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# Task 5 Deliverable: Report on baseline performance for UCSD DER operation under current rates and incentives

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**Grant Title:**
**Innovative Business Models, Rates and Incentives that Promote Integration of High Penetration PV with Real-Time Management of Customer Sited Distributed Energy Resources.**

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# Task 5: Establish baseline performance for UCSD DER operation under current rates and incentives

A report in partial fulfillment of a California Solar Initiative (CSI) Grant requirement

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# Table of contents


- **Overview of UCSD resources …** **Slide 4**
- **Baselining methodology …** **Slide 11**
- **Historical operations …** **Slide 18**
  - Campus needs, annual loads, and central plant efficiency … Slide 19
  - Understanding daily operations … Slide 25
  - Output and efficiency of individual systems … Slide 31
  - Summary of historical operations … Slide 39
- **Understanding campus needs …** **Slide 40**
  - Monthly and yearly analysis … Slide 42
  - Analysis of day type effects … Slide 50
- **Preliminary business analysis …** **Slide 56**
- **Further research and next steps …** **Slide 63**

# Glossary

- ***CHP***: combined heat and power
- ***CHW***: chilled water
- ***CUP***: central utility plant
- ***HTW***: hot water
- ***HX***: heat exchanger
- ***Gens***: generators
- ***TES***: thermal energy storage
- ***UCSD***: University of California, San Diego
- ***WC***: denotes a chiller at the Central Utility Plant (either electric or steam)

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# OVERVIEW OF UCSD RESOURCES

# UCSD microgrid

## UC San Diego operates a 42 MW microgrid

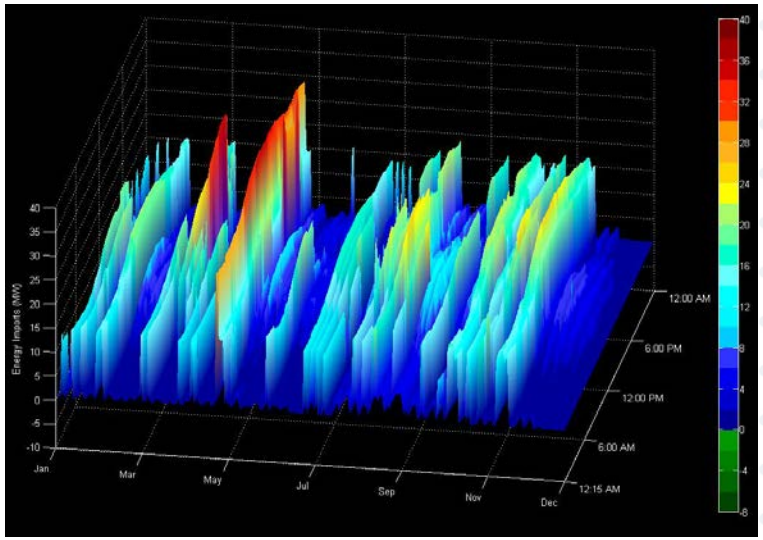
With a daily population of over 45,000, UC San Diego is the size and complexity of a small city.

11 million sq. ft. of buildings, $250M/yr of building growth

Self generate ~ 90% of annual demand

- 30 MW natural gas Cogen plant
- 2.8 MW of Fuel Cells in operation
- 1.2 MW of Solar PV installed, additional 2 MW planned
- Twice the energy density of commercial buildings

UC San Diego grid imports 2007



# Central plant resources

- **The central plant is rich with dispatchable resources**
  - Two 13 MW natural gas generators
  - One 3 MW steam generator
  - Three Steam driven chillers (~ 10,000 tons capacity)
  - Five electric driven chillers (~ 7800 tons capacity)
  - 3.8 million gal thermal storage tank
  - Backup diesel generation
- **> 1 MW of solar PV**
- **~ 1.4 MW of DR-ready reducible building load**
- **Visibility at the building level**

Chilled water tank at UCSD campus

# UCSD's cogeneration system

**Cogeneration is a core component of UCSD's microgrid**

Steam chiller at UCSD campus

## + The UCSD cogeneration system has the following

- Natural gas turbines generate electricity for onsite use & steam
- Steam is used to generate hot water, more electricity (steam turbine) and chilled water (steam-driven chillers)
- Cogeneration offsets imported electricity, boiler fuel use for generating hot water & chilled water, and electricity consumption required to generate chilled water

# Flexibility of the UCSD resources

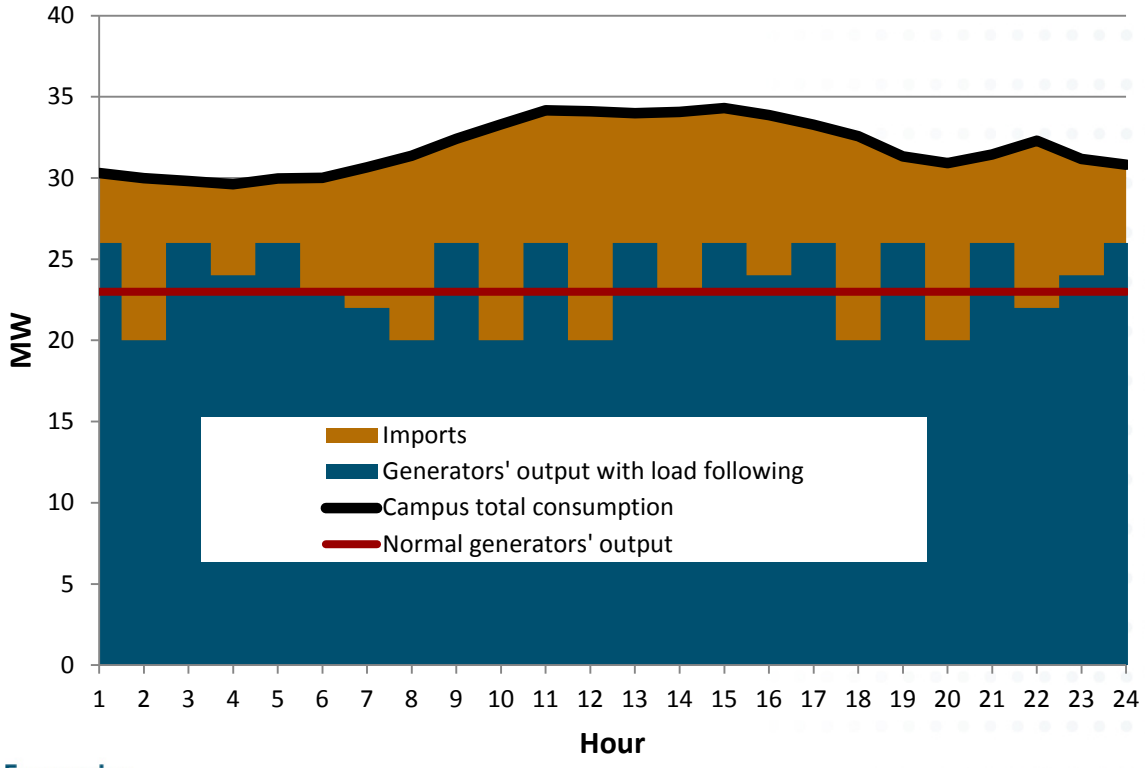
- **UCSD resources can shift load, reduce load and move load between gas and electricity fuels**
  - Natural gas generators produce electricity and steam; once on, they have a controllable range of up to ~ 6 MW
  - Tank can deliver significant portion of campus chilled water needs and can be variably charged/discharged
  - Steam from generators can be used to generate hot water, chilled water and additional electricity in varying amounts
  - Building load can be reduced ~ 1.4 MW for DR events

# UCSD online energy dashboard

Source: http://energy.ucsd.edu/campus/campus.php

# Example of renewables integration using UCSD DER's

- **Hypothetical load following scenario using UCSD actual data for 6/7/2011**
  - Generators are ramped up and down within their acceptable operating range throughout the day



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# BASELINING METHODOLOGY

# Review of baselining effort

## Overall goals for baselining

- Understanding how flexible the resources are and to what extent they can be leveraged to support more solar and renewables
- Understanding thermal & electrical campus needs
- Quantify efficiencies & understand operating strategies
- Identify opportunities for operational improvement
- Validate / calibrate VPower to ensure tool generates plausible operational strategies

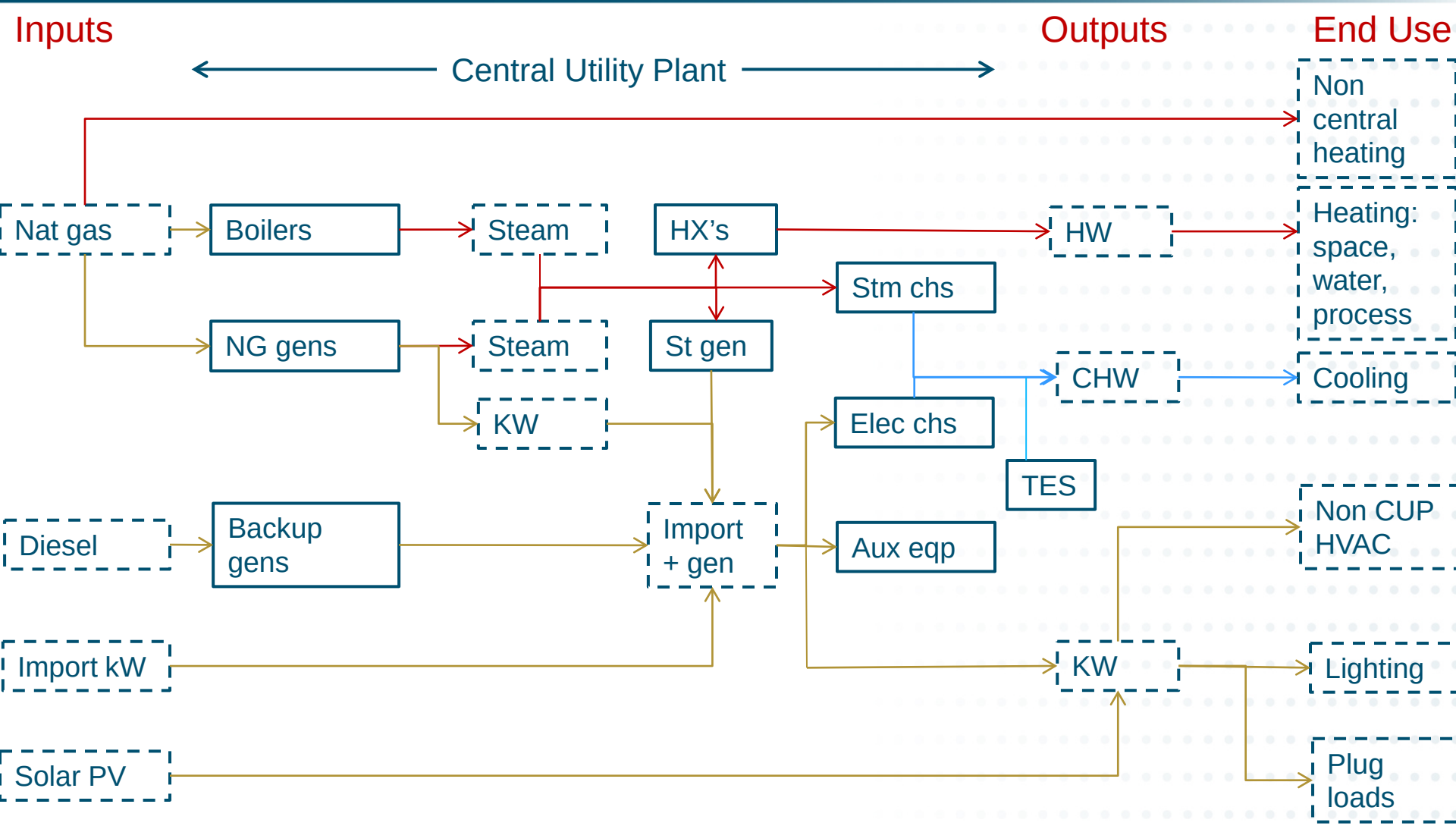
## Key questions

- How do the campus needs vary by hour, season, month?
- What are the overall system efficiencies (CHP, steam utilization) and equipment-level efficiencies (chillers, generators, etc.)?
- What are the regular modes of operation of each system?
- How much capacity is available for changing operations?

# UCSD data resources

- **Baselining data obtained from multiple sources:**
  - MSCADA system: 15-minute power data
  - Johnson Control Metasys System: thermal storage tank data
  - 'BOP' System: steam data for boilers, generators
  - 'Efftrack' chiller diagnostic system: chiller data
  - Daily central plant logs: gas usage
  - UCSD expert knowledge (i.e., John Dilliott, Energy Manager)
  - Solar data from Prof. Jan Kleissl
- **Future: disparate data sources have been integrated into a campus-wide data historian**

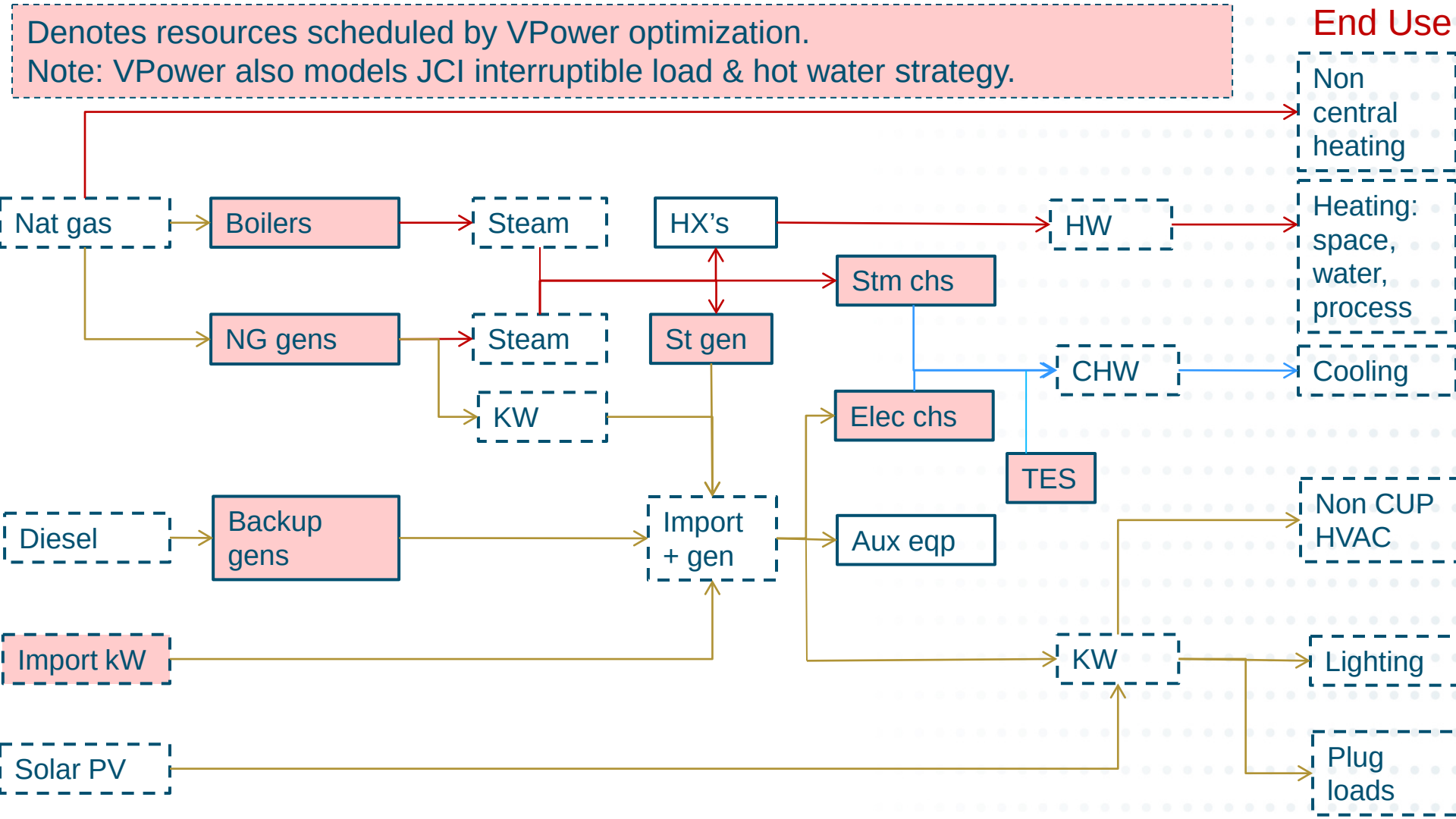
# Analytical framework




Baseline data gives input / output relationships, equipment efficiency, capacity factors, seasonal and diurnal patterns of usage, historical costs.

