battery, hot water storage, chilled water storage* • *Absorption chillers* • No grid

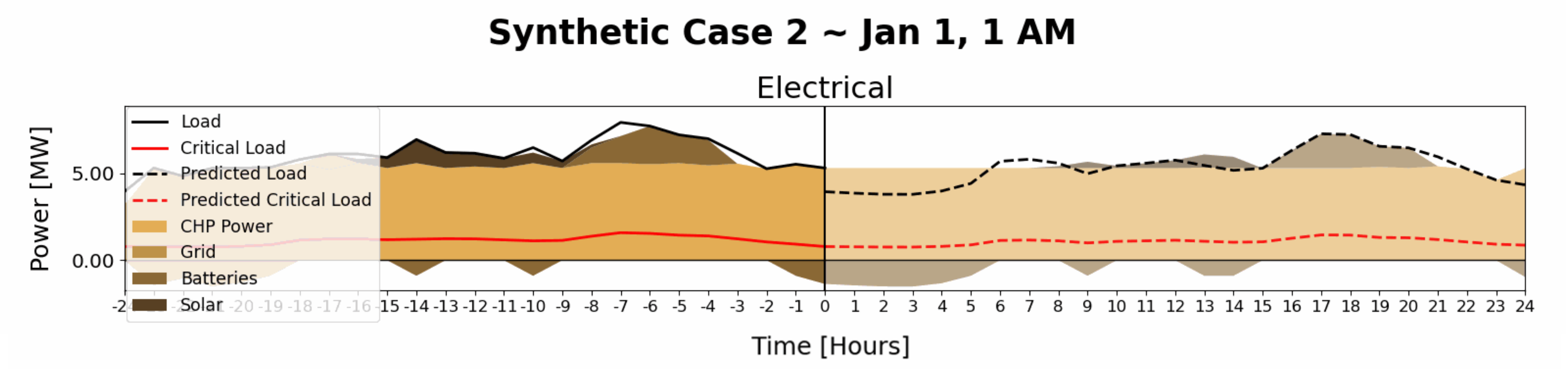
Case 1 vs. Case 2



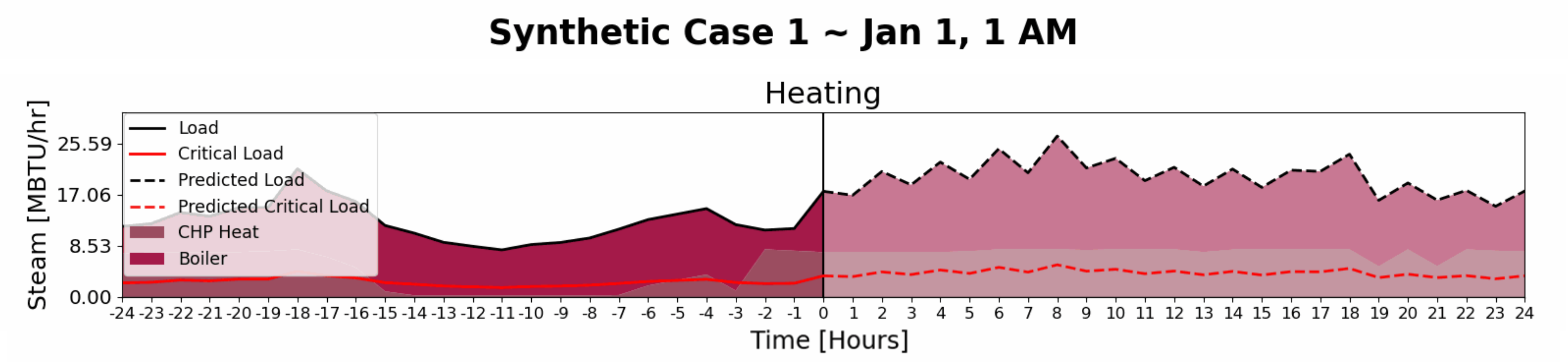


