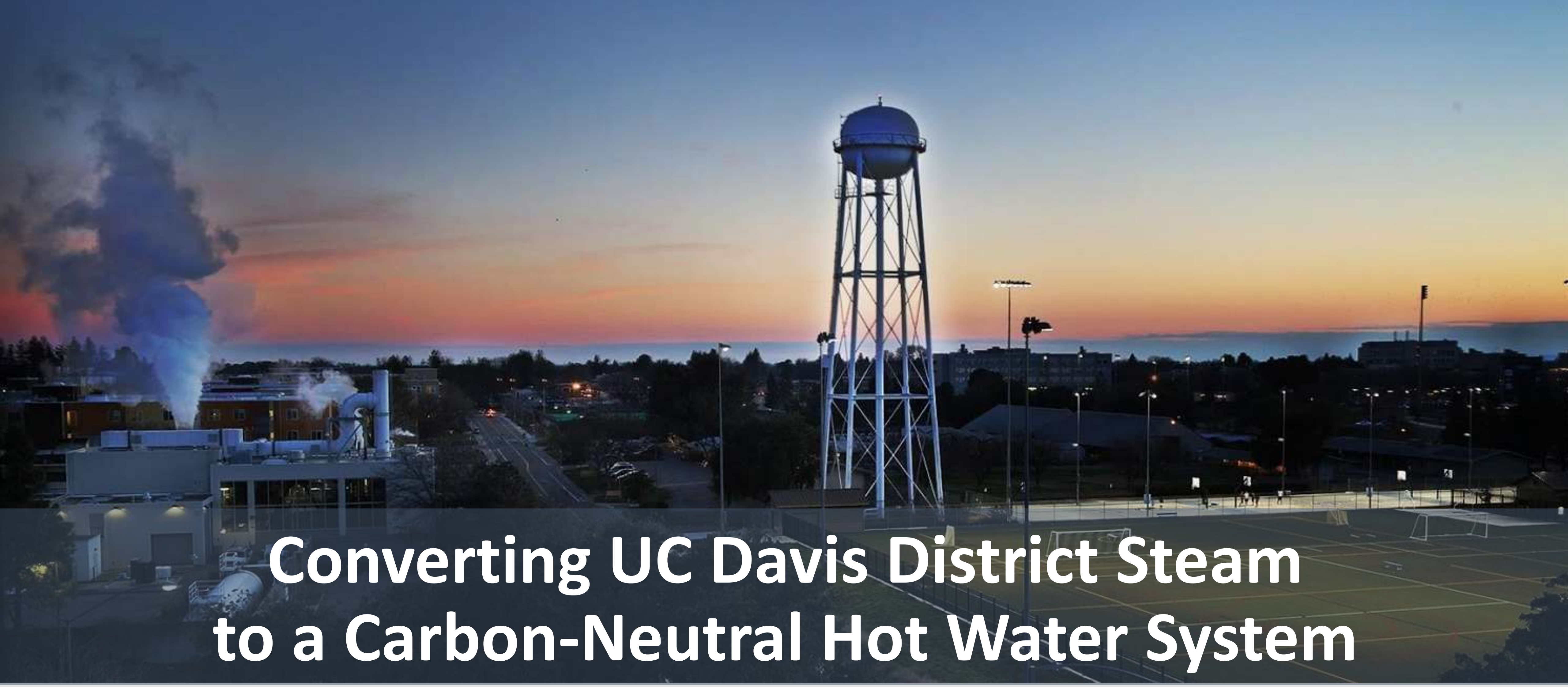


Converting UC Davis District Steam to a Carbon-Neutral Hot Water System