# Analytical framework

Denotes resources scheduled by VPower optimization.
Note: VPower also models JCI interruptible load & hot water strategy.




Services that VPower will treat as constant: CUP CHW, CUP HW, kW net CUP electric chillers

# Methodology steps

## + Collect data

- **Electrical data:** Imports, central plant generators, chillers, auxiliary, solar
- **Thermal data:** Chillers, boilers (partial), campus hot water & chilled water needs, thermal storage tank operation, generator fuel
- Up to 3 years of data collected

## + Assemble data

- To understand system level operation: generate data sets with consistent time stamps to understand inputs/ outputs across the energy flow diagram
- Quantifying individual operating efficiencies and capacities: all individual equipment data can be used

## + Visualize and analyze data

- Daily, monthly, yearly summaries of main loads
- Calculate equipment level efficiencies
- Calculate system level efficiency (overall inputs to outputs)
- Forecast campus needs based on binning analysis

# Data collected and analysis completed

## + Daily data

- Operator logs ('Greensheet') dating back 2005
- Imports, hours of op, CUP gen, gen gas use, some chiller kW

## + Hourly data

- Chilled water & hot water to campus (dating back 2007)

## + 15 minute interval data

- MSCADA: Imports, CUP gen
- JCI system: TES
- BOP: steam data for boilers, generators

## + Solar data

- 15 minute inverter & meter data dating back 2009

## + Historical price info

- Gen & delivery prices dating back 2009 (CAISO day-ahead, NGI; ALTOU, EG and GTNC tariffs)

## + Efftrack

- Chiller data obtained
- Nameplate capacity and efficiency info
- Historical data dating back to June 2011

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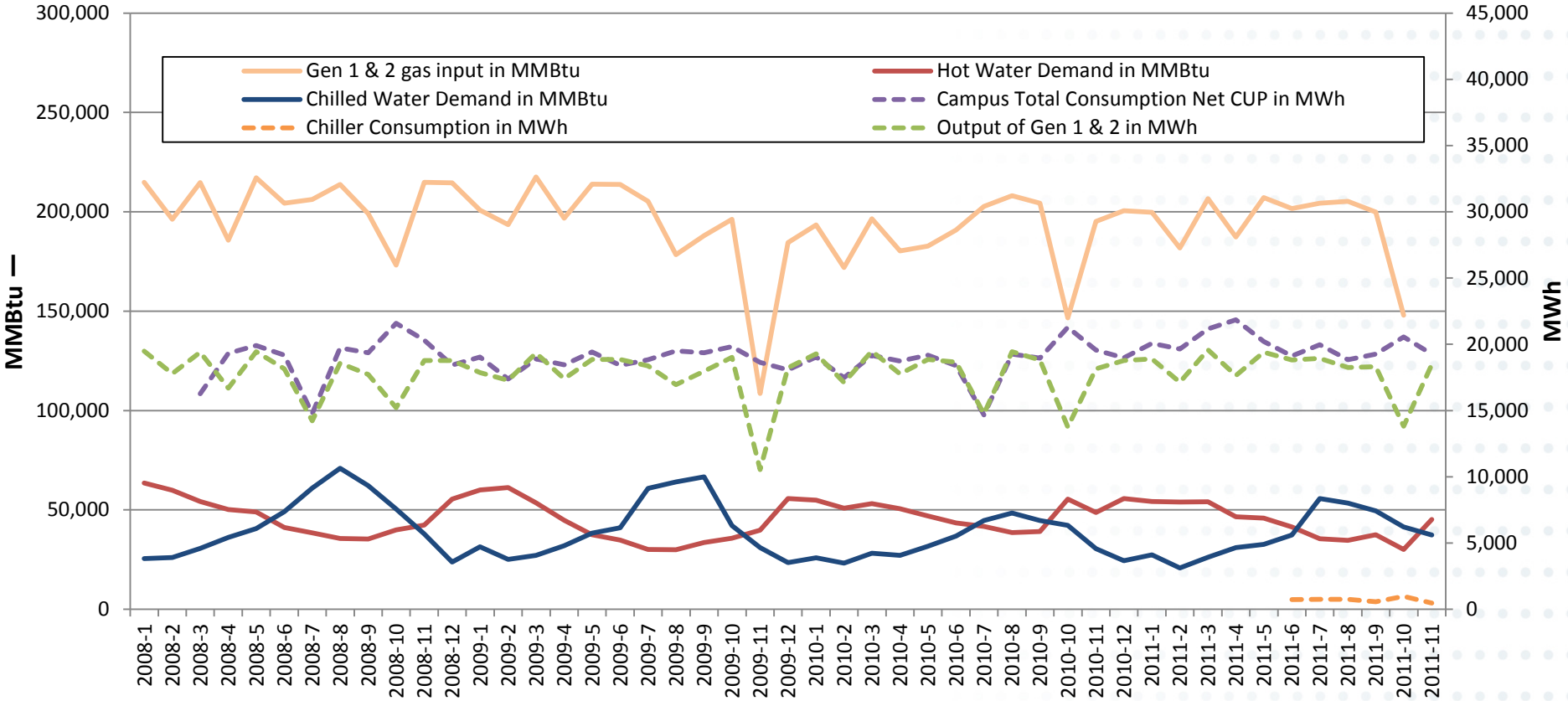
# HISTORICAL OPERATIONS

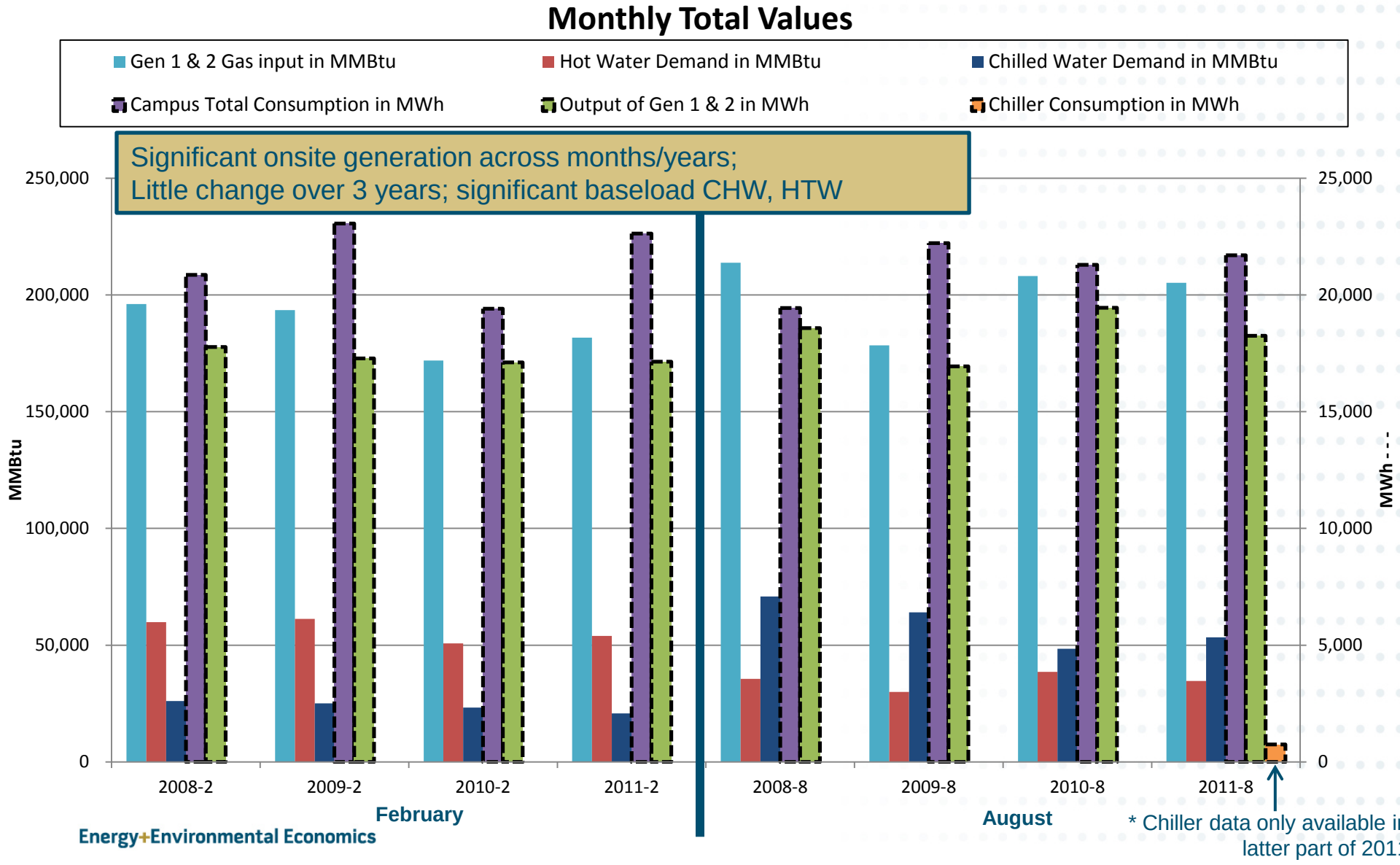
# Campus needs, annual loads and central plant CHP efficiency

# Overview of campus needs: monthly values, entire data set




- Thermal loads (CHW & HTW) are characterized by seasonal variability but also have a strong baseload component.
- Generation satisfies much of campus needs (non-CUP)
- Little load growth over the monitoring period

# Overview of campus needs: comparison of monthly totals

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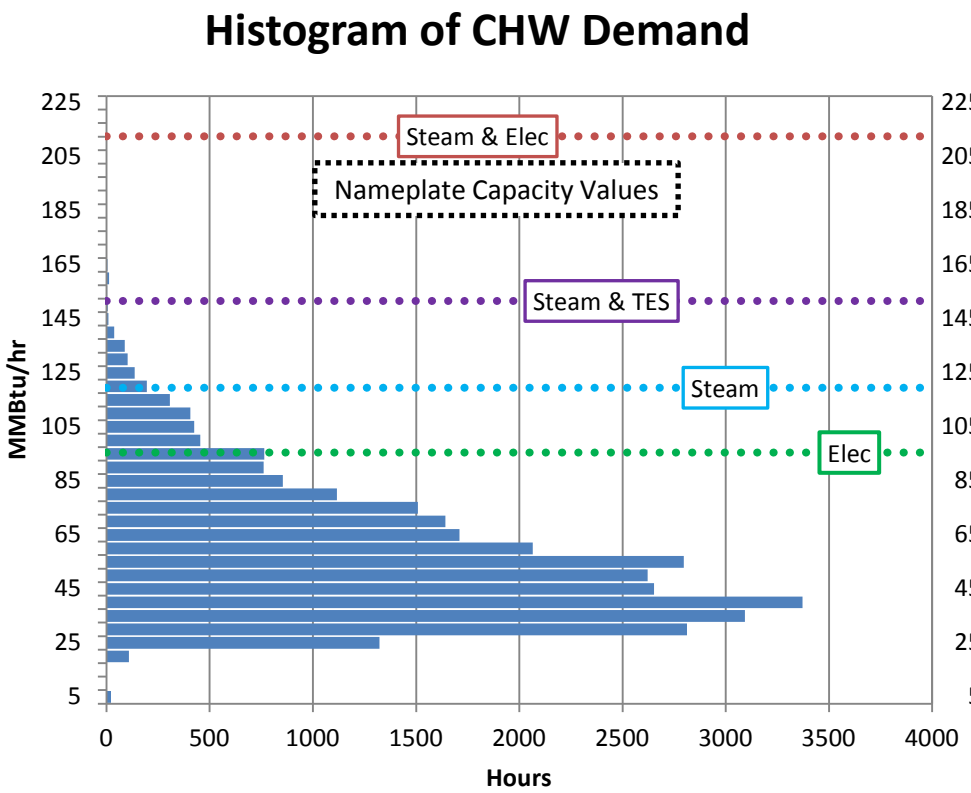
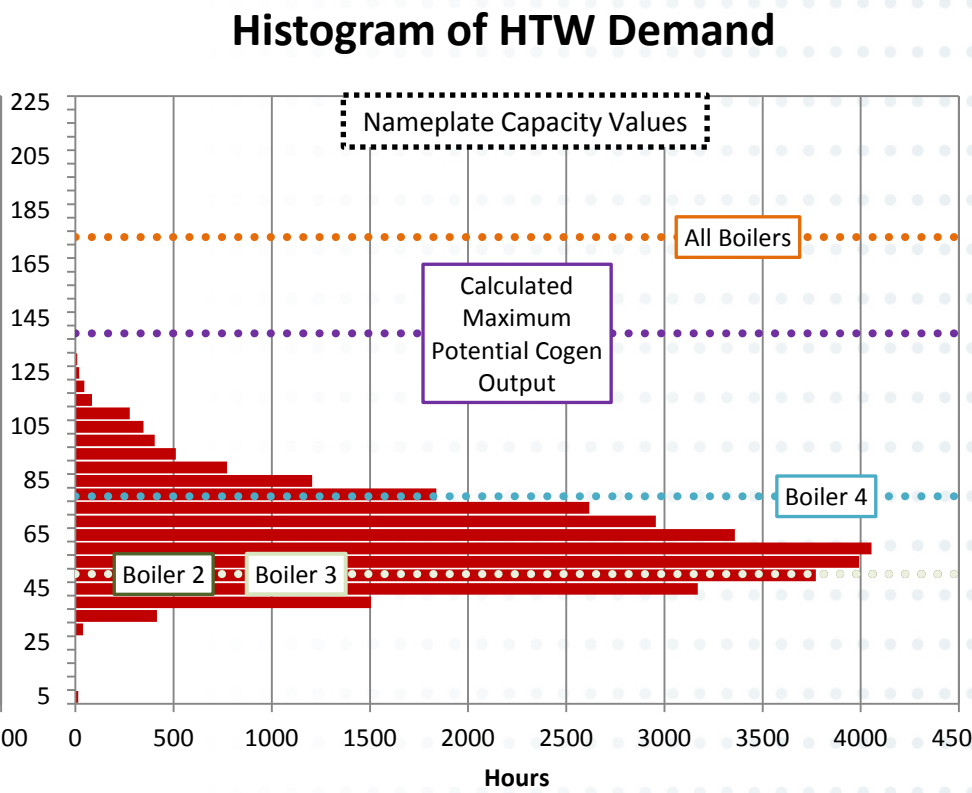
# Flexibility in providing campus hot water and chilled water