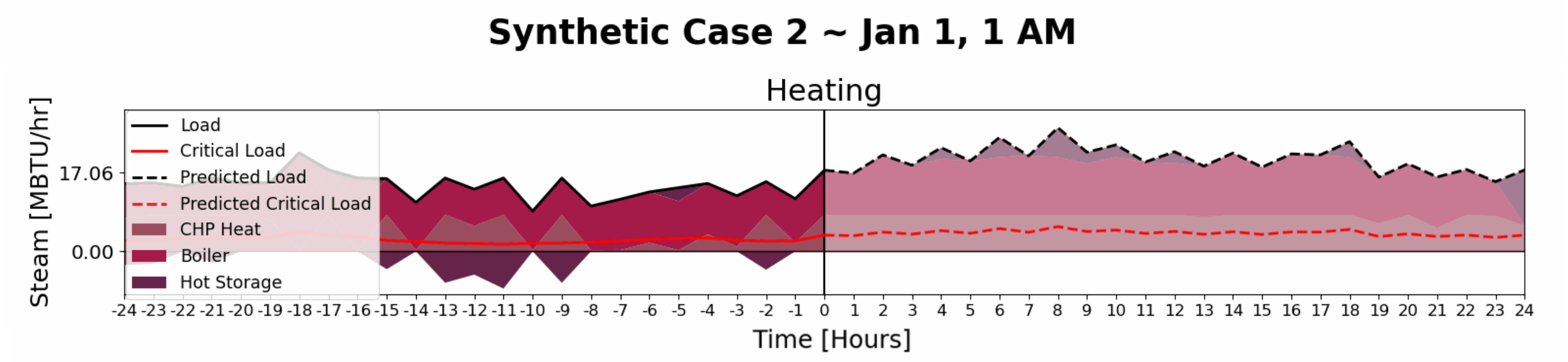
Synthetic DES Case 1 vs. Case 2: Electricity



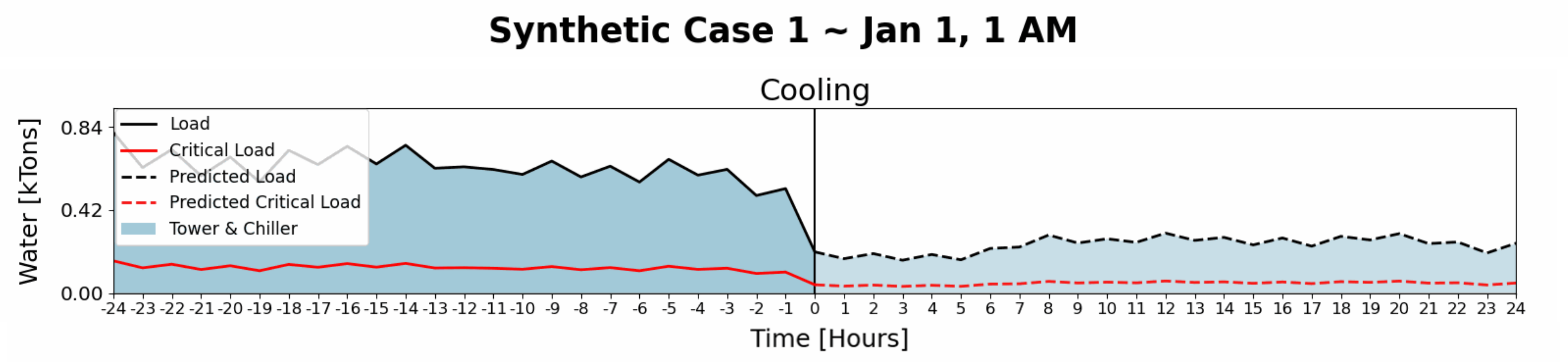


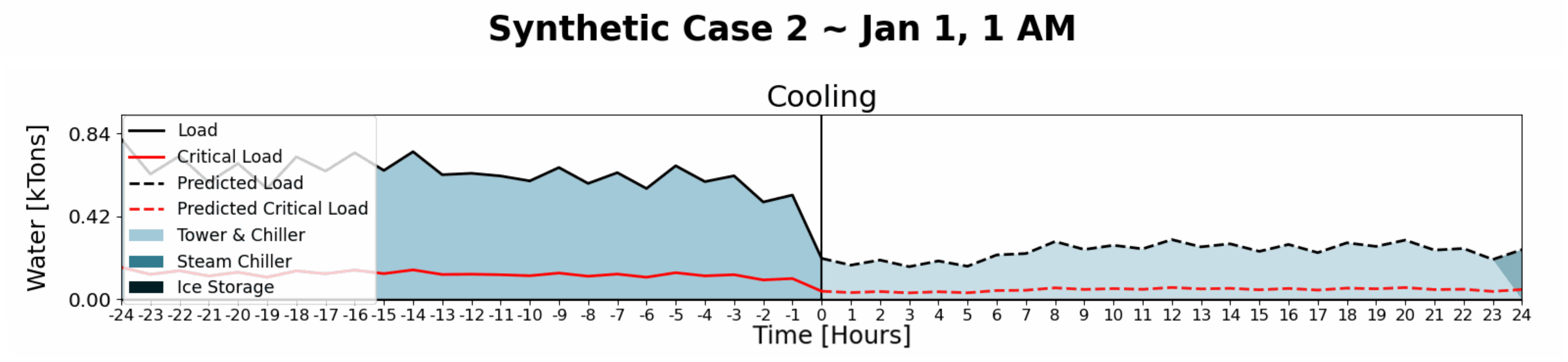
Synthetic DES Case 1 vs. Case 2: Heating