Colin Moyer, Michael Bove

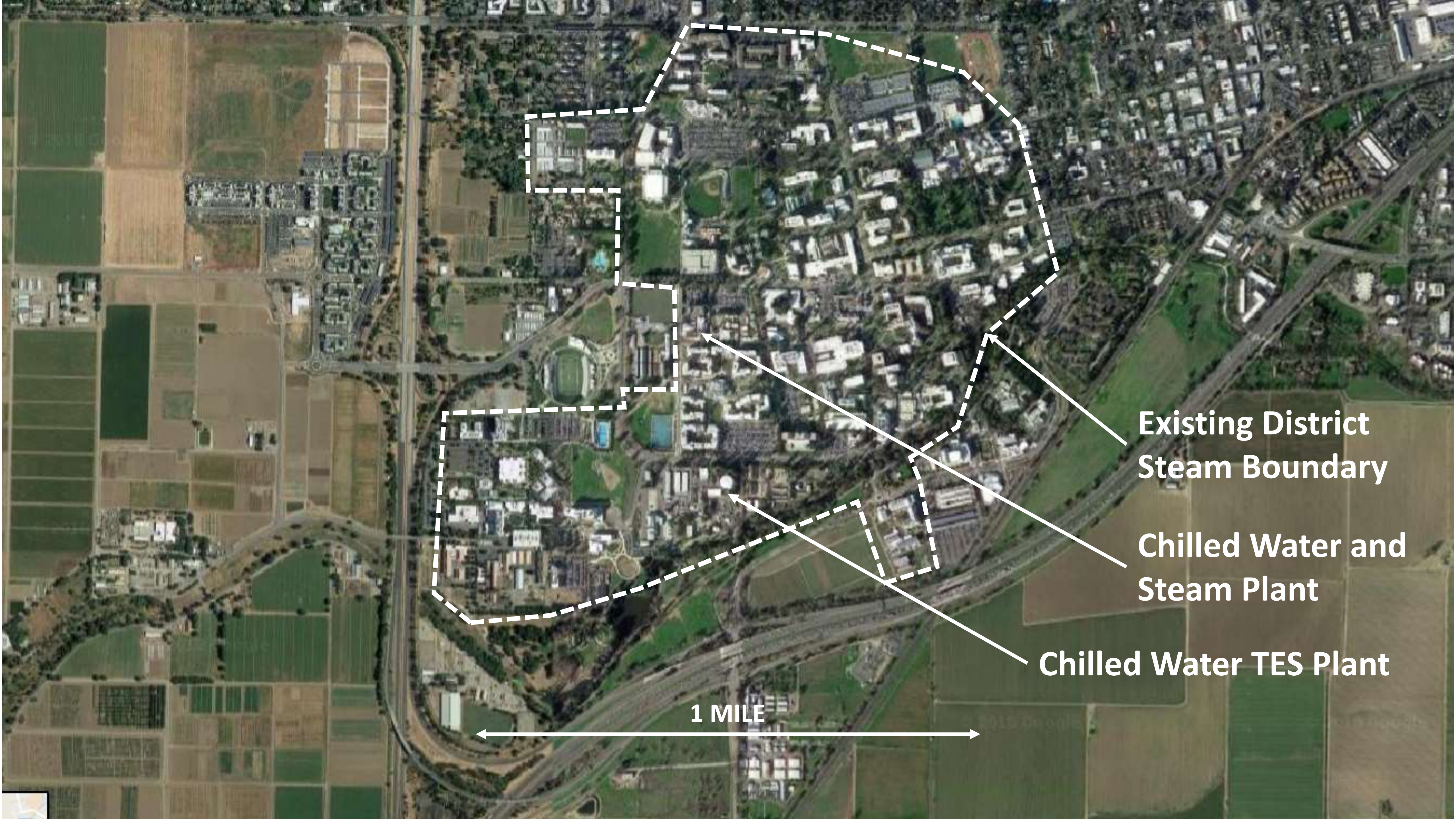
AEI Affiliated Engineers®

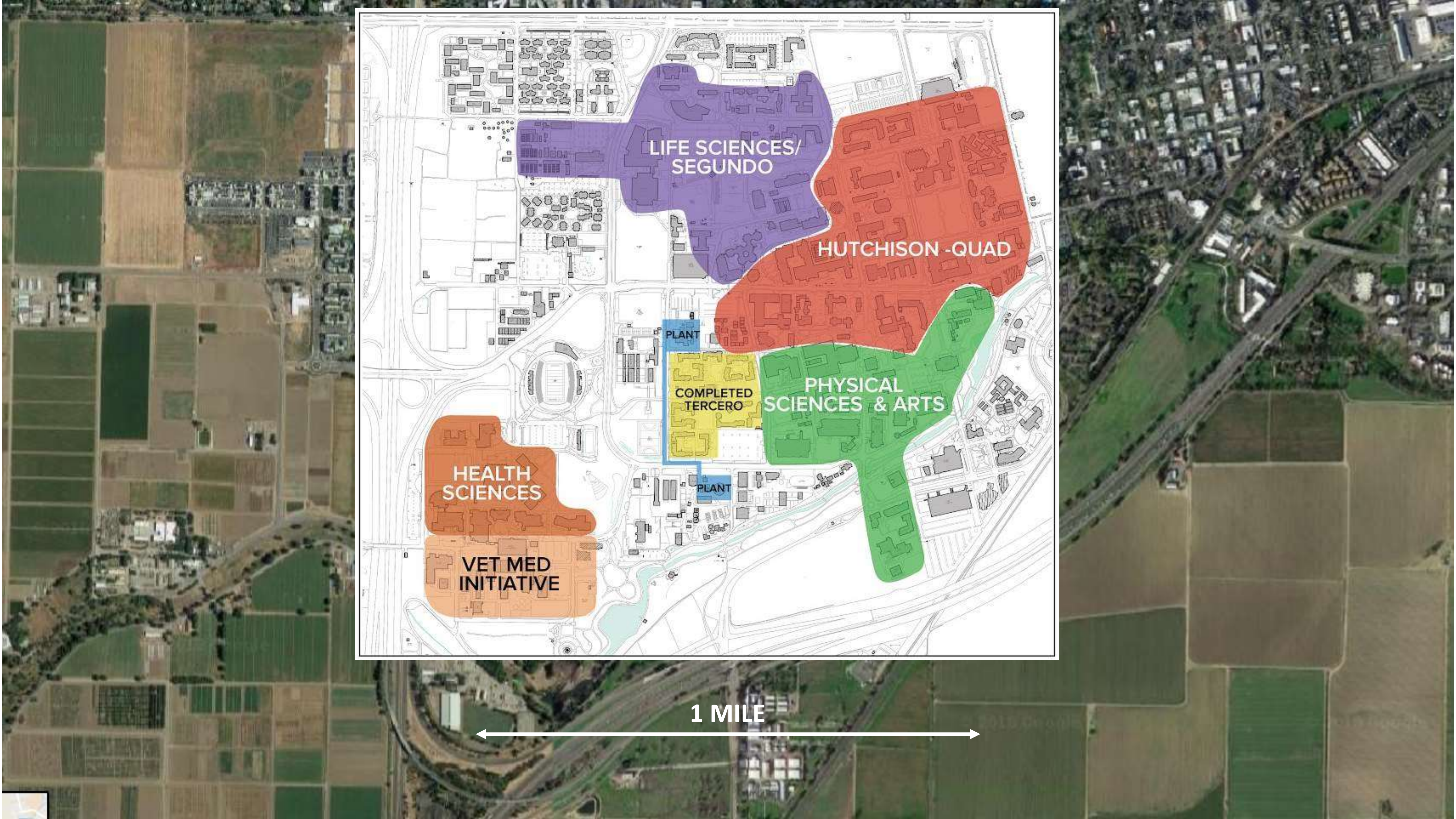