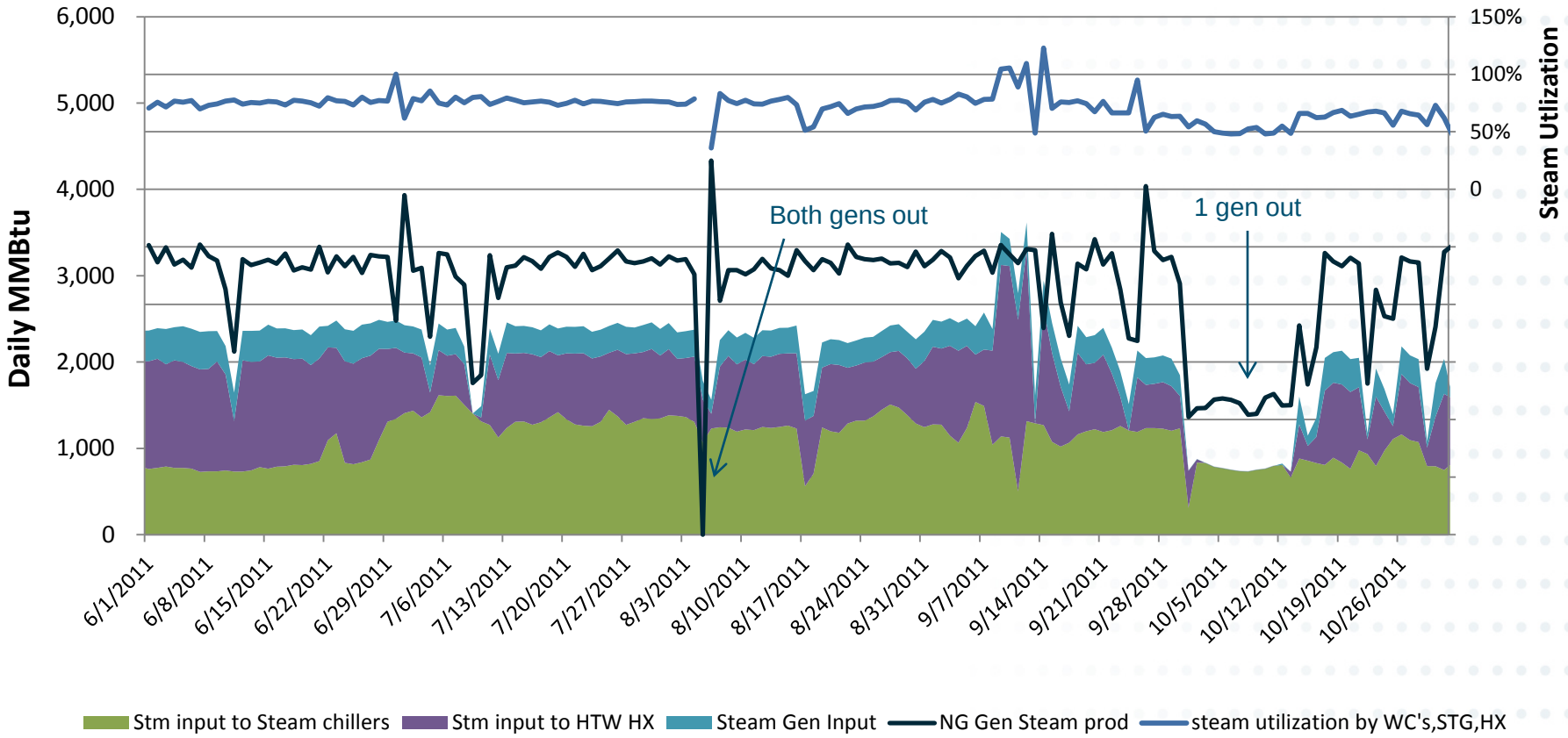
Based on ~ 4 years of data



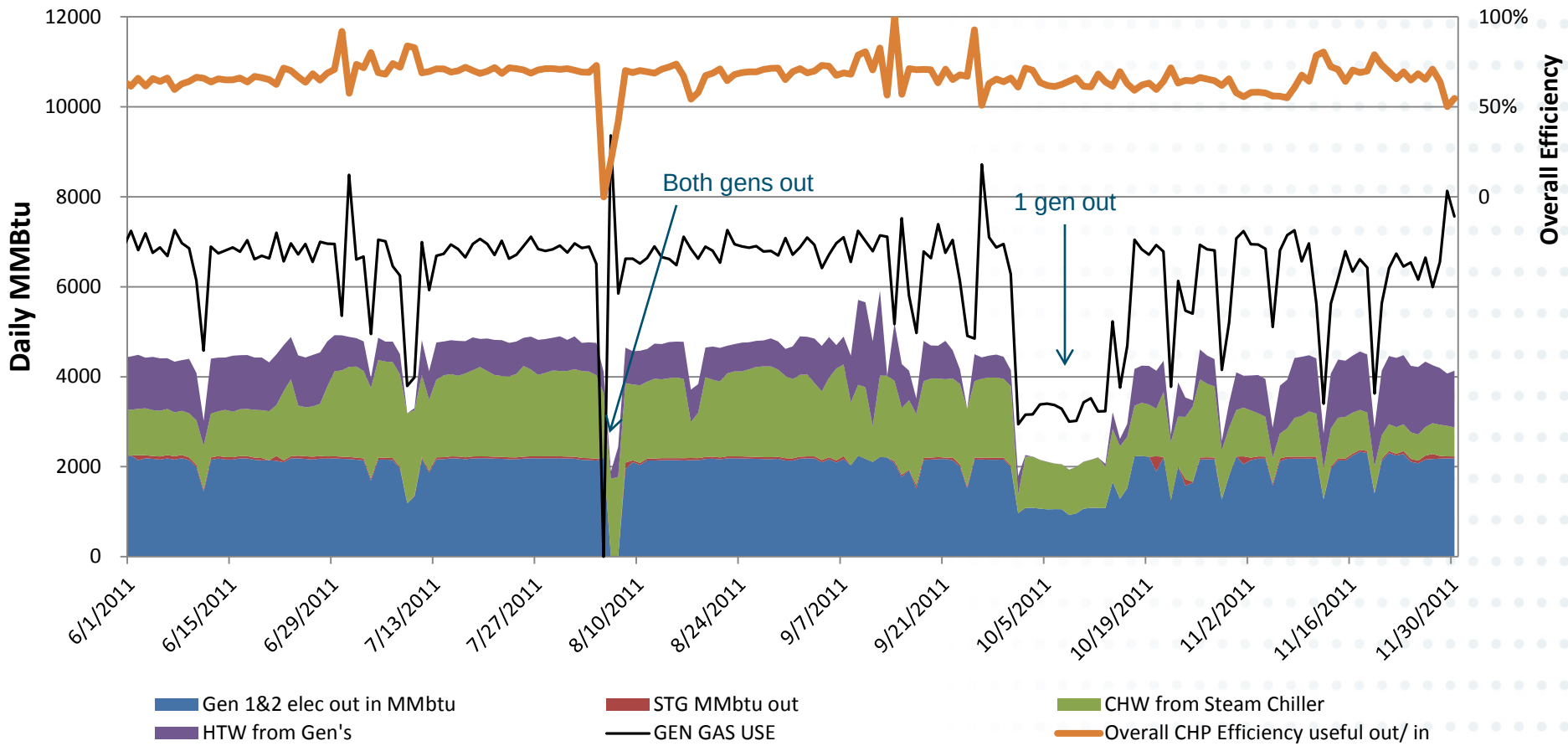

- Campus CHW and HTW needs can be met amply through existing resources
- There is flexibility to meet the need through different combinations of electric/steam chilling for CHW; boiler and cogen operation for HTW
- For some hours, need to operate a combination of steam/electric/TES to meet CHW needs

# CHP system energy flows based on daily totals (1)




- Key systems utilizing steam are shown: steam chillers, steam generator, hot water HX
- Loading order can be observed: generally steam chillers first, then hot water, then steam turbine
- Steam utilization by key systems – steam chillers, hot water HX, steam turbine shown; not 100% because other systems have 'baseload' steam requirements

# CHP system energy flows based on daily totals (2)



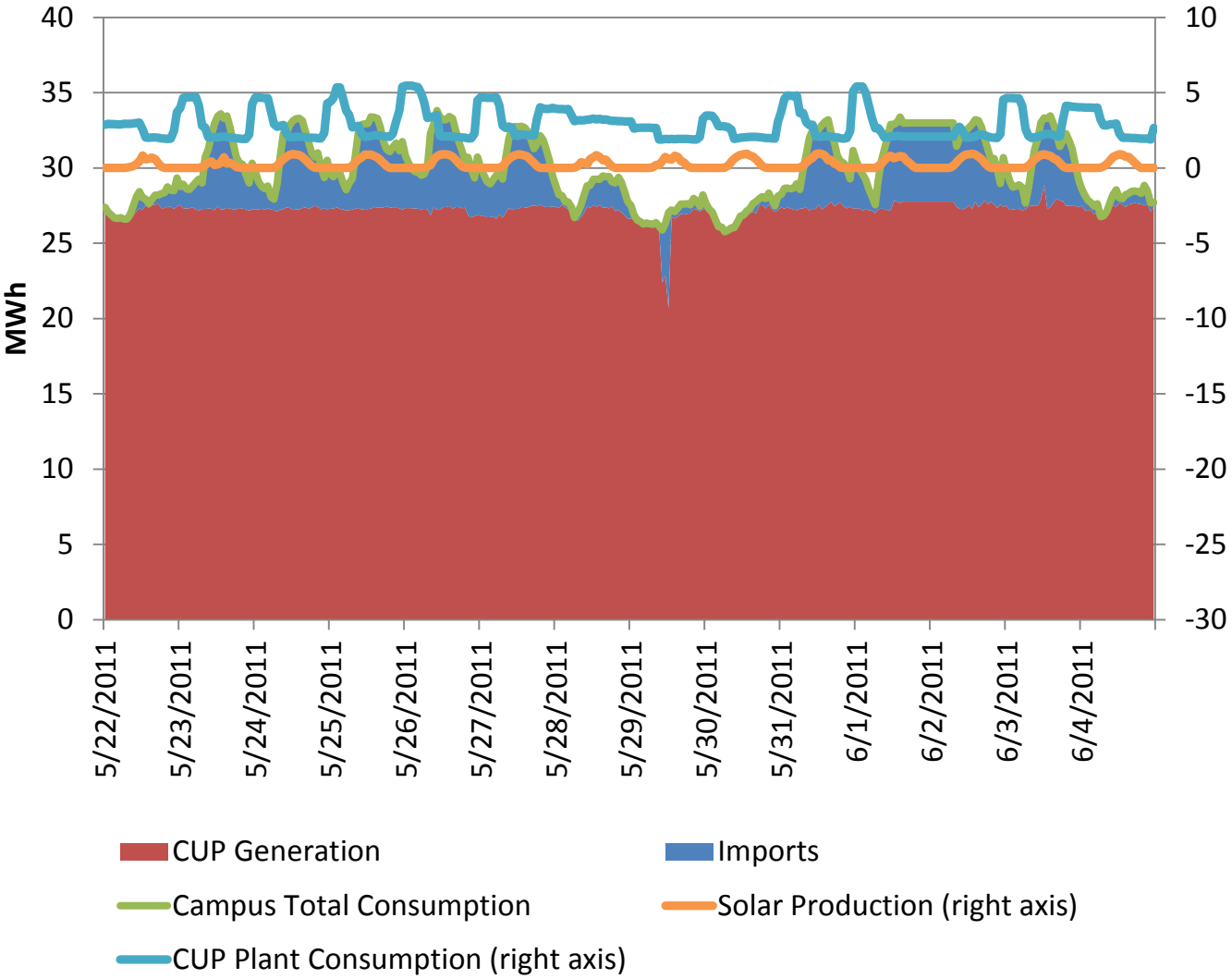

- Overall system efficiency shown (roughly 60-70%, median 65%)
- Heat rate of natural gas generators shown (roughly 30%, equivalent to ~ 12 MMBtu/MW)

# CHP system efficiency metrics

- **We characterized the CHP system using these metrics:**
- **Overall efficiency**
  - Defined as the ratio of useful output to useful input
  - Median efficiency of ~ 65% estimated; for context, the CPUC 2010 Impat Evaluation report for the self generation program reported total system efficiencies ranging from ~40-65%
- **Thermal utilization**
  - We define as the ratio of steam generated to the heat content of the fuel input net of the power generated
  - Median efficiency of ~ 70% estimated
- **Steam utilization by 'dispatchable' variable load systems**
  - We defined as the fraction of steam generated used by steam chillers, turbine, hot water heat exchanger (other 'baseload' systems use a constant amount of steam year-round)
  - Median steam utilization by the variable load systems of 75% estimated (due to improvements in baseload steam utilization systems, future utilization of ~ 85% is expected)

# Understanding daily operations

# Snapshot of electrical loads: hourly / 15 min data

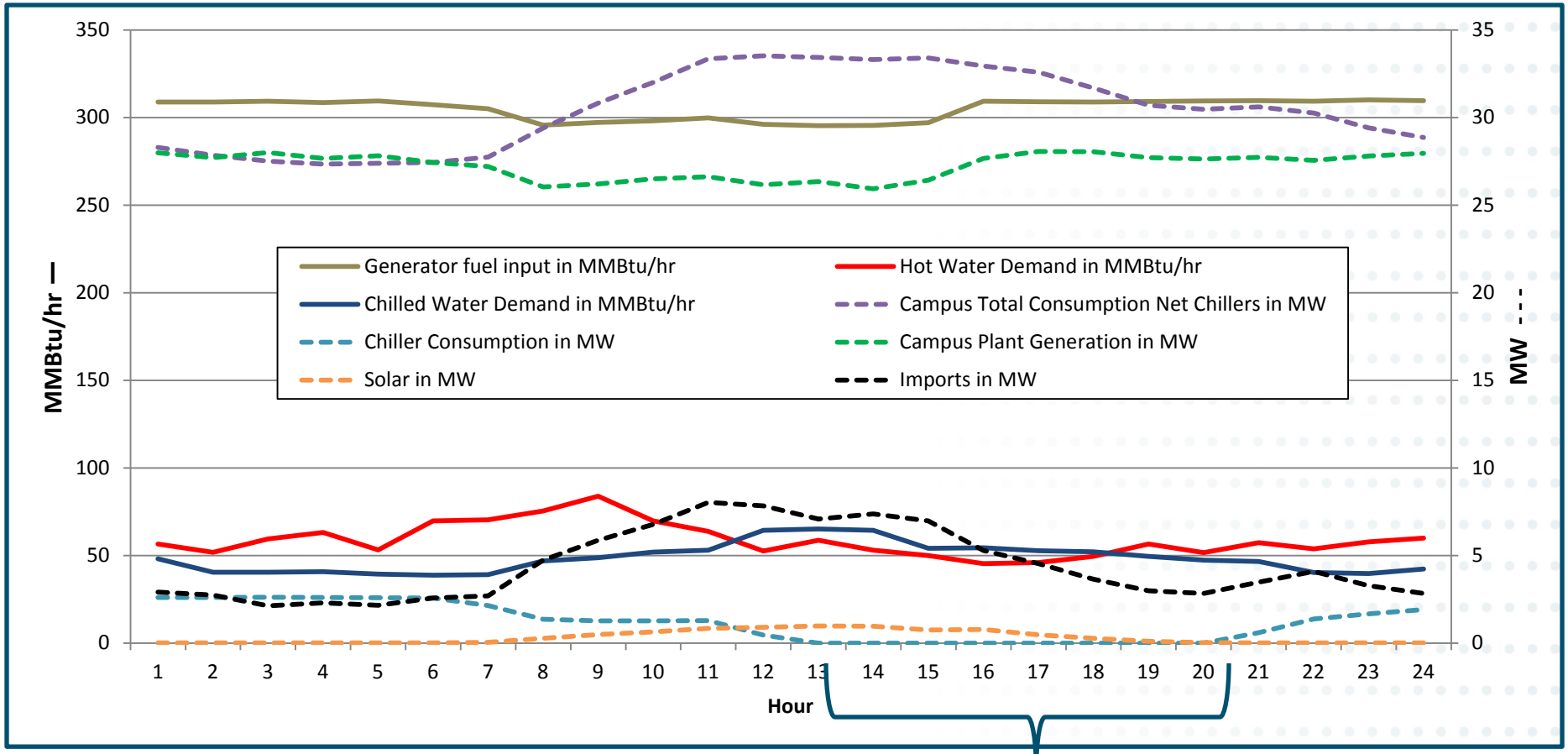



- Cogen output relatively constant
- Imports show expected diurnal pattern: peak during day
- CUP consumption shows an 'inverted' load profile due to the thermal storage tank

Data from 5/22/11

# Actual operations: June 7, 2011 example

Thermal and electrical needs vary over the day but contain significant baseload components (high load factor).