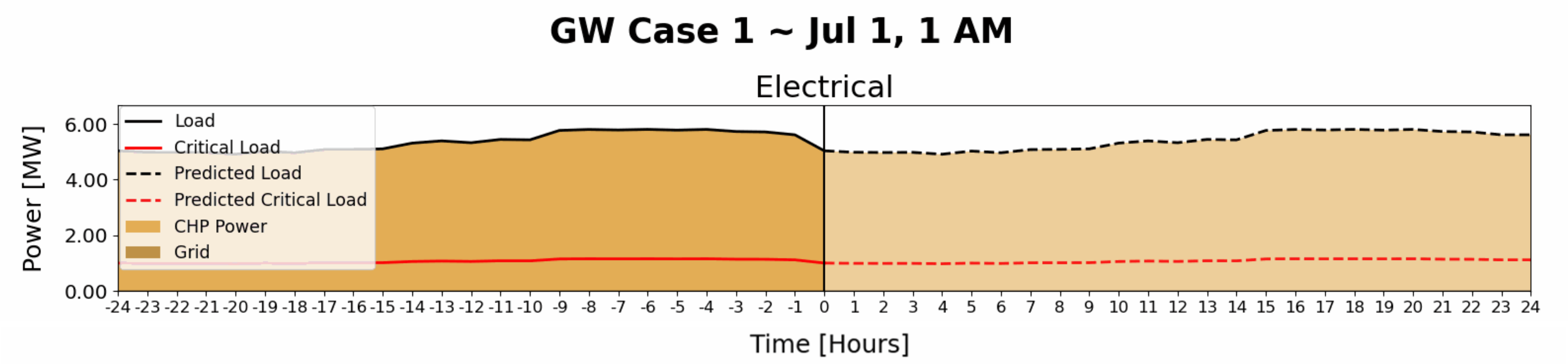


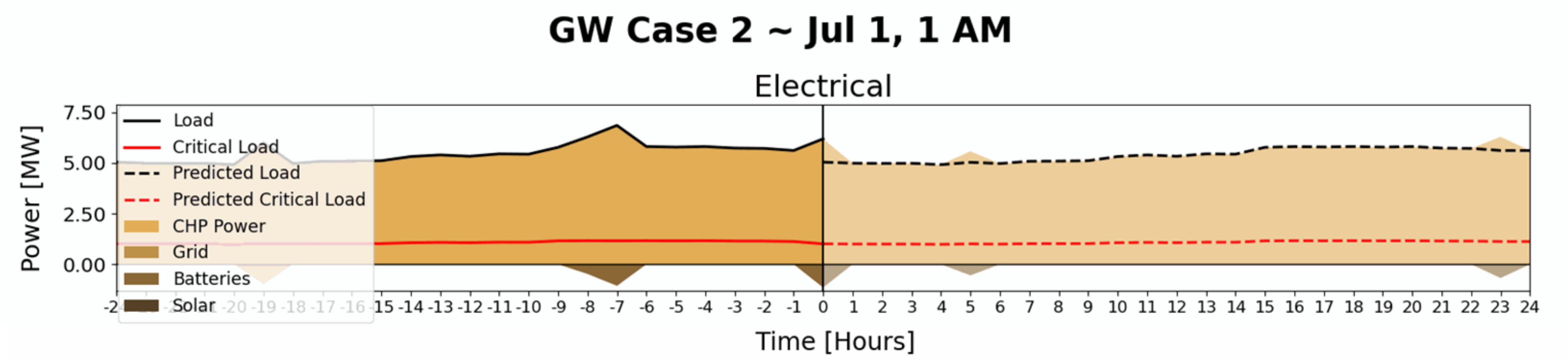
Synthetic DES Case 1 vs. Case 2: Cooling