Joshua Morejohn

UC DAVIS

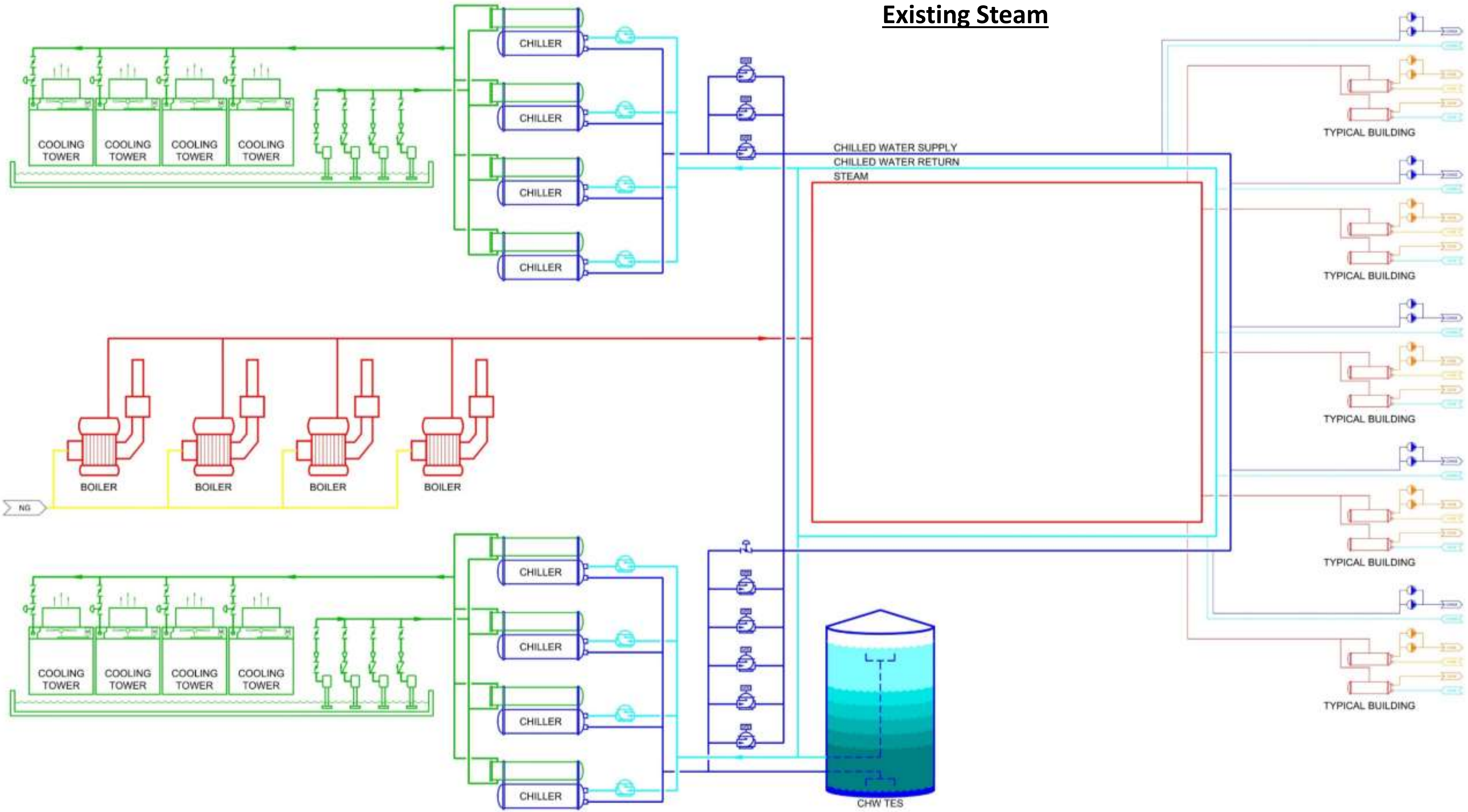
Agenda

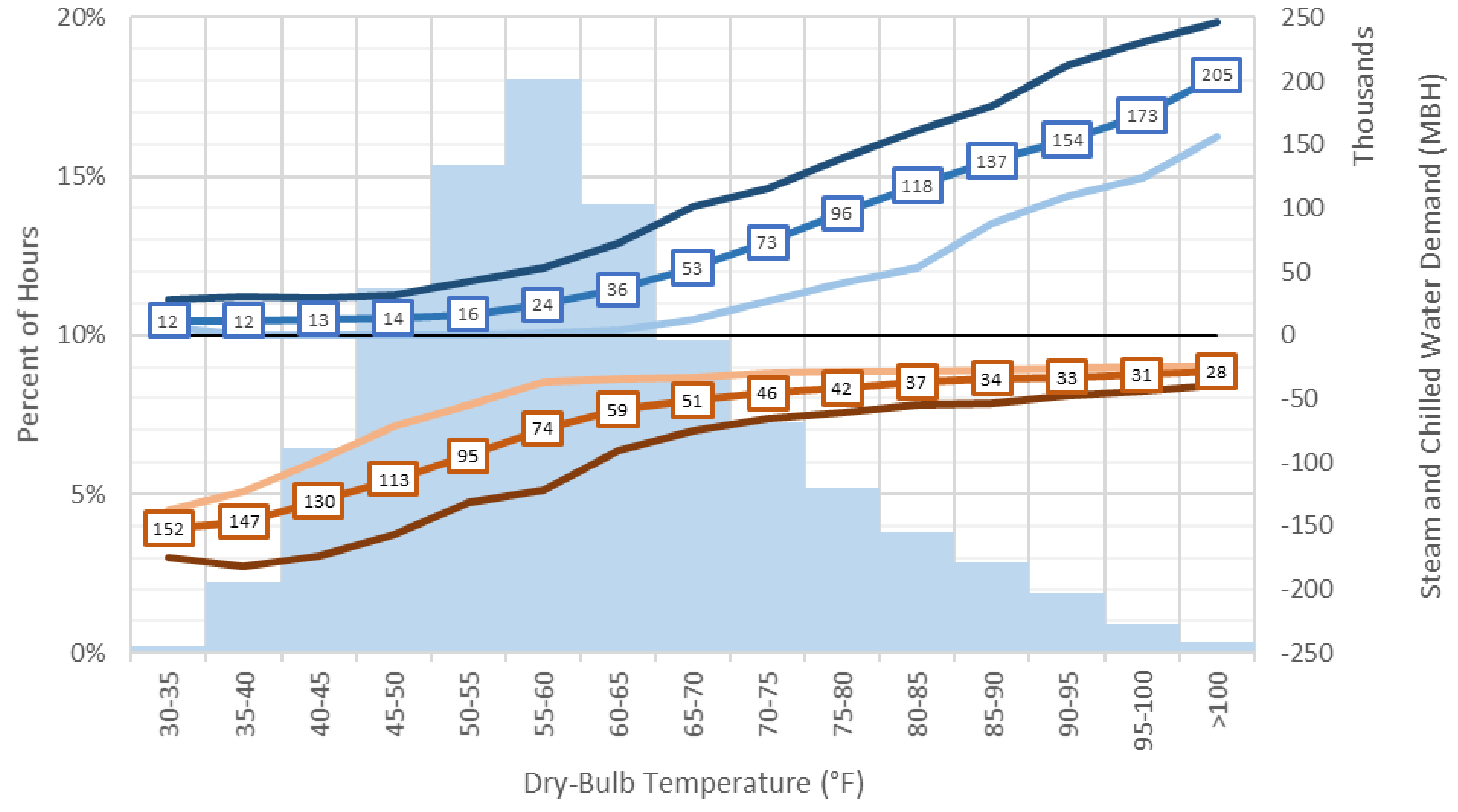
- Existing system description
- Options considered
- Qualitative analysis
- Quantitative analysis
- Results
- Recommendation


Existing District
Steam Boundary
Chilled Water and
Steam Plant
Chilled Water TES Plant
1 MILE