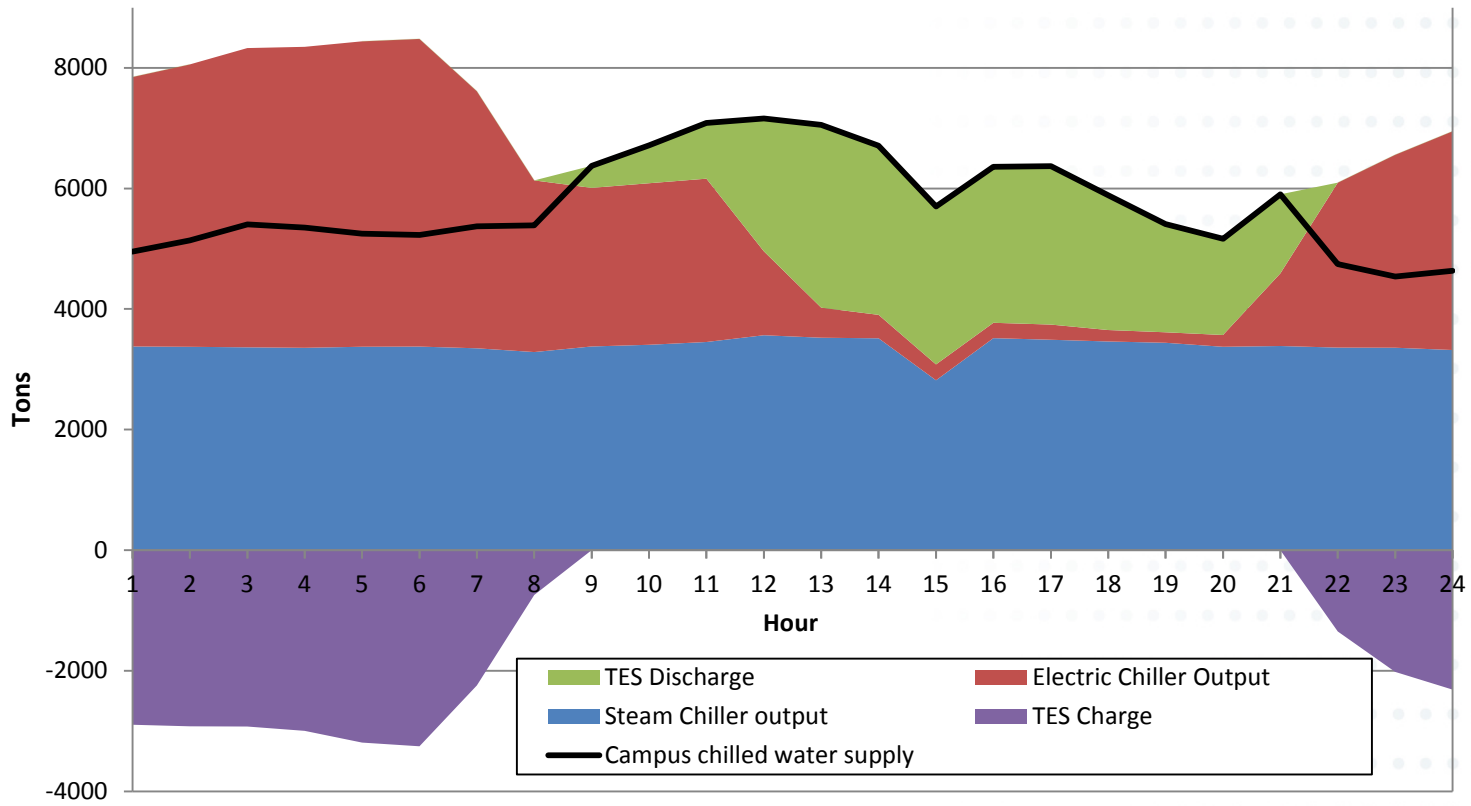



Solar PV output ~ 1 MW

Load shifting from thermal storage lowers electrical chiller consumption

# Actual operations chilled water system: June 7, 2011

- Roughly constant steam chiller output across all hours
- Electric chiller output is reduced during peak hours (11-6 pm) and greatest when charging the thermal energy storage (TES) tank
- Tank is charged at night and early morning and discharged during peak hours



# Observations on daily operation

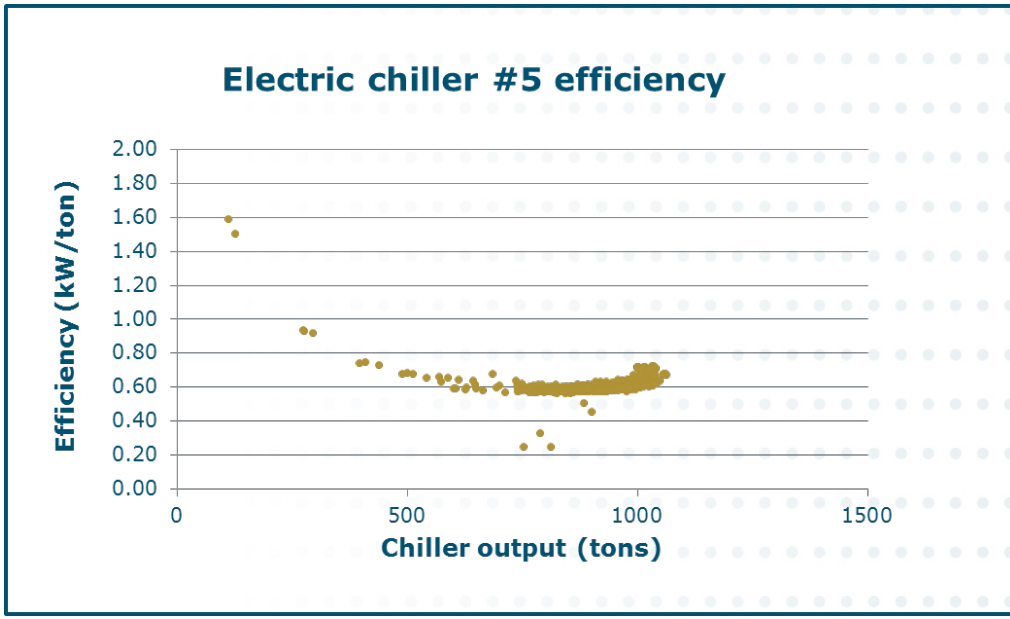
- **Generators operated at full capacity & steady state**
  - Natural gas generators can be operated between ~ 10 and 13 MW without experiencing nitrogen oxide emissions problems
- **Steam chillers typically operated all hours and at constant output**
- **Electric chillers operated minimally during peak periods and operated mainly to charge the TES**
- **TES is operated conservatively* such that it always maintains capacity to compensate for unexpected steam chiller outage**
  - *TES is not discharged to the 'optimal' rate, assuming perfect foresight on chilled water demand
- **Solar PV generation peaks at ~ 1 MW (3% of electrical load)**

# Individual systems

# Chiller efficiencies and capacity

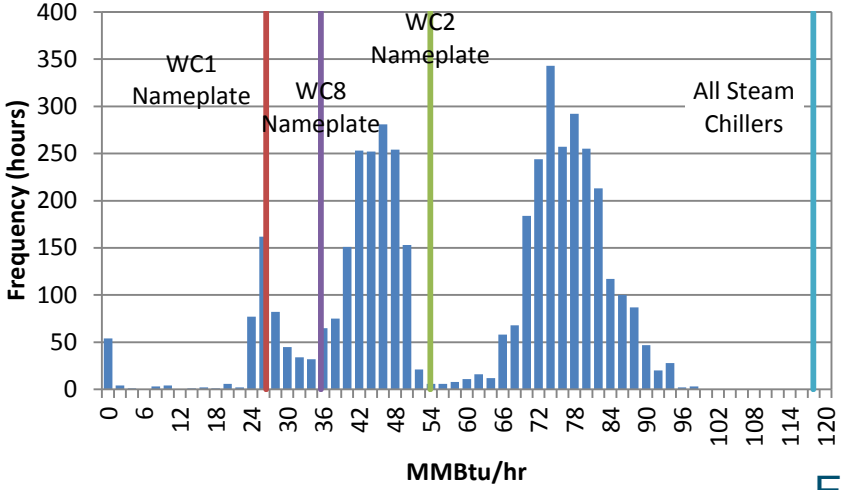
- **Electric chiller (all are centrifugal) efficiency ranges from ~ 0.5 to 0.7 kW/ton (coefficient of performance, COP ~ 5-6*)**
- **Steam driven chiller efficiency ranges from ~ 8000 Btu/hr/ton to 10,500 Btu/hr /ton (COP ~ 1.4-1.7*)**
- **Chiller loading as function of nameplate typically ~ 70-90% (50th & 90th percentiles)**
  - Exceptions include steam chiller WC1 ~ 40-50% and electric chillers WC 7 & 9 ~ 50-80% (WC1 underwent a refrigerant retrofit, which accounts for its low loading)

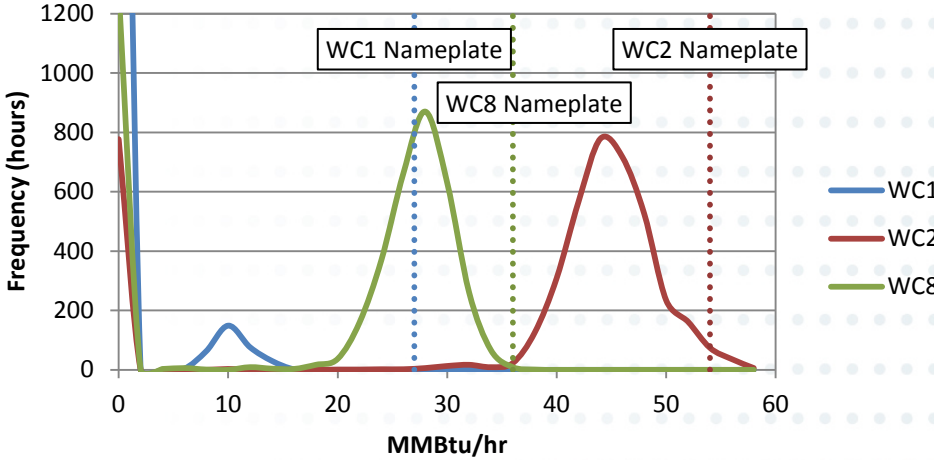
*** Electric chillers are known to have greater efficiencies than condensing steam-turbine driven chillers; the efficiencies observed here are within range of that expectation.**



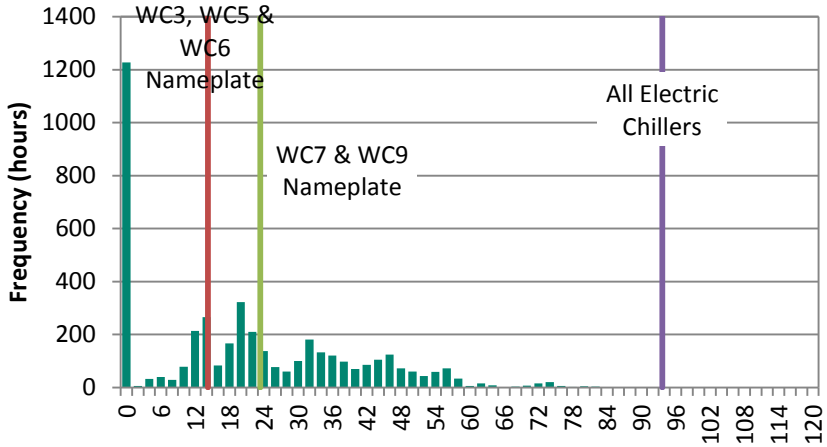
# Chiller loading (5 month period)

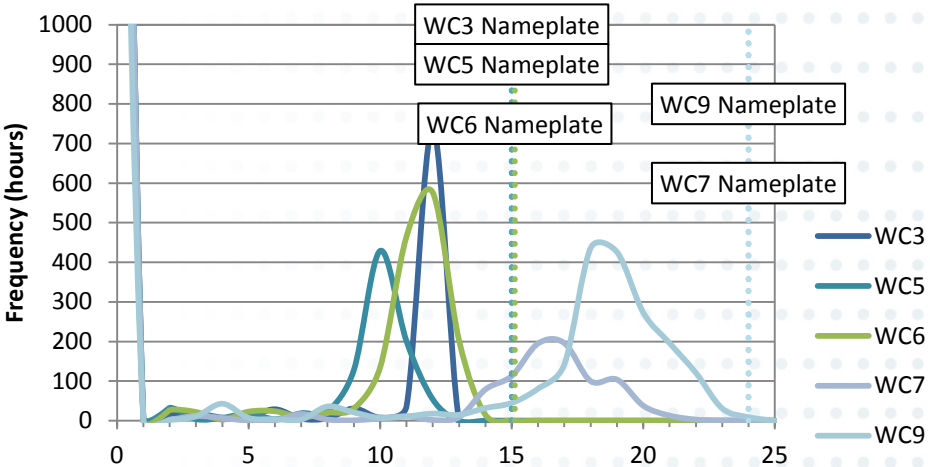
## Steam chillers



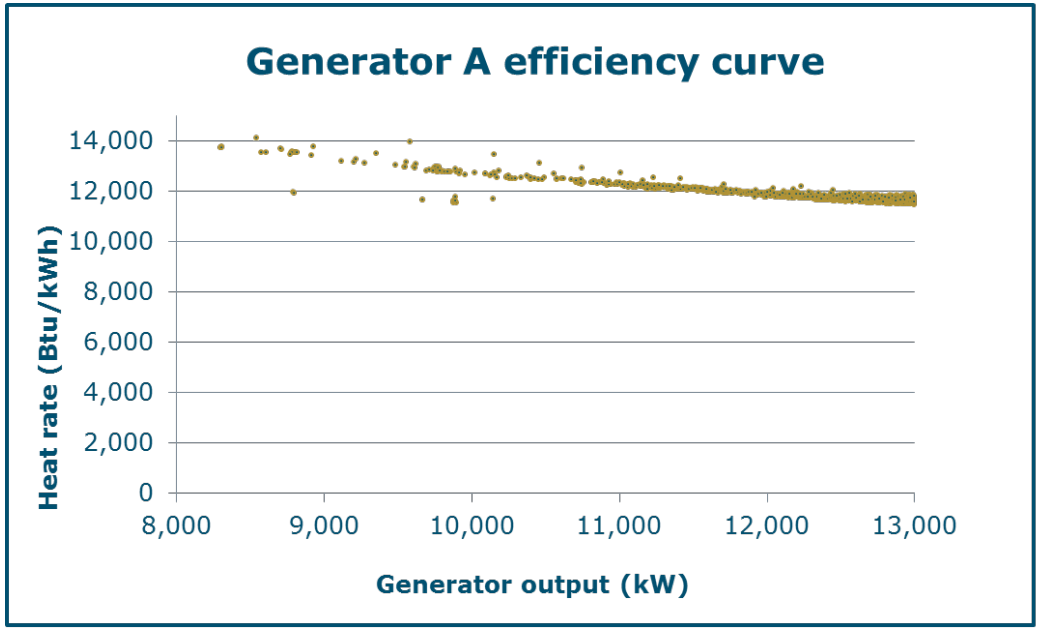

## Electric chillers




- Confirms steam chillers meet majority of cooling needs; steam chillers WC2 and WC8 operated the most;
- Of electric chillers, WC 7 and 9 operated more; chillers are loaded ~ 70-80% (WC1 has poorest loading)