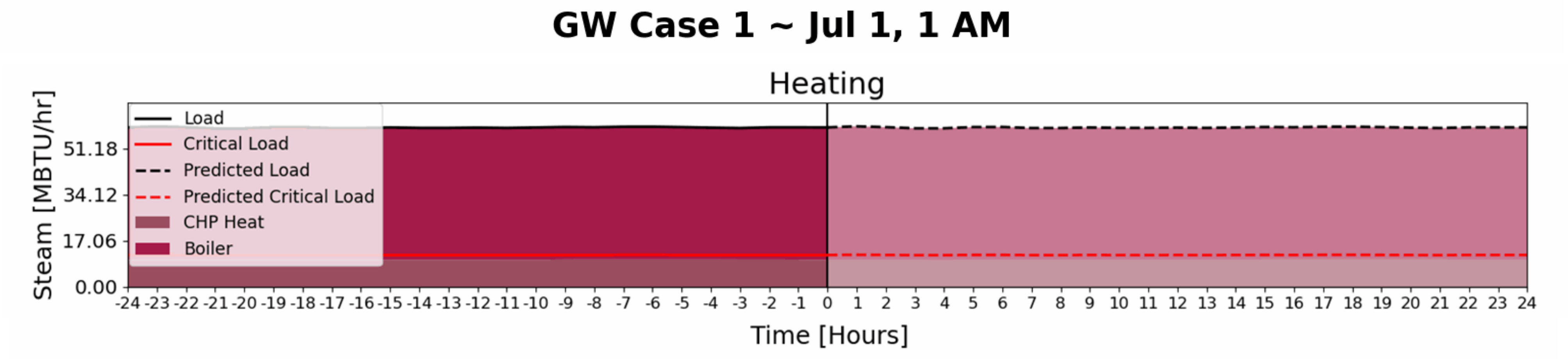


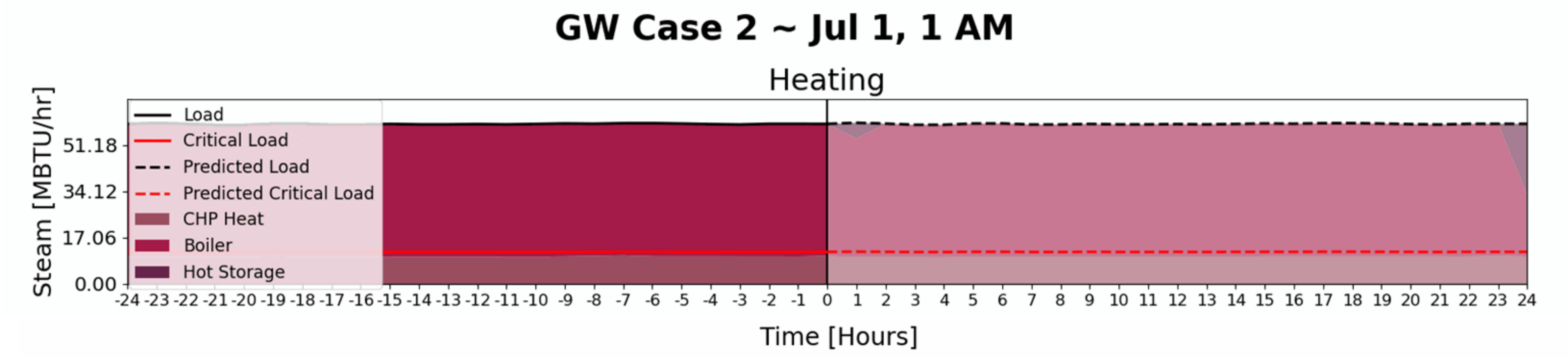
GWU DES Case 1 vs. Case 2: Electricity



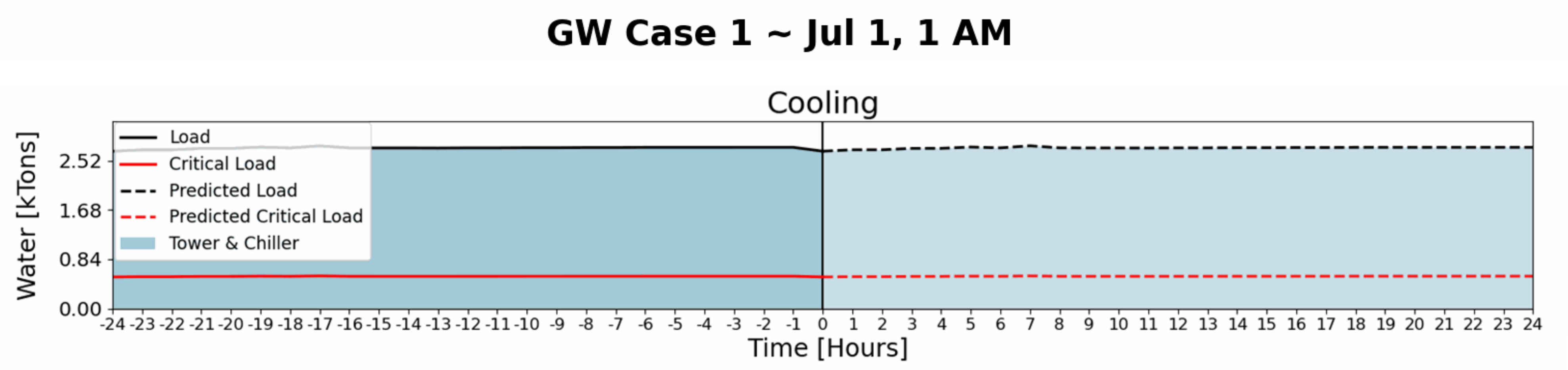


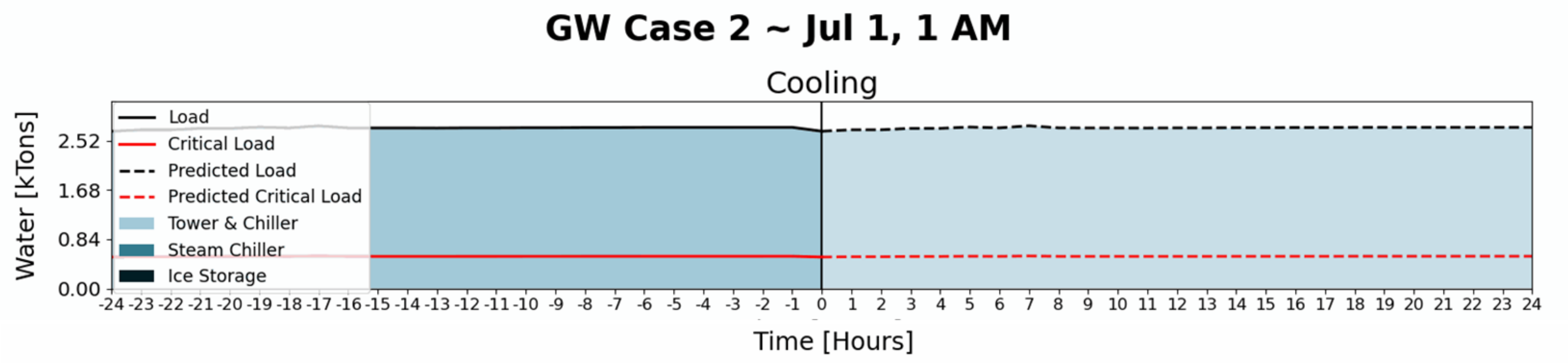
GWU DES Case 1 vs. Case 2: Heating





GWU DES Case 1 vs. Case 2: Cooling





Technoeconomic Framework

Reliability

- **Loss of Energy Expectation:** Expected number of days in which the daily peak load exceeds the available generating capacity

$$Loss\ of\ Energy\ Expectation = \sum Days\ where\ the\ maximum\ load > Generation\ Capacity$$

- **Probability that Energy Needs are Met:** Percentage of simulations where the demands of the system are adequately met and do not fail the system

$$Probability\ Energy\ Load\ is\ met = \frac{\sum hours\ where\ load > Generation\ Capacity}{8760\ (hours\ in\ a\ year)} \times 100$$

Resilience

- **Probability of Recovery:** Percentage of time intervals in which the system, previously operating in deficit, is now meeting demand

$$Probability\ of\ Recovering\ from\ Failure = \frac{\sum hours\ following\ failure\ where\ load < Generation\ Capacity}{\sum Hours\ where\ load\ > Generation\ Capacity} \times 100$$

Technoeconomic Framework

Vulnerability

- **Average Failure:** Average failure load deficit divided by the average load during failure

$$Average\ Failure = \frac{\Sigma\ Load\ during\ failure\ hours\ - \Sigma\ Generation\ capacity\ during\ failure\ hours}{\Sigma\ hours\ where\ load > Generation\ capacity}$$

Return on Investment (ROI)

$$ROI = \frac{\Sigma\ Installed\ technologies\ energy\ costs\ - \Sigma\ DES\ technology\ enery\ cost}{Capital\ cost\ of\ DES\ technologies}$$