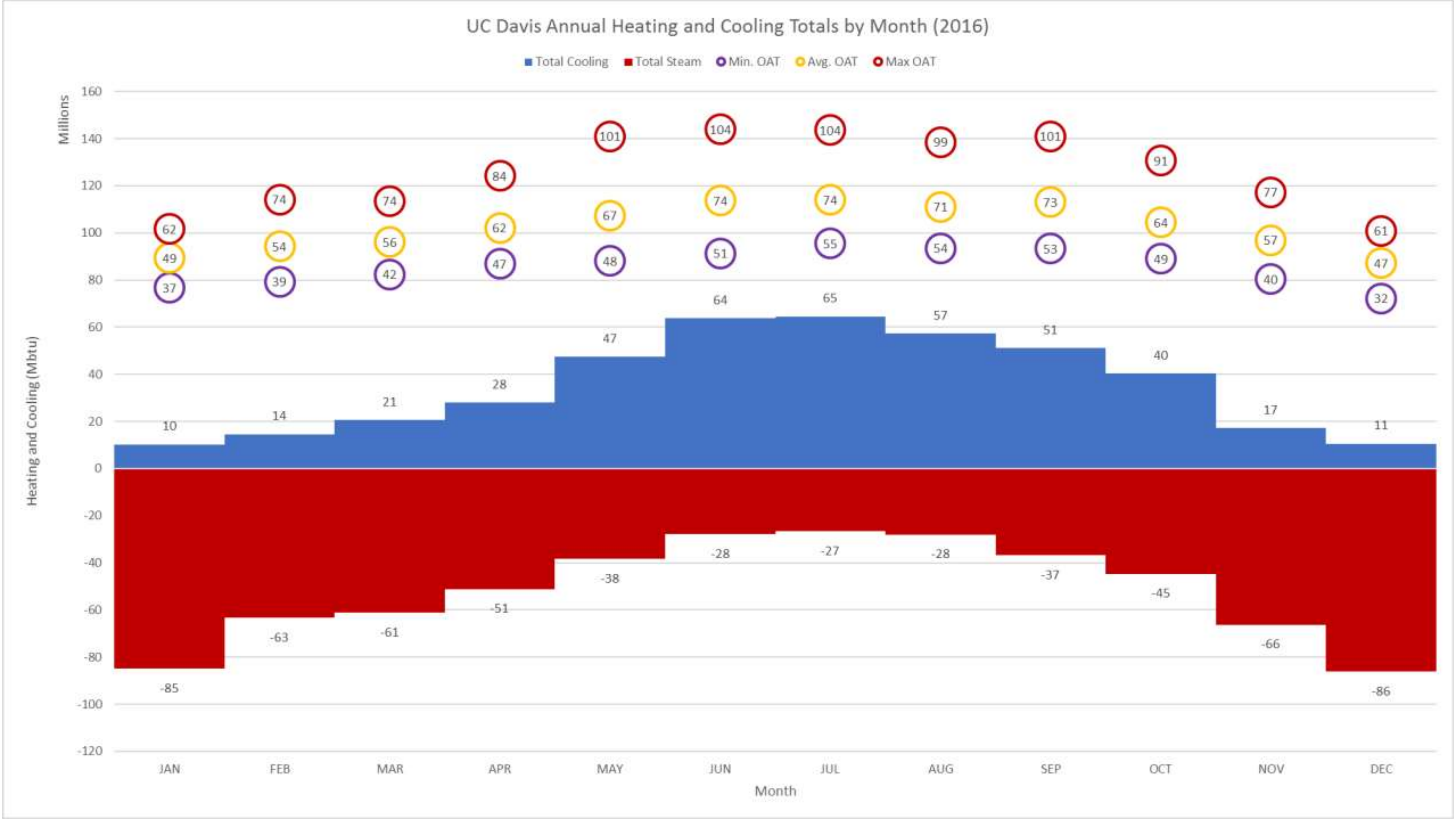

LIFE SCIENCES/ SEGUNDO
HUTCHISON -QUAD
PLANT
COMPLETED TERCERO
PHYSICAL SCIENCES & ARTS
PLANT
HEALTH SCIENCES
VET MED INITIATIVE
1 MILE