# Generator & boiler efficiencies



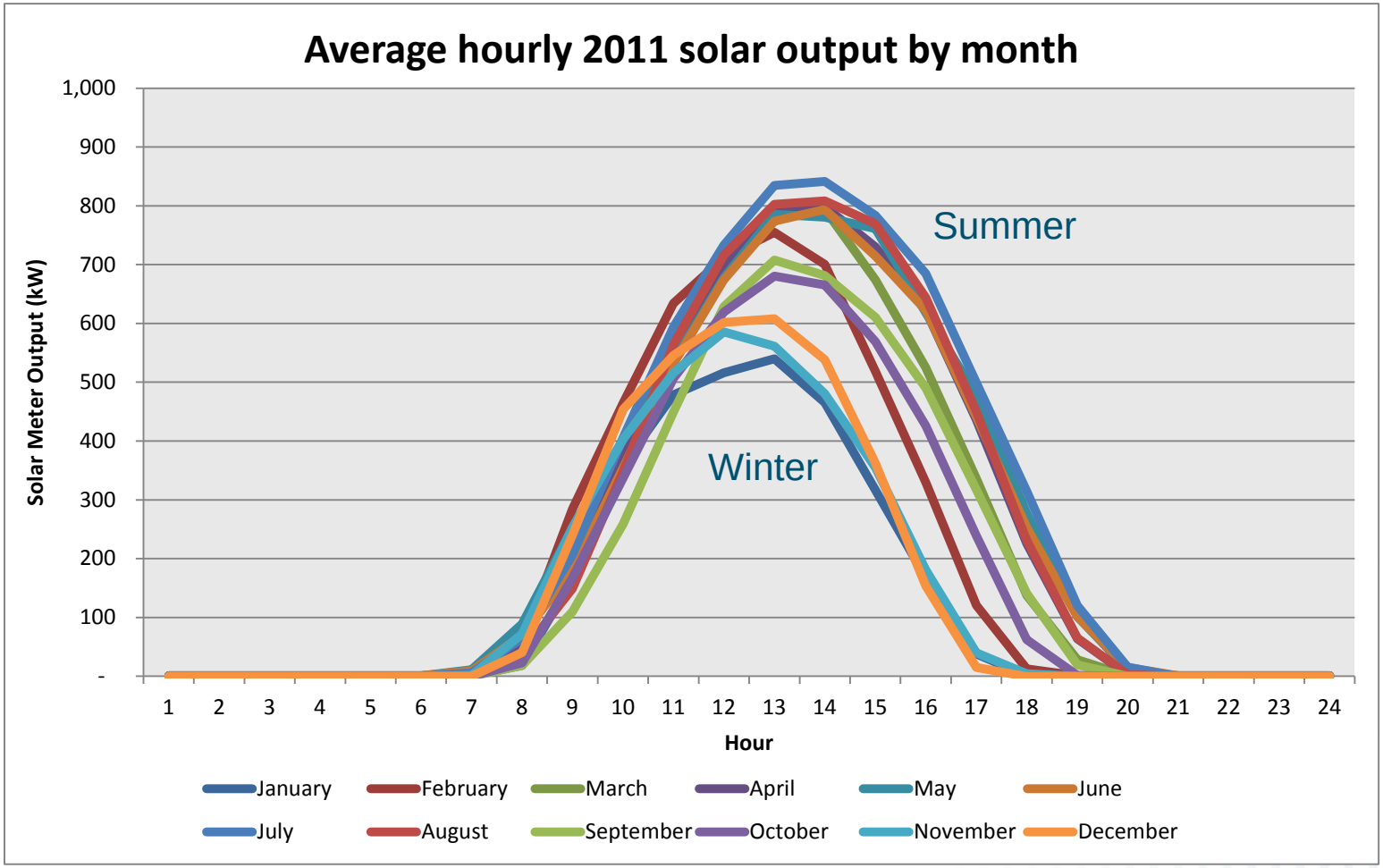

- Two natural gas generators have a median heat rate of ~ 11.5 MMBtu/MWh & have an output of ~ 98% of nameplate capacity
- Steam turbine is ~ 15% efficient
- Three boilers have median efficiency of ~ 75%

# Thermal energy storage tank

- Tank capacity ~ 32,000 ton-hr (at 13 °F delta T)
- Discharge/charge capacity ~ 3100 ton or ~ 35 MMBtu/hr (5800 gpm and 13 °F delta T)
- Thermal storage tank was analyzed: charge, discharge times, rates, losses generated

| Quantity | 10th % | Median | 90th % |
|---|---|---|---|
| Daily discharge - ton-hr | 6,401 | 16,250 | 24,504 |
| Charge start time (hr starting) | 21 | 23 | 1 |
| Charge duration (hr) | 8 | 10 | 13 |
| | | | |
| Discharge start time (hr starting) | 8 | 9 | 12 |
| Discharge duration (hr) | 10 | 14 | 16 |
| Flow rate (gpm) | 663 | 2,491 | 4,958 |
| Delta T (deg F) | 11 | 13 | 14 |
| Overall tank efficiency over measurement period | | | |
| Charge ton-hr | 6,751,512 | | |
| Discharge ton-hr | 6,454,207 | | |
| Losses | 4.4% | | |

# Snapshot: solar PV analysis




- Graph shows average
- Installed capacity of solar PV is ~ 1.2 MW
- Winter peak production ~ 0.5 MW and summer peak production ~ 0.85 MW

# Summary of UCSD solar PV output

| Solar Meter Location | ID | First Day of Output | Total Rated Power (kW DC) | Inverter Efficiency | Rated Power (kW AC) | Max. Solar Meter Output (kW) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | 2009 | 2010 | 2011 |
| Birch Aquarium | BIRC_1608 | **9/8/2009** | 49.2 | 95% | 46.7 | 44.6 | 47.0 | 45.1 |
| Campus Services Complex - Buildings A to E & Trade Shops | CSC_1604 | **9/17/2009** | 258.4 | 97% | 249.7 | 249.7 | 258.9 | 261.8 |
| Campus Services Complex - Fleet Services Building | FLSV_1361 | **Pre-2009** | 28.7 | 96% | 27.5 | 24.4 | 24.4 | 24.4 |
| East Campus Central Utilities Plant | ECUP_1287 | **Pre-2009** | 28.7 | 96% | 27.4 | 24.5 | 24.4 | 24.5 |
| Engineering Building Unit 2 | EBU_1362 and EBU_1363 | **Pre-2009** | 80.4 | 95% | 76.5 | 66.6 | 66.6 | 66.5 |
| Gilman Parking Structure | GILM_1364 | **Pre-2009** | 195.0 | 99% | 192.9 | 138.1 | 137.8 | 135.3 |
| Hopkins Parking Structure* | HOPK_1365 | **Pre-2009** | 338.0 | 99% | 334.3 | 370.8 | 373.8 | 370.8 |
| Price Centers, Buildings 1 to 4* | PRIC_1409 | **Pre-2009** | 206.6 | 96% | 199.3 | 199.4 | 200.8 | 219.4 |
| **Total** | | | 1,185.0 | | 1,154.3 | 855.6 | 1,075.6 | 1,071.9 |

**Solar Meter Output from July 1, 2010 to June 30, 2011 was only provided as a daily average (kWh).*

| Solar Meter Location | Annual Energy (kWh) | | | Operating Hours | | | Capacity Factor (%) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2009 | 2010 | 2011 | 2009 | 2010 | 2011 | 2009 | 2010 | 2011 |
| Birch Aquarium | 16,471 | 68,389 | 65,890 | 2,751 | 8,756 | 8,754 | 12.8% | 16.7% | 16.1% |
| Campus Services Complex - Buildings A to E & Trade Shops | 87,132 | 399,739 | 415,048 | 2,928 | 8,760 | 8,760 | 11.9% | 18.3% | 19.0% |
| Campus Services Complex - Fleet Services Building | 50,805 | 47,928 | 45,293 | 8,759 | 8,759 | 8,008 | 21.1% | 19.9% | 20.6% |
| East Campus Central Utilities Plant | 44,458 | 47,745 | 50,470 | 8,172 | 8,759 | 8,759 | 19.8% | 19.9% | 21.0% |
| Engineering Building Unit 2 | 127,833 | 122,500 | 116,428 | 8,760 | 8,760 | 8,760 | 19.1% | 18.3% | 17.4% |
| Gilman Parking Structure | 220,738 | 206,717 | 202,387 | 8,759 | 8,510 | 7,854 | 13.1% | 12.6% | 13.4% |
| Hopkins Parking Structure* | 536,719 | 504,082 | 524,575 | 8,759 | 8,759 | 8,753 | 18.3% | 17.2% | 17.9% |
| Price Centers, Buildings 1 to 4* | 281,352 | 292,998 | 338,367 | 8,760 | 8,760 | 8,760 | 16.1% | 16.8% | 19.4% |
| **Total** | 1,365,409 | 1,690,041 | 1,742,042 | 8,760 | 8,760 | 8,760 | 13.5% | 16.7% | 17.2% |

# Summary of historical operations

# Overall observations from historical performance

- **Majority of operating rules and efficiencies have been validated**
  - Nat gas generators operated steady state at ~ full capacity
  - Loading order of steam utilizing systems
- **Loads have significant baseload component, but there is expected variability by hour, season**
  - CHW and HTW loads all year, all hours w/ higher CHW load in summer; higher HTW load in winter
  - Electrical load factor (net of CUP electric chillers) is relatively high
- **Flexibility in resources to meet loads confirmed**
  - Fuel 'arbitrage' opportunities: excess capacity between electric/steam chillers; excess boiler capacity
  - Load shifting opportunities: chiller operation; thermal energy storage tank operation (optimizing discharge/charge)

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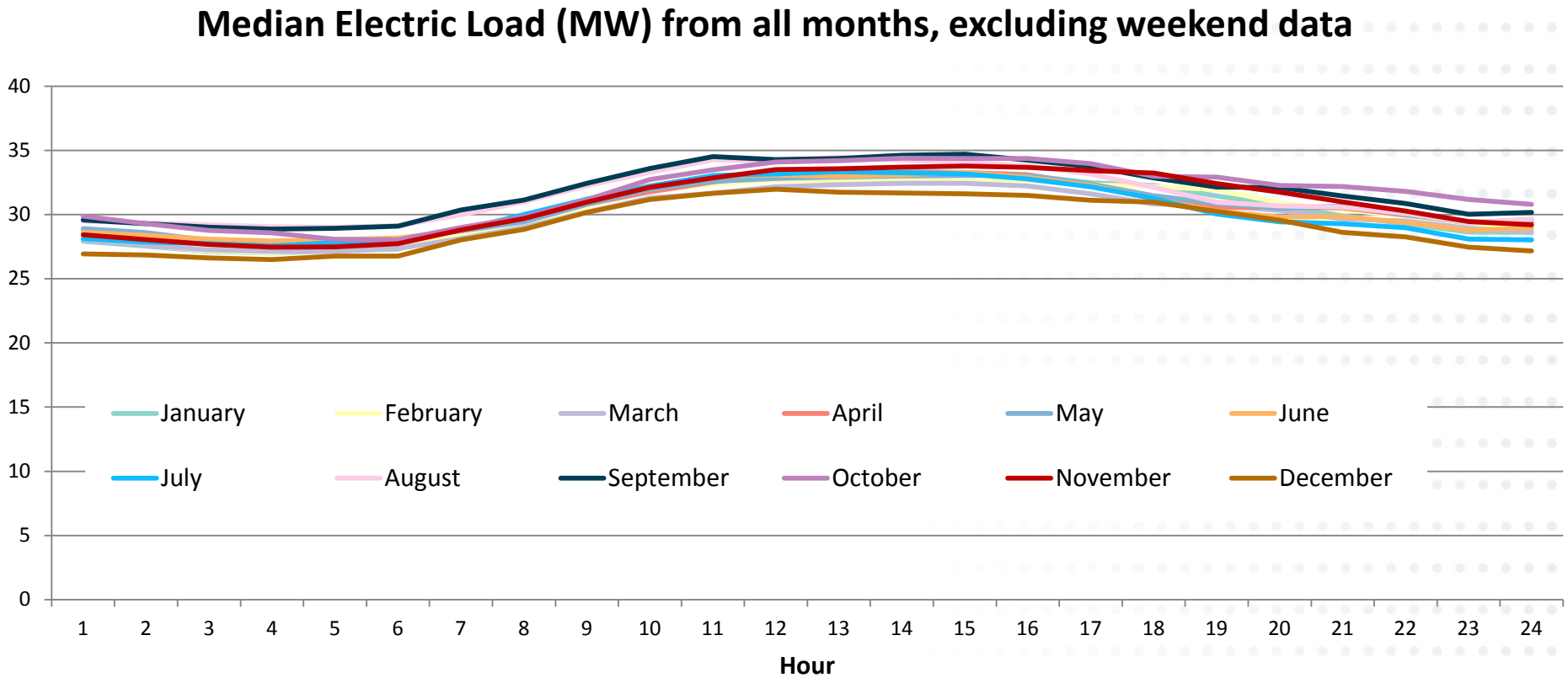
# UNDERSTANDING CAMPUS NEEDS

# Binning analysis to understand electrical and thermal loads

- **Goal: Understand the dependence of the main campus load types to influencing factors (e.g., hour, month, day type, year)**
- **Methodology:**
  - Analyzed chilled water, hot water, campus total power requirements over 3 years
  - Conducted a ‘binning’ analysis to understand what variables significantly influence the load
  - Binned data according to the hour, month, day type, year and generated time-series hourly plots
  - Compared the confidence intervals to identify which variables are key influencing factors

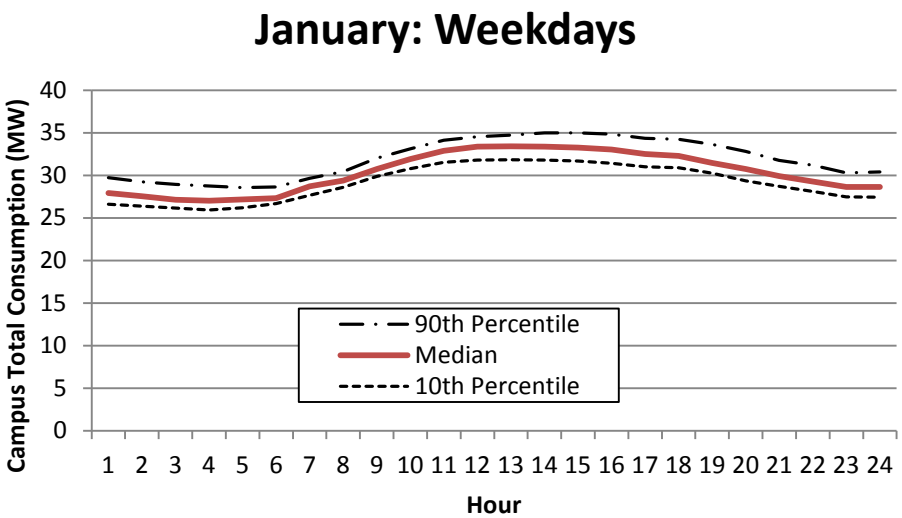
# Monthly and yearly analysis

# Electrical load by month

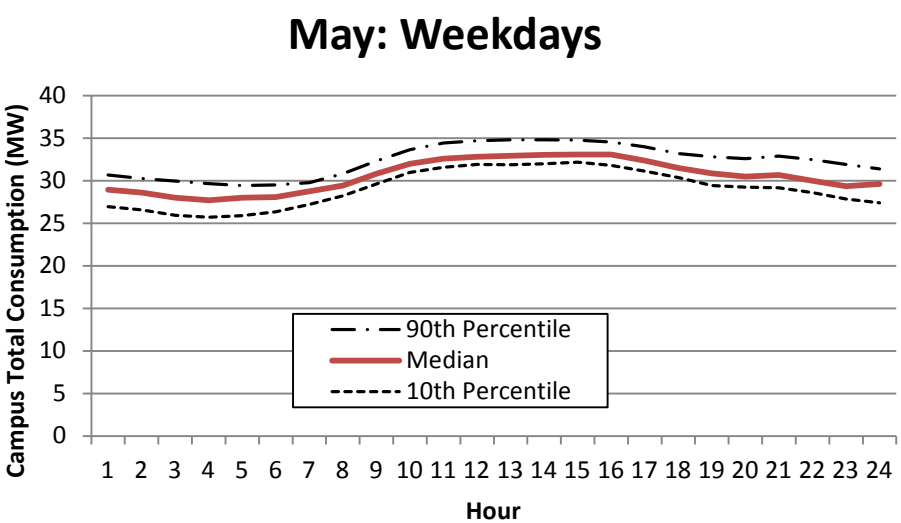


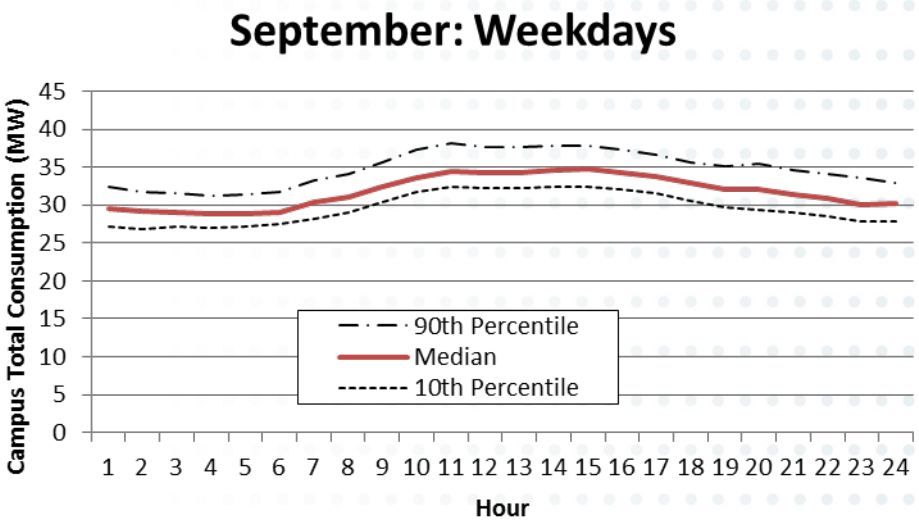

- Total campus electrical load is not very 'peaky' (i.e., high load factor throughout the year)
- Monthly variation is minimal (~ 5 MW or 10-15%)