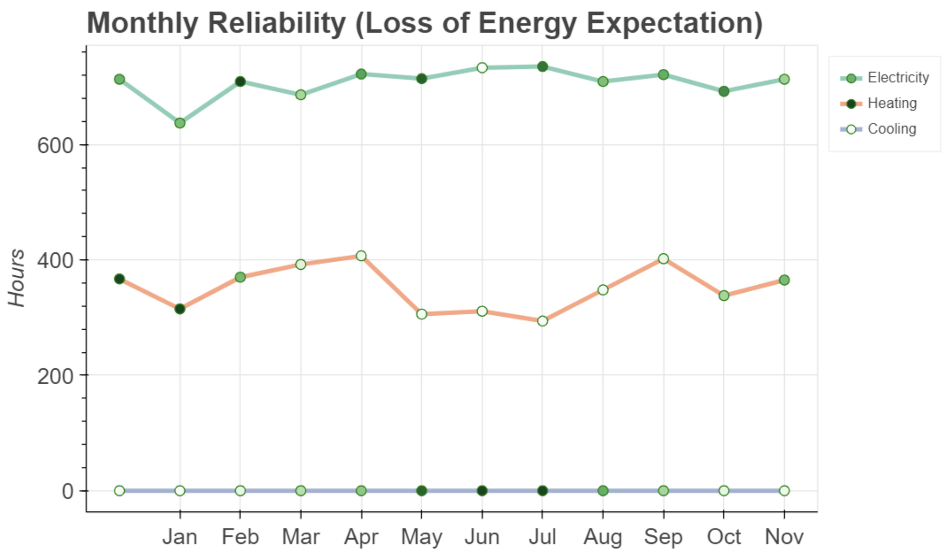
Cost

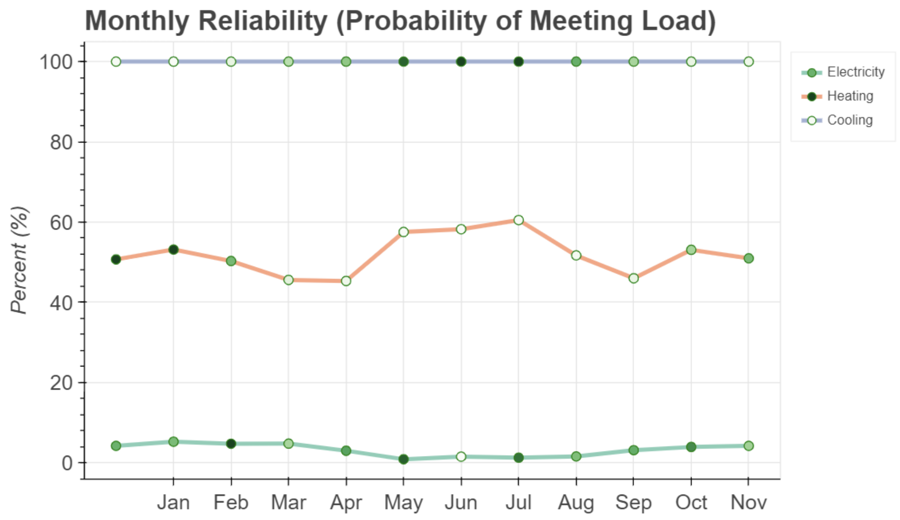
- **Cost per Significant Unit:** Total cost of the system output divided by a relevant system unit

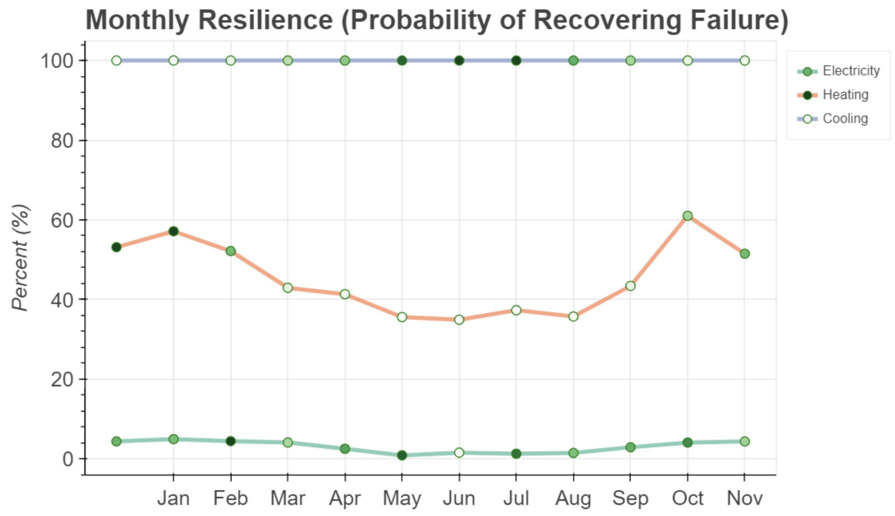
$$Storage\ Cost = \frac{Capital\ Cost\ of\ Technology}{Storage\ Capacity\ (kWh)}$$