Existing Steam



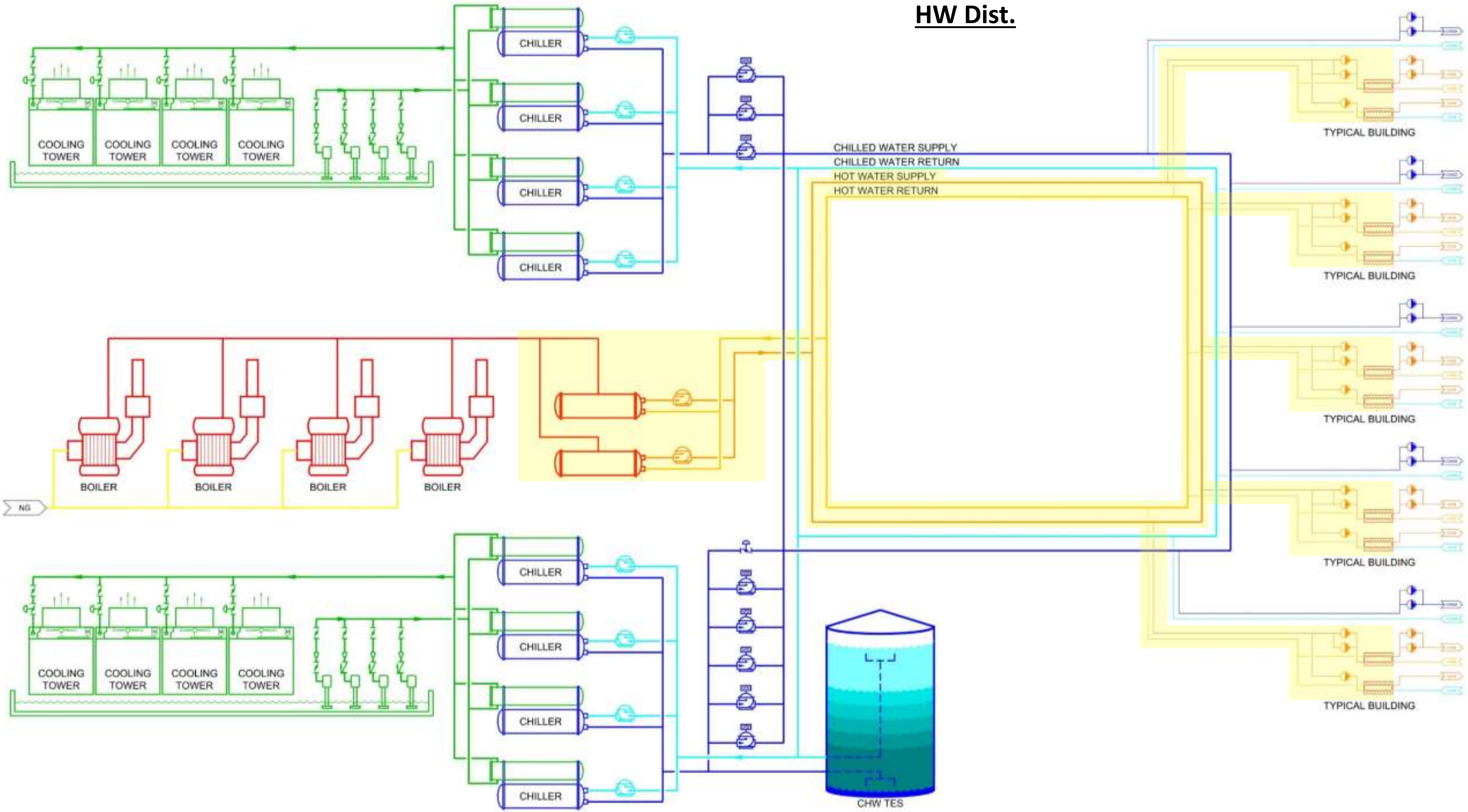


20%
15%
10%
5%
0%
Percent of Hours
250
200
150
100
50
0
-50
-100
-150
-200
-250
Thousands
Steam and Chilled Water Demand (MBH)
12
12
13
14
16
24
36
53
73
96
118
137
154
173
205
152
147
130
113
95
74
59
51
46
42
37
34
33
31
28
30-35
35-40
40-45
45-50
50-55
55-60
60-65
65-70
70-75
75-80
80-85
85-90
90-95
95-100
>100
Dry-Bulb Temperature (°F)