# Snapshot: variation of electrical loads across months

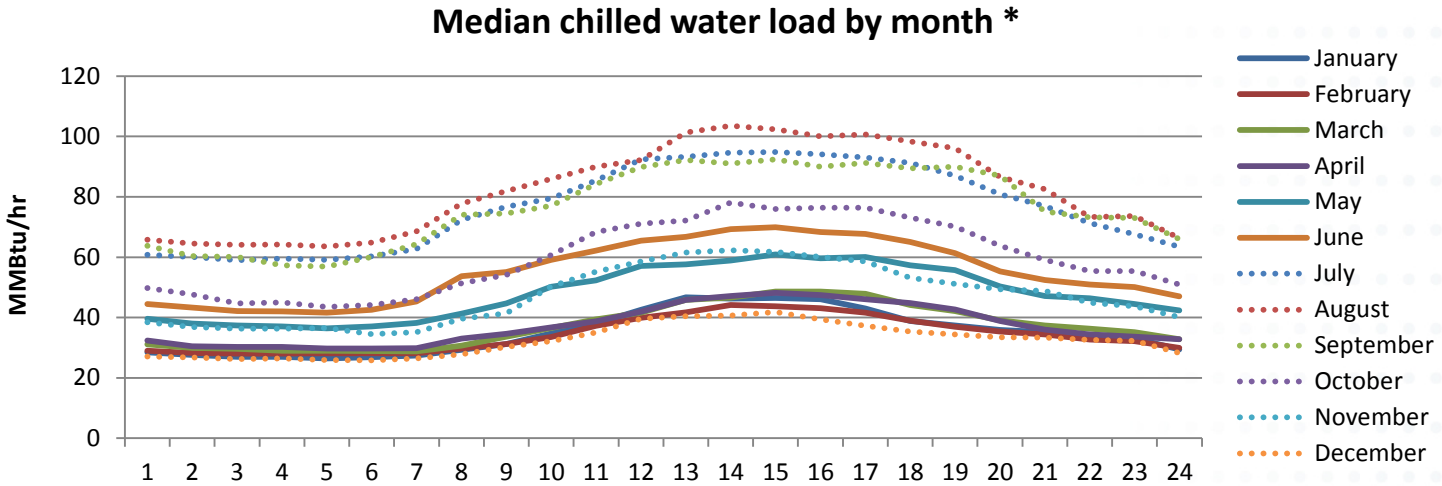


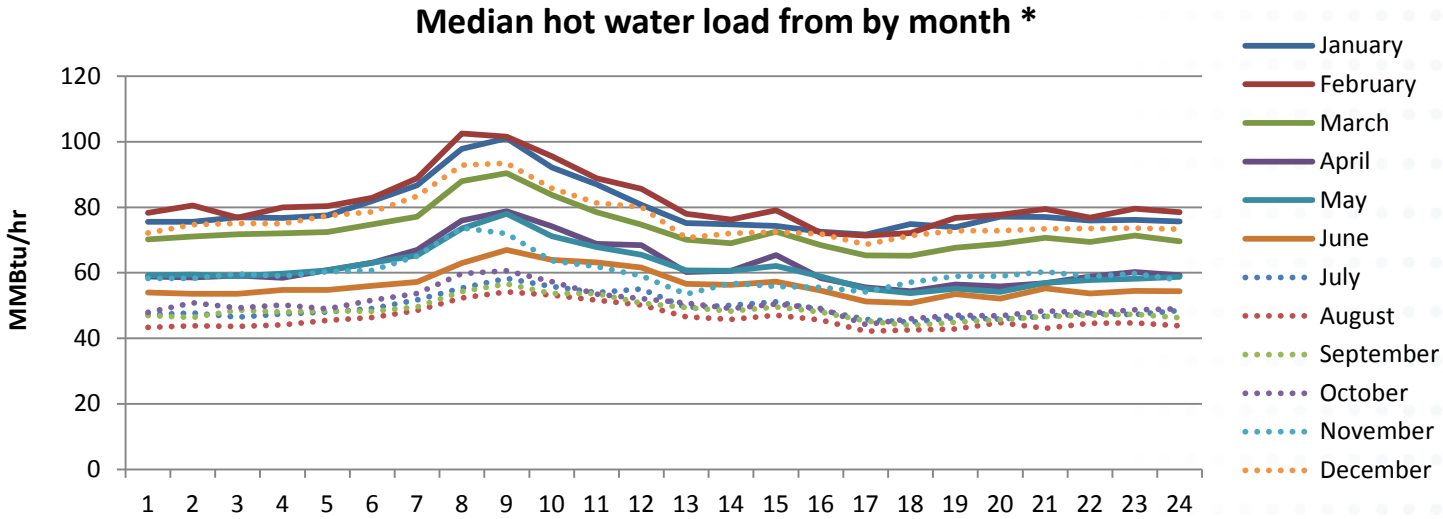

- Variability of the electrical load within an hour is similar across months (shown by the 80% confidence interval)



# Thermal loads by hour and month




- Thermal loads show strong seasonal and hourly dependence
- Chilled water loads peak in mid afternoon; hot water in morning
- Significant baseload component, although the load factors are greater than for electrical loads
- Summer months have higher chilled water loads; winter months have higher hot water loads

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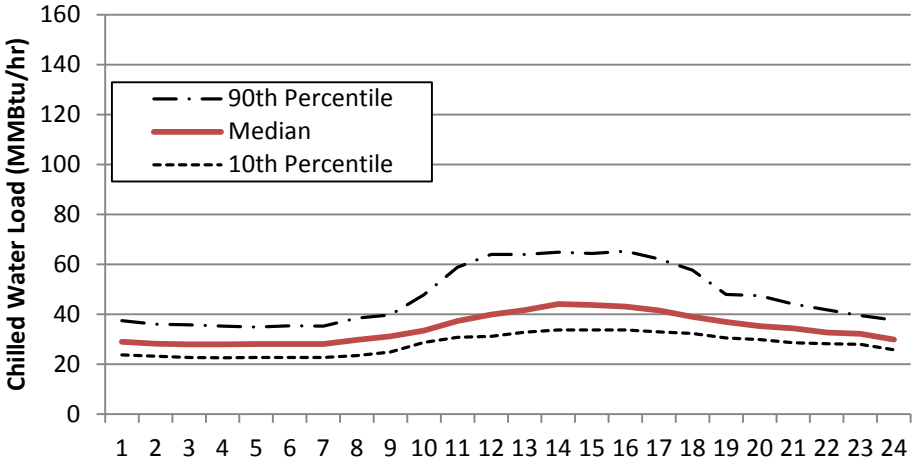
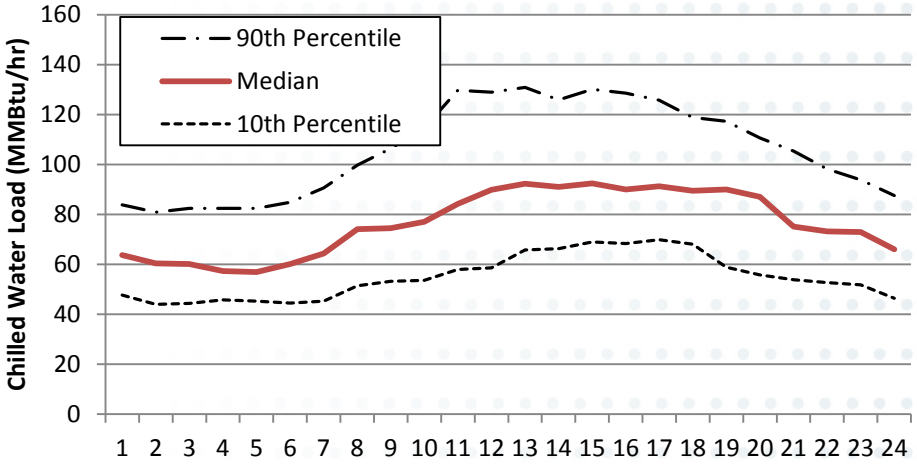
* ~ 3.5 years of data; excludes weekend points

# Snapshot: variability of thermal loads by hour

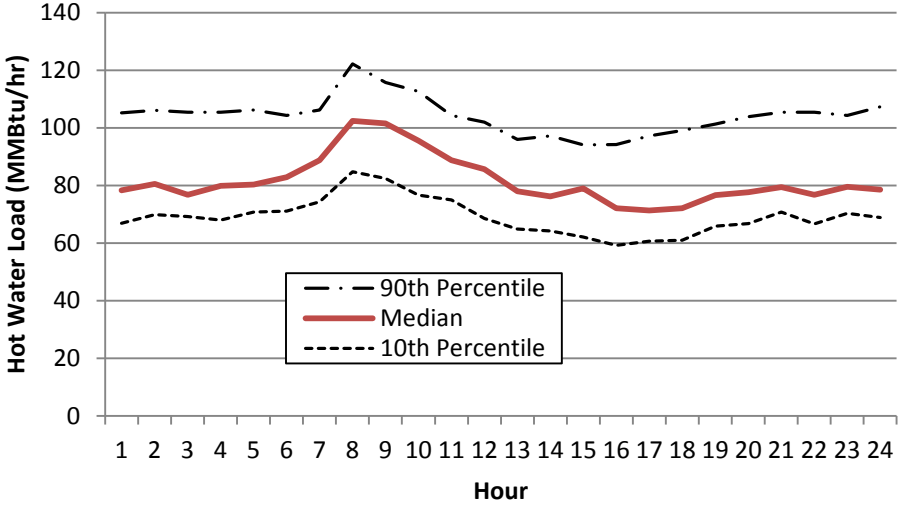
## February: weekdays (~ 3.5 years data)

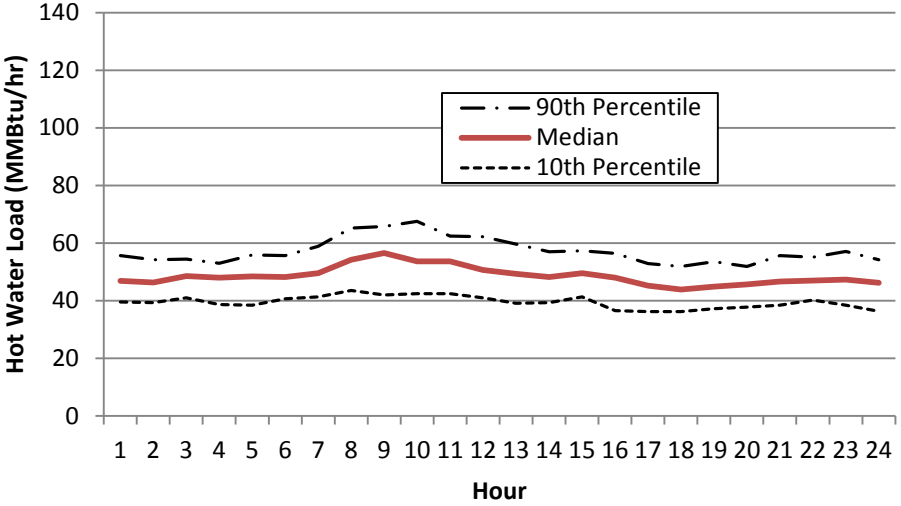



## September: weekdays (~ 3.5 years data)

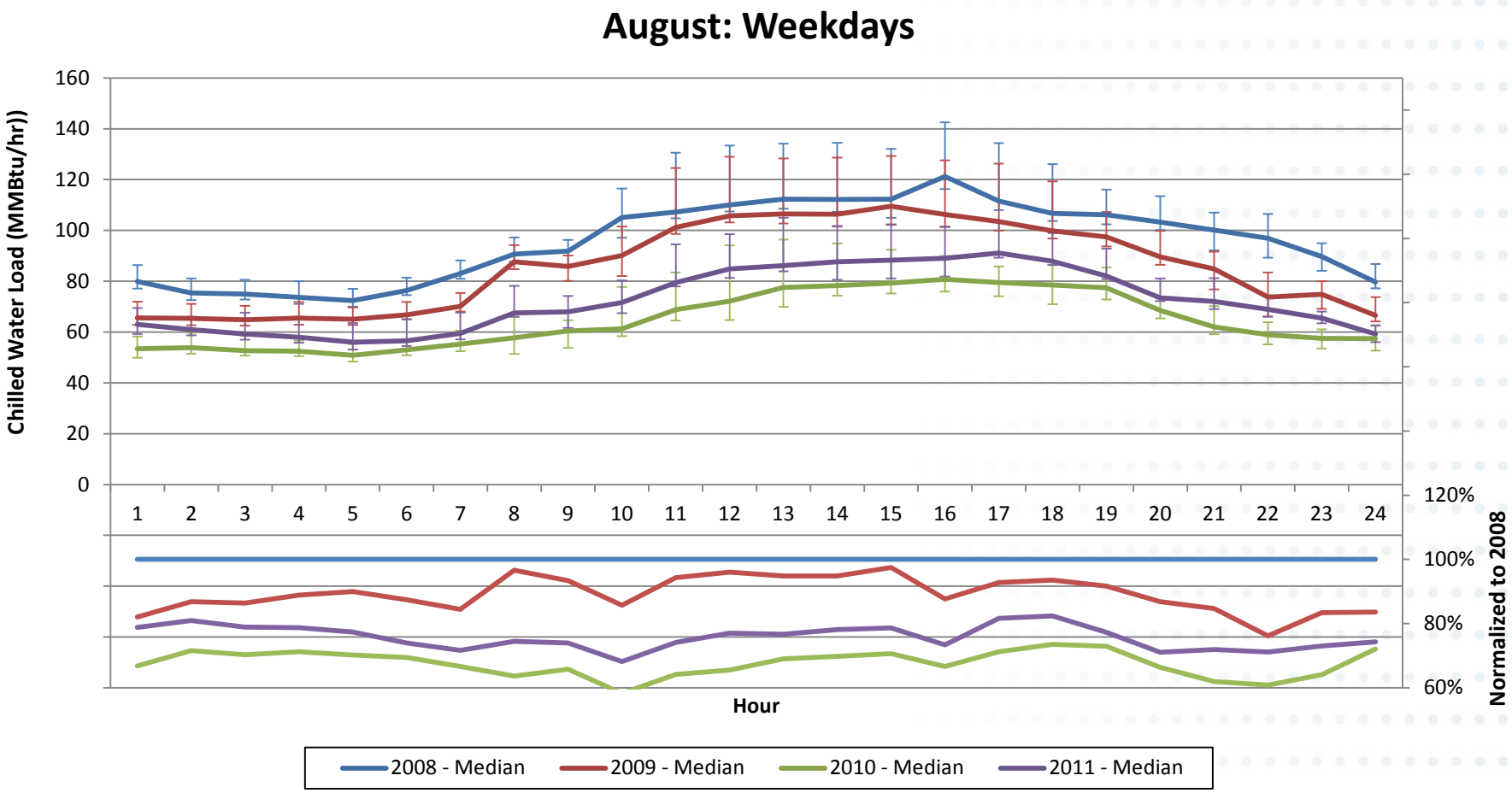



- Variability in thermal loads for a given hour is significant (80% confidence interval ranges from ~ 40% to 70%) and is larger than observed for electrical loads
- Variability in chilled water load is greater during peak periods; more uniformly spread for hot water