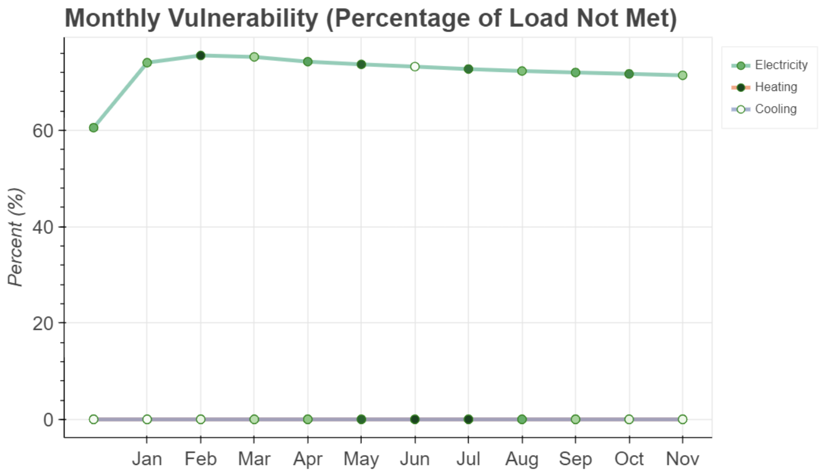
$$Generation\ Cost = \frac{Capital\ Cost\ of\ Technology}{Generation\ Capability\ (kW)}$$

Synthetic DES Overview: Sample Output









Synthetic DES: Electricity

Metric	Scenario				
	Status Quo	Islanding	Grid Buying	Grid Selling	w/ New Tech
Reliability [%]	100	18.36	100	18.36	100
Resiliency [%]	100	3.54	100	3.54	100
Vulnerability [%]	0	58.15	0	58.15	0
Average Operating Cost [$/day]	47,899	44,894	44,231	48,602	66,923
Capital Cost [$]	0	0	0	0	17,585,440
Return on Investments	N/A	N/A	N/A	N/A	-0.39 (-2.6 years)

- *Cost to operate DES with PV & battery storage technologies is more expensive because current model uses flat rate electricity pricing.*