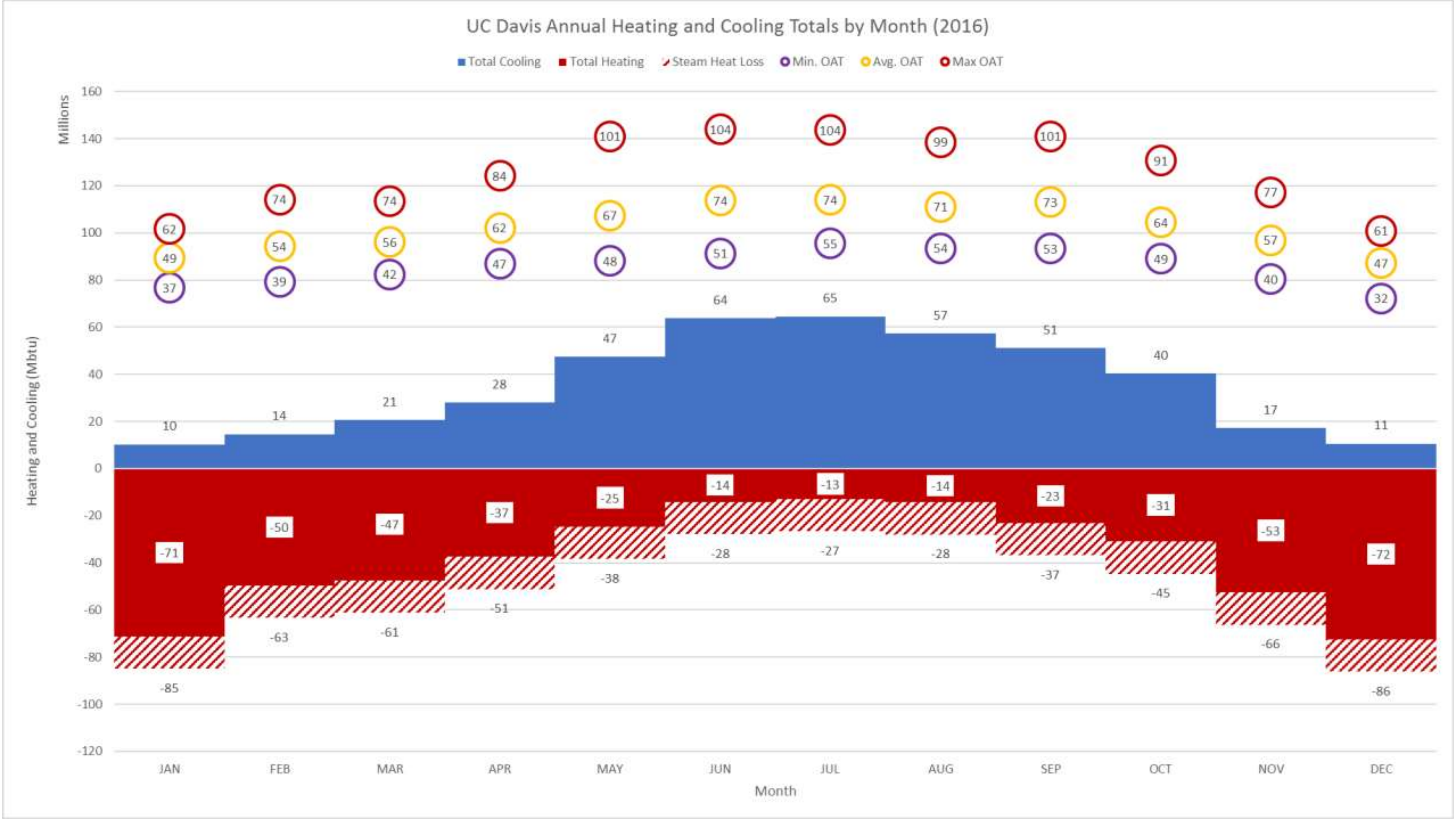


UC Davis Annual Heating and Cooling Totals by Month (2016)
Total Cooling
Total Steam
Min. OAT
Avg. OAT
Max OAT
Millions
Heating and Cooling (Mbtu)
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Month
62 74 74 84 101 104 104 99 101 91 77 61
49 54 56 62 67 74 74 71 73 64 57 47
37 39 42 47 48 51 55 54 53 49 40 32
10 14 21 28 47 64 65 57 51 40 17 11
-85 -63 -61 -51 -38 -28 -27 -28 -37 -45 -66 -86

HW Dist.



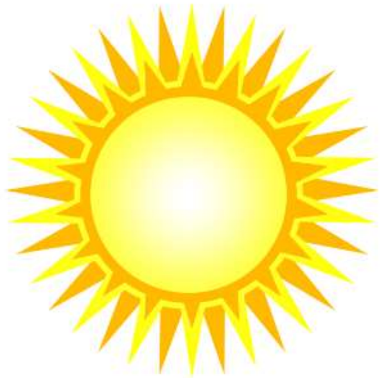
COOLING TOWER
COOLING TOWER
COOLING TOWER
COOLING TOWER
CHILLER
CHILLER
CHILLER
CHILLER
CHILLED WATER SUPPLY
CHILLED WATER RETURN
HOT WATER SUPPLY
HOT WATER RETURN
TYPICAL BUILDING
TYPICAL BUILDING
TYPICAL BUILDING
TYPICAL BUILDING
TYPICAL BUILDING
BOILER
BOILER
BOILER
BOILER
NG
COOLING TOWER
COOLING TOWER
COOLING TOWER
COOLING TOWER
CHILLER
CHILLER
CHILLER
CHILLER
CHW TES



UC Davis Annual Heating and Cooling Totals by Month (2016)
Total Cooling
Total Heating
Steam Heat Loss
Min. OAT
Avg. OAT
Max OAT
Millions
Heating and Cooling (Mbtu)
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
62 49 37
74 54 39
74 56 42
84 62 47
101 67 48
104 74 51
104 74 55
99 71 54
101 73 53
91 64 49
77 57 40
61 47 32
10 14 21 28 47 64 65 57 51 40 17 11
-71 -50 -47 -37 -25 -14 -13 -14 -23 -31 -53 -72
-85 -63 -61 -51 -38 -28 -27 -28 -37 -45 -66 -86
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Month