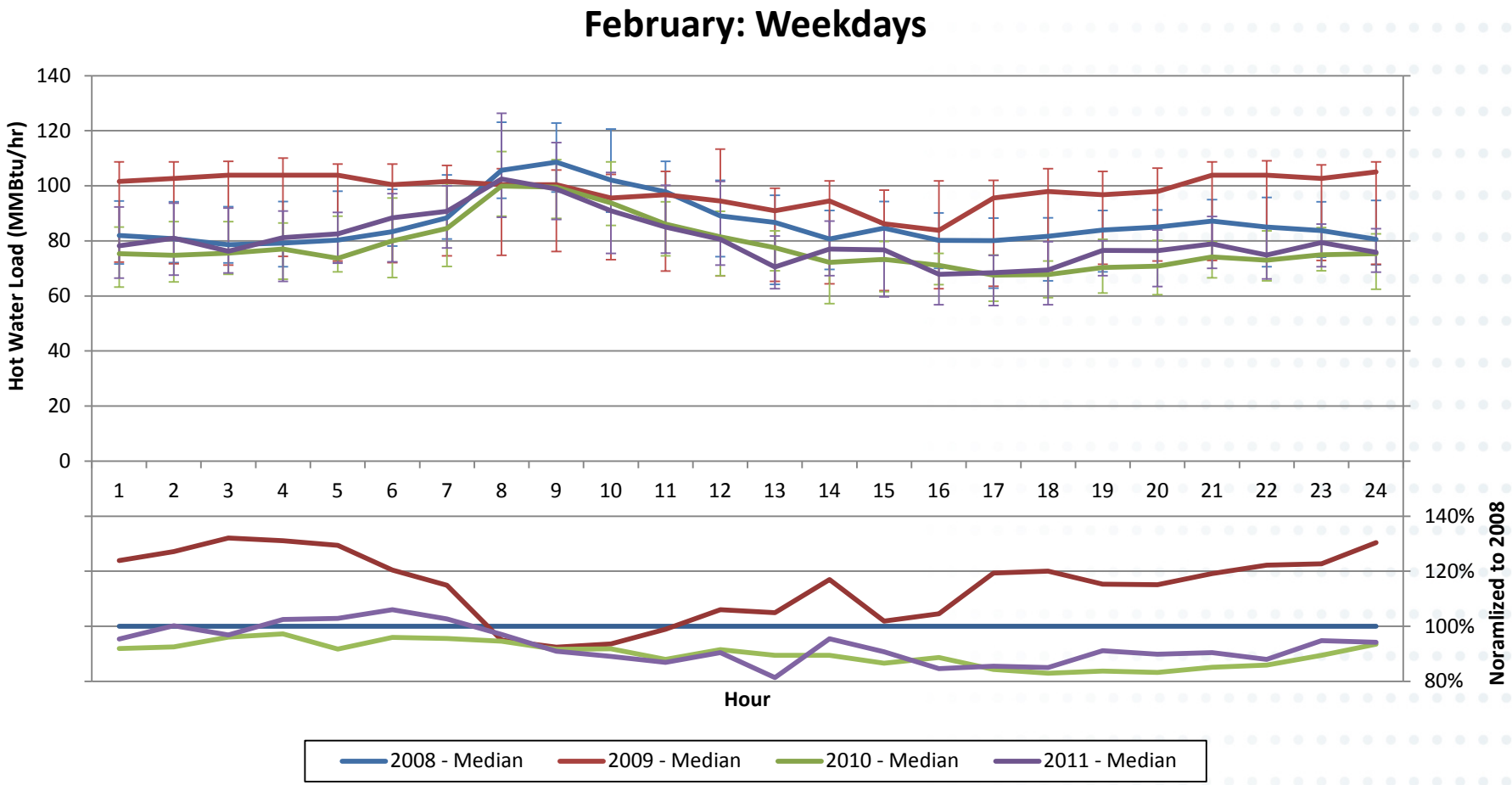



# Chilled water load: year to year differences




- Year to year variability in chilled water load for a given hour accounts for the wide confidence intervals observed in the previous slide
- Variability by year is likely due to temperature differences

# Hot water load: year to year differences




- Similar observations as with chilled water loads: year to year variability in hot water load for a given hour accounts for the wide confidence intervals observed in the previous slide
- Variability by year is likely due to temperature differences

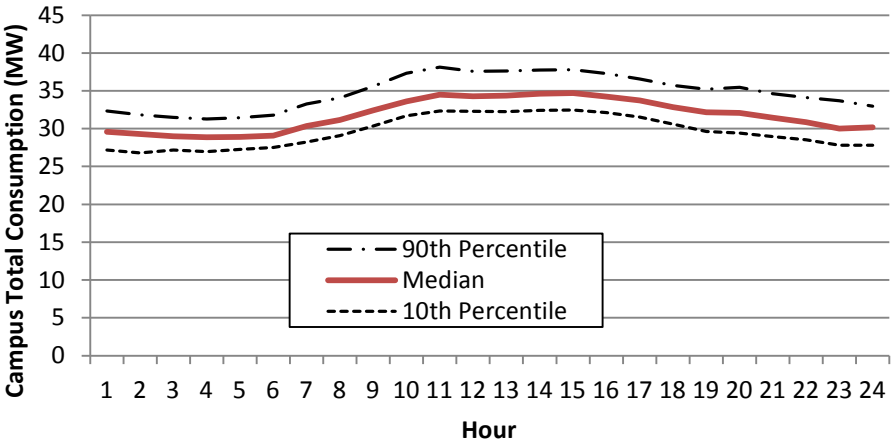
# Summary of monthly analysis

- **Power consumption exhibits the least amount of variability; hourly profiles follow typical shapes with high load factors**
- **Chilled water and hot water loads exhibit significant variability across months and hours**
  - Variability for a specific hour within the month is mainly due both to year-to-year and day-to-day varying conditions
  - Year to year effects likely driven by temperature variability (as opposed to significant differences in electrical and other internal loads)

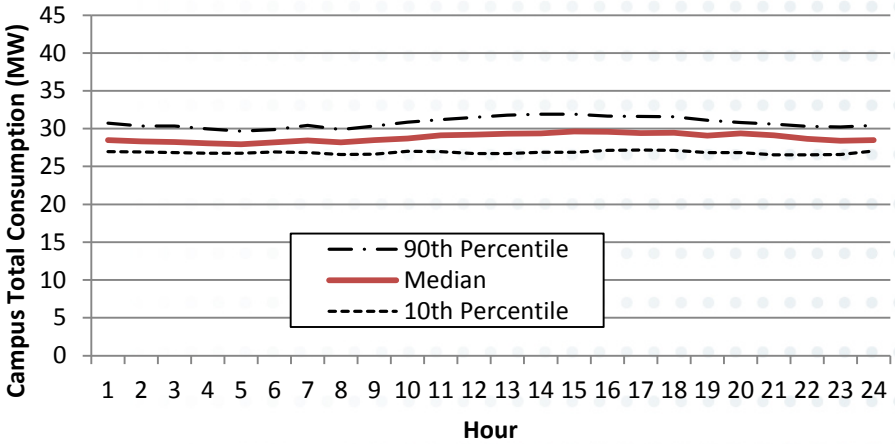
# Analysis of day type effects

# Day type influence: electrical loads

## September: Weekdays

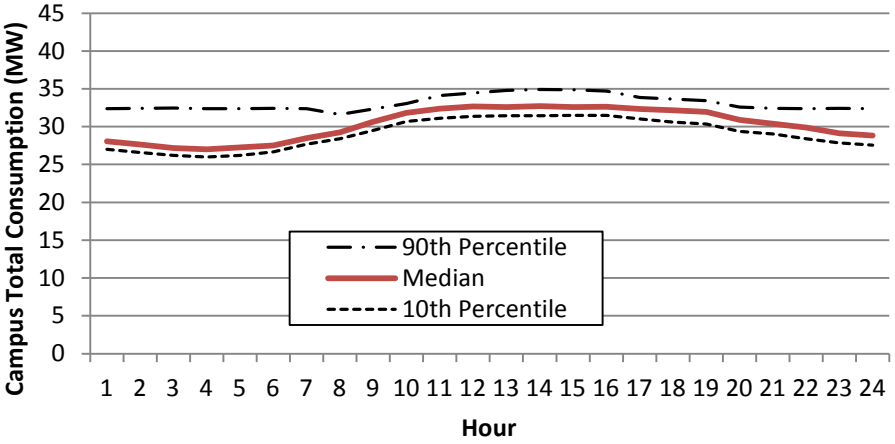



## September: Weekends

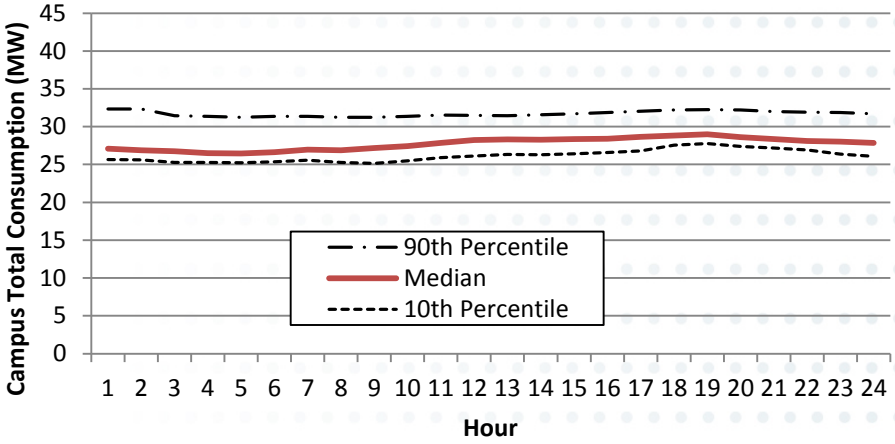



10th percentiles are lower for electrical load profiles when the weekend data are included; this is consistent with lower occupancy on weekends. The effect is greatest during the peak periods.