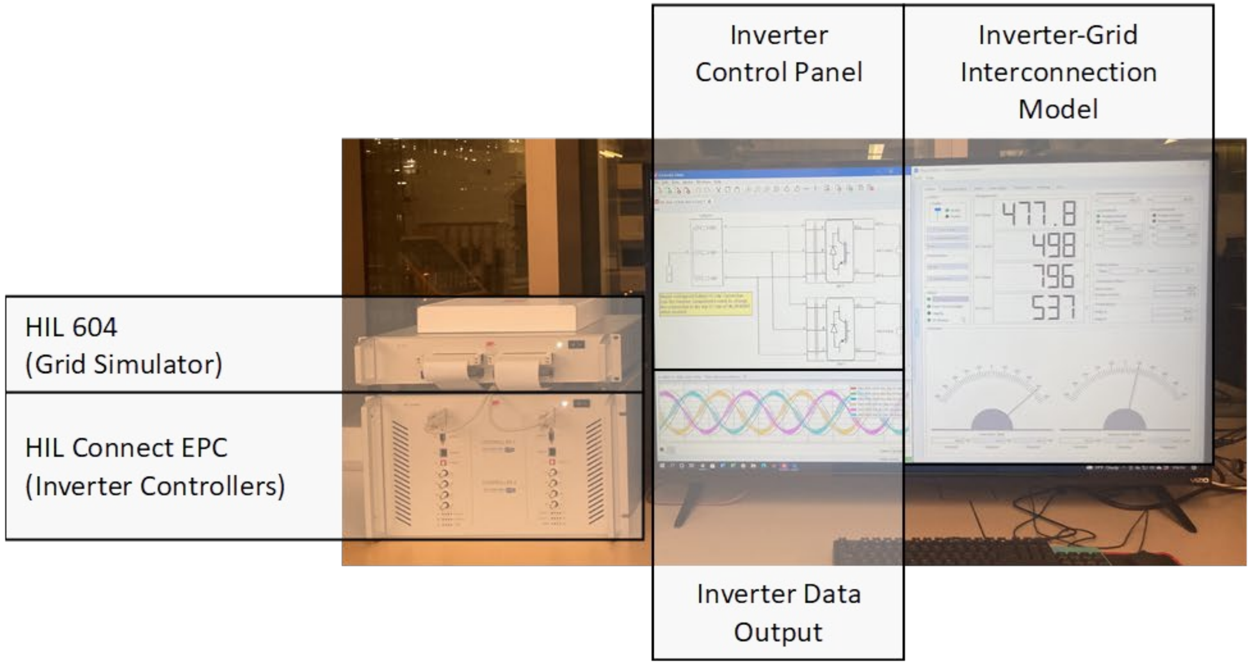
Synthetic DES: Heating & Cooling

Metric	Scenario				
	Status Quo	Islanding	Grid Buying	Grid Selling	w/ New Tech
Reliability [%]	100	97.37	100	97.37	100
Resiliency [%]	100	47.39	100	47.39	100
Vulnerability [%]	0	0.13	0	0.13	0
Average Operating Cost [$/day]	3,124	3,441	3,137	3,438	4,398
Capital Cost [$]	0	0	0	0	1,285,864
Return on Investments	N/A	N/A	N/A	N/A	-0.36 (-2.7 years)

Metric	Scenario				
	Status Quo	Islanding	Grid Buying	Grid Selling	w/ New Tech
Reliability [%]	100	100	100	100	100
Resiliency [%]	100	100	100	100	100
Vulnerability [%]	0	0	0	0	0
Average Operating Cost [$/day]	2,160	2,160	2,160	2,160	1,491
Capital Cost [$]	0	0	0	0	1,316,246
Return on Investments	N/A	N/A	N/A	N/A	0.19 (5.3 years)

Hardware-in-the-Loop Testbed

- Typhoon HIL hardware & software
- Battery emulator
- Grid, PV generation simulation
- Communication between all energy resources



Next Steps

- Integrate physics-based modeling of energy resources into Energy Management System
- Incorporate dynamic pricing into EMS and techno-economic framework

- Evaluate EMS output with sensitivities and uncertainties
- Apply EMS and framework to multiple scenarios/cases
- Include urban DES characteristics as constraints
- Suggest ways to improve resilience, reliability, ROI
- Perform laboratory demonstration of DES operation with distributed generation and storage
- Implement sensors/meters in GW DES to collect and verify data

Dissemination of Results to the Community

DEPARTMENT OF ENERGY & ENVIRONMENT
GOVERNMENT OF THE DISTRICT OF COLUMBIA

Presented to D.C.'s DOEE Battery Storage Working Group, April 7, 2021

LEADING THE WAY
CampusEnergy2022
Feb.15-18 | Westin Boston Seaport District Hotel | Boston, MA

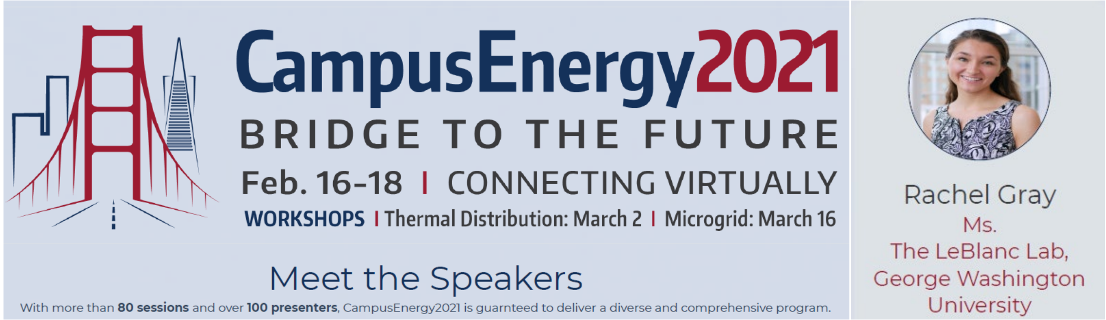
Presented at IDEA CampusEnergy 2022

GWTODAY
GW'S OFFICIAL ONLINE NEWS SOURCE
MENU
Home ▸ Foggy Bottom 'Living Lab' Provides Ideal Case Study for Energy System Management

Foggy Bottom 'Living Lab' Provides Ideal Case Study for Energy System Management

A SEAS research team uses GW's campus to explore how complex urban energy systems can gain resilience as technology evolves.

Rachel Gray receives John Gray Professional Scholarship at IDEA 2022



Presented at IDEA CampusEnergy 2021

ASHRAE HVAC&R INDUSTRY NEWS

INTERNATIONAL DISTRICT ENERGY ASSOCIATION
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This Week in District Energy

Project covered in GWTODAY & featured in ASHRAE and IDEA newsletters

INTERNATIONAL DISTRICT ENERGY ASSOCIATION

Panelist for webinar
Battery Storage: Where is the Technology Going and What are the Practical Applications?

Acknowledgments

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U.S. DEPARTMENT OF ENERGY

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