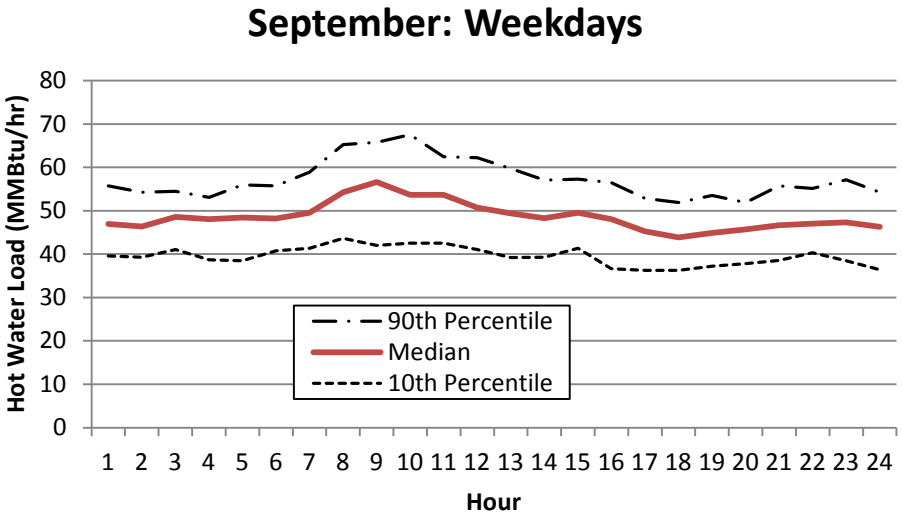
## February: Weekdays

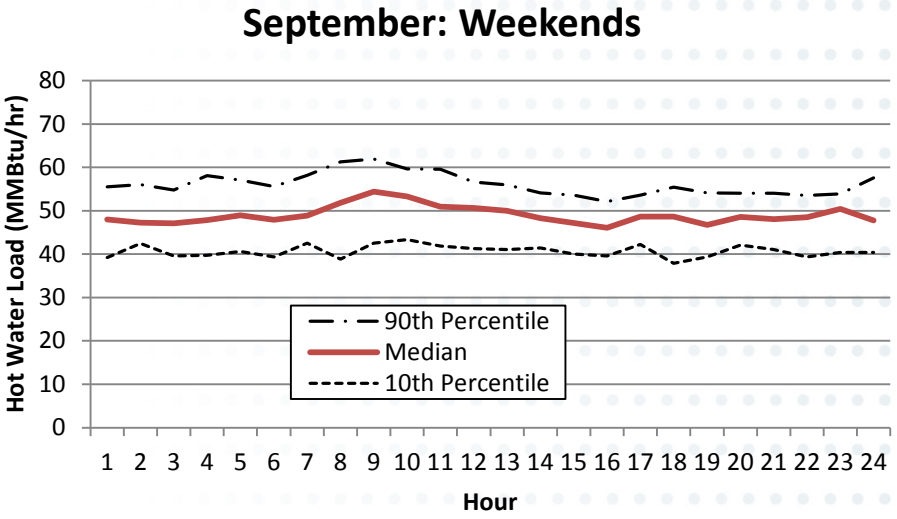



## February: Weekends

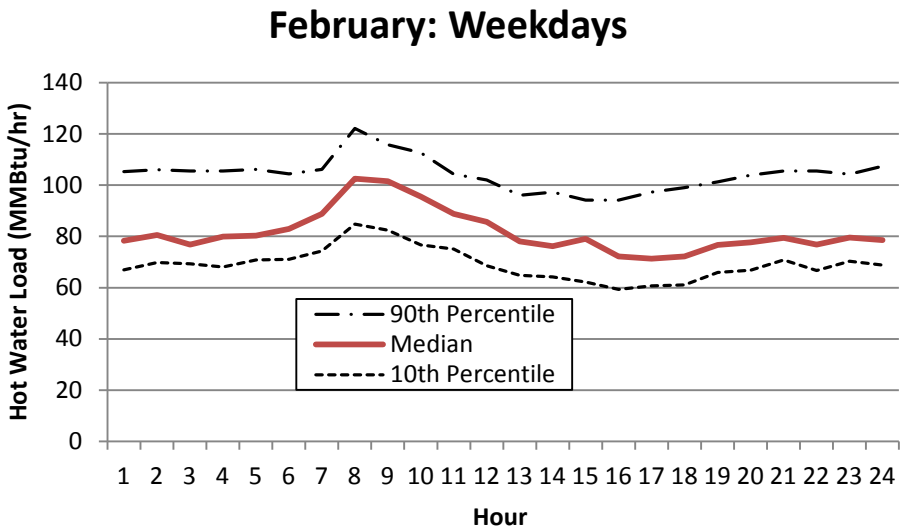


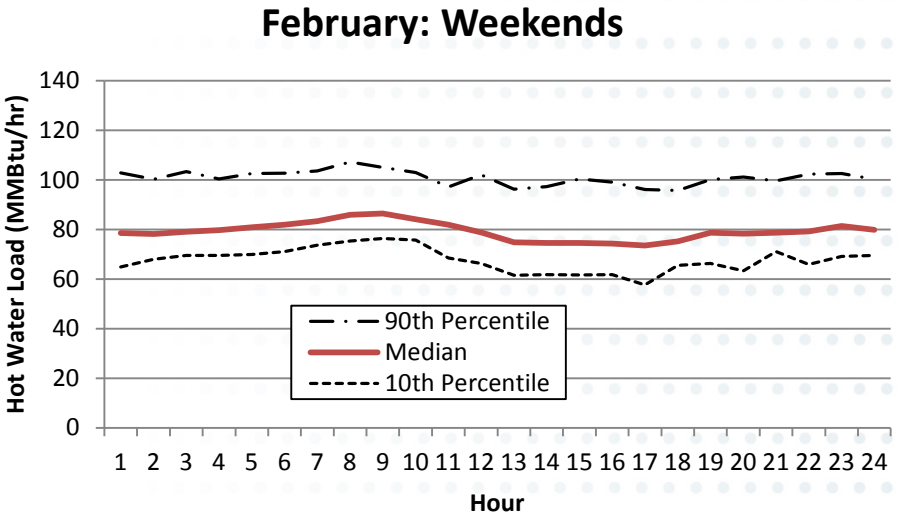
# Day type influence: hot water loads



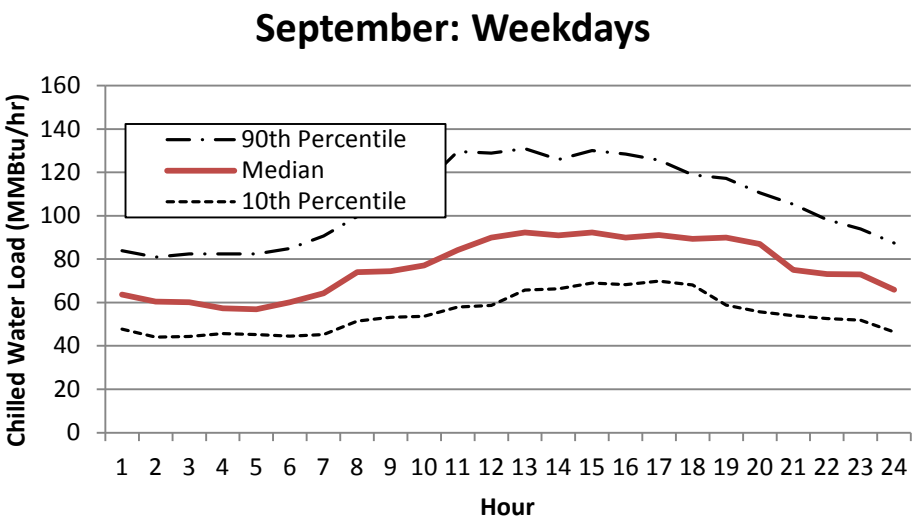



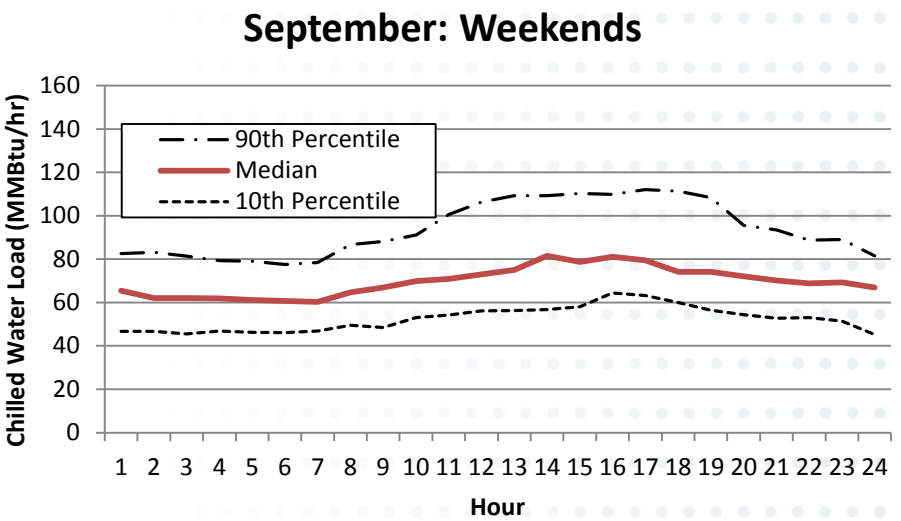

Hot water loads reveal a small weekend effect in February which occurs during morning warm-up hours. There is no perceptible weekend effect in September and in other hours.

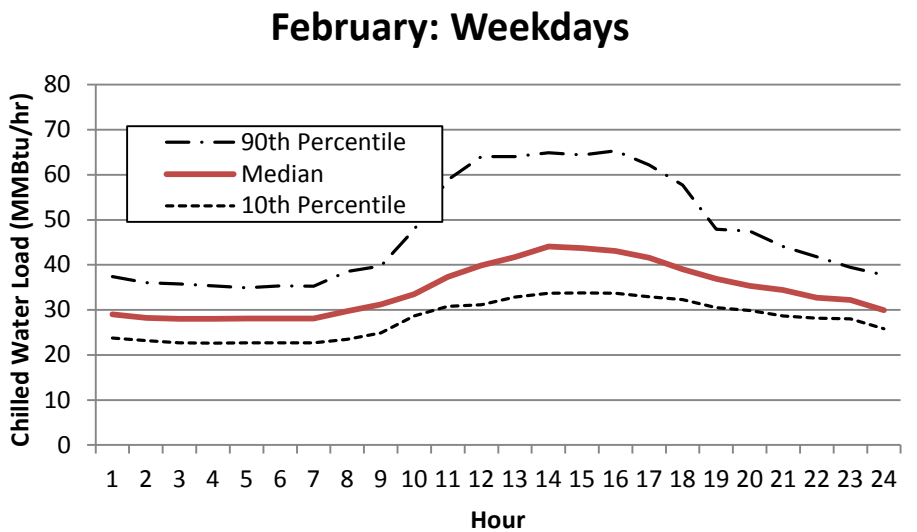


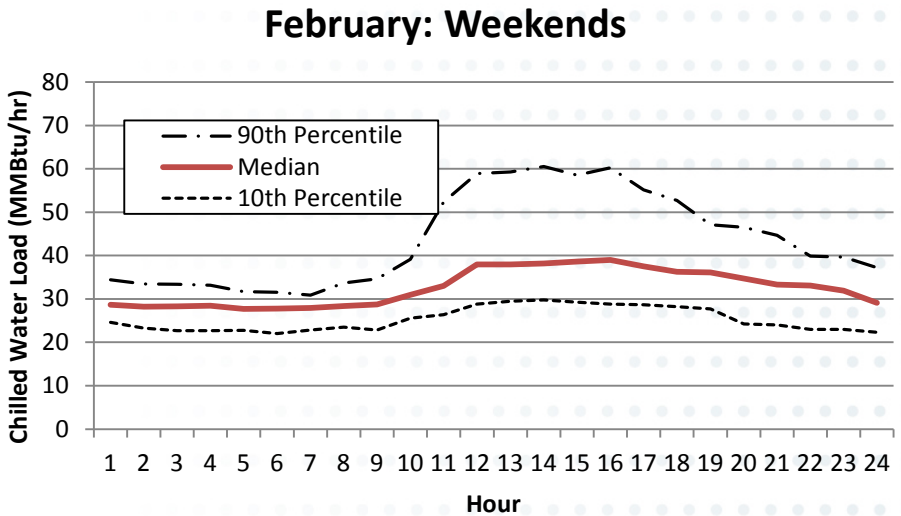



# Day type influence: chilled water loads




Chilled water loads reveal a small weekend effect during peak cooling load hours of ~ 10%; no observable weekend effect exists in other hours.

# Day type summary

- **Day type impacts all load types but at different levels**
- **All load types (electrical & thermal) are lower on weekends as exhibited by the 10th percentile**
- **Electrical loads are most sensitive to day type**
  - 10th percentile curve is ~ 10% lower during mid-day hours for plots that include weekend data)
  - Weekend effect is greatest during peak periods and less in morning/ evening
- **Chilled water and hot water loads are mildly sensitive to day type as the lower bound on the confidence intervals are only marginally lower when including weekend data**
  - For chilled water, 10th percentile curve is ~ 3% lower
  - Hot water loads are minimally sensitive to day type

# Key insights of binning analysis

- **Each load exhibits significant baseload across all hours**
  - Electrical load factors significantly greater than thermal loads
- **Characteristics of variability:**
  - Seasonal dependence exists largely for CHW and HTW
  - Differences in weekday vs. weekend are more apparent for mid-day hours and for power consumption, as compared to chilled water and hot water loads
  - Variability across years exists across all load types but these are not load growth related
  - Likely due to temperature effects and other factors
- **Applying historical loads for future forecast**
  - Statistical characteristics of loads developed
  - These characteristics could be used (along with time series data) to develop dispatch schedules and assess how sensitive these schedules are to uncertainty in future loads

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# PRELIMINARY BUSINESS ANALYSIS

# Preliminary business analysis

- **How should UCSD operate its microgrid to maximize its revenues and reduce costs?**
  - Should it run cogen to maximum capacity?
  - How should the tank be operated?
  - What should be the loading order of systems utilizing exhaust heat?

# Scenarios analyzed

- **What is the value of the UCSD assets to lowering campus costs?**
- **Spreadsheet model developed to analyze the following scenarios using real UCSD load data**
  - Scenario 1: full import
  - Scenario 2: full import + thermal storage tank
  - Scenario 3: cogen (natural gas generators, steam chillers, hot water heat exchanger, steam generator)
    - Conducted sensitivities on 1 vs. 2 generator, steam gen
  - Scenario 4: cogen + thermal storage tank
    - Conducted sensitivities on steam gen

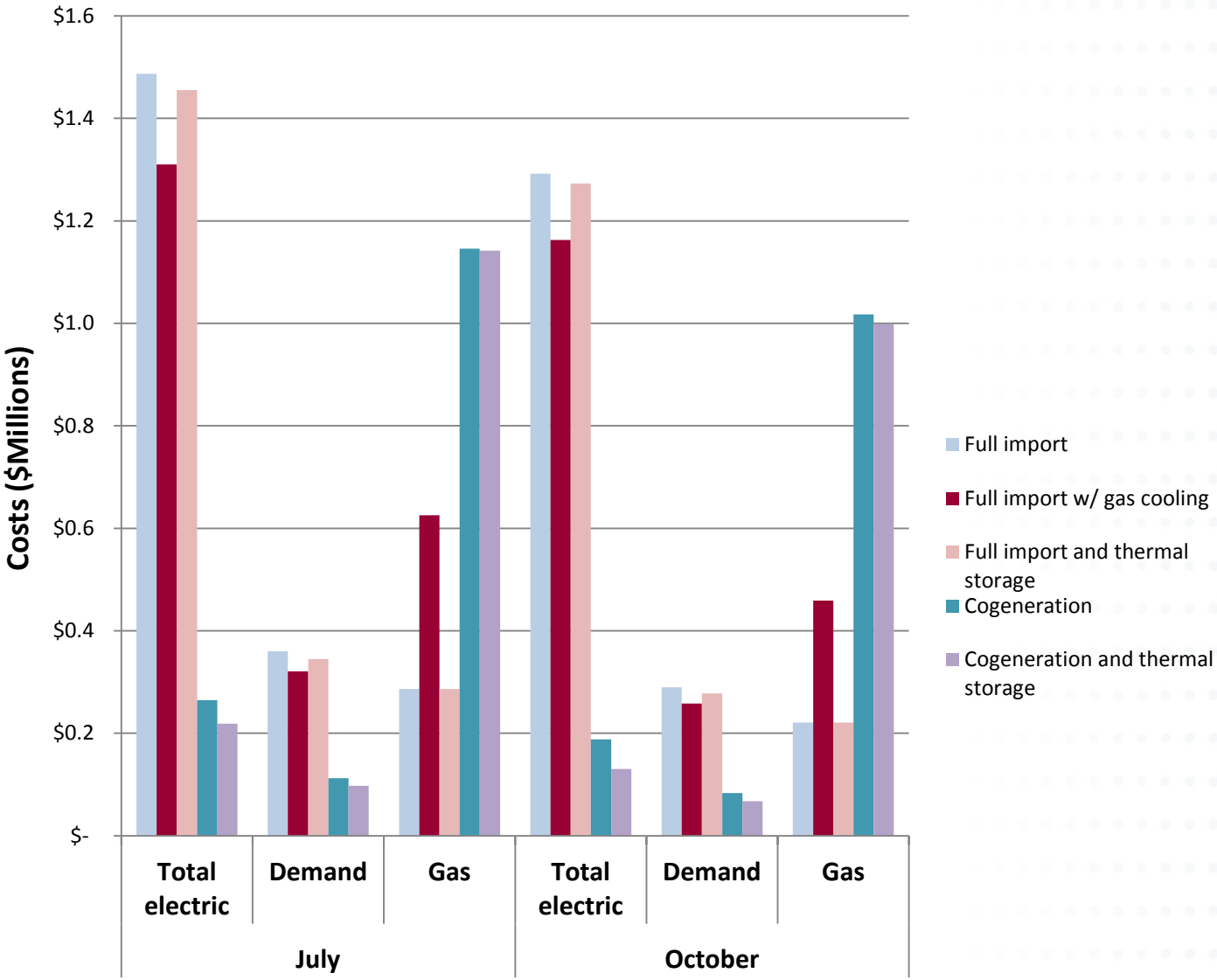
# Methodology

- **Spreadsheet model developed to analyze the cases using real UCSD load data from June-Oct 2011**
  - Consistent with campus thermal and elec needs
  - Loading order consistent with UCSD operations
  - Efficiencies & capacities from baseline effort used

Results of preliminary business analysis:

| Estimated energy costs between June 1 and October 31 2011 for the idealized scenarios | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $Millions | | Electrical | | Gas | | Total | | Savings |
| Full import | $ | 6.8 | $ | 1.3 | $ | 8.2 | | 0% |
| Full import w/ gas cooling | $ | 6.1 | $ | 2.7 | $ | 8.8 | | -8% |
| Full import and thermal storage | $ | 6.7 | $ | 1.3 | $ | 8.0 | | 2% |
| Cogeneration | $ | 1.1 | $ | 5.4 | $ | 6.48 | | 21% |
| Cogeneration & thermal storage | $ | 0.9 | $ | 5.2 | $ | 6.10 | | 25% |

# Breakdown by month and energy / demand charges




- Demand charges significant component of elec charges in both summer / winter
- More significant cost component in the cogeneration cases
- Savings from load shifting weighted towards energy savings

# Insights and opportunities for further optimization (1)

- **Preliminary scenario analysis suggests general operating strategy saves campus $**
- **Baseline and preliminary analysis suggest opportunities for enhancement, for example:**
  - Optimize tank discharge such that more of the tank capacity is utilized during peak hours; charge tank during lowest wholesale energy price periods
  - Modify generator output within allowable limits such that low off-peak SP-15 wholesale prices are taken advantage of and thermal utilization is optimized (optimal output may not be constant maximum output)
  - Stage the chillers such that they operate at a higher loading factor, such that better efficiency is achieved

# Insights and opportunities for further optimization (2)

## + Limitations of preliminary analysis

- The dispatch schedules of the resources are fixed across all days in the analysis period
- Analysis performs limited number of sensitivities that assumes an operating scenario (rather than solving for it)
- Assumes perfect foresight of campus needs
- To manage the complexity of the problem space, a realtime optimization tool is beneficial

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# FURTHER RESEARCH AND NEXT STEPS

# Using baselining results

- **Baselining activity has determined necessary inputs for the business models, such as**
  - Individual and system level efficiencies (e.g., kW/ton, Btu/kWh, thermal utilization)
  - Typical system capacity factors
  - Opportunities to move loads among central plant systems
- **Variability of campus electrical and thermal loads have been characterized & inform inputs to the optimizer**
- **By calibrating the physical model to UCSD operations and loads, the business cases are realistic**

# Further research: modeling improvements

- **Develop more detailed models for individual systems to reflect efficiency as a function of output & some inputs, for example**
  - Chiller efficiency as function of condenser supply and chilled water output temperature, and output
  - Generator heat rate curve as function of output
- **Enhance model such that a loading order for steam utilization is not assumed**
- **Enhance model such that unique hourly dispatch schedules can be developed for all systems**
- **Evaluate business cases against uncertainty in load forecasts (electrical and thermal)**

# Further research on supporting solar and renewables

## + Utilize the model to answer these questions:

- How much additional solar and renewables can UCSD's resources support?
- How do import prices and tariffs incent or not incent UCSD to utilize its resources to smooth the imported power over a month?
- What business models can create incentives for UCSD to utilize its resources to integrate solar and renewables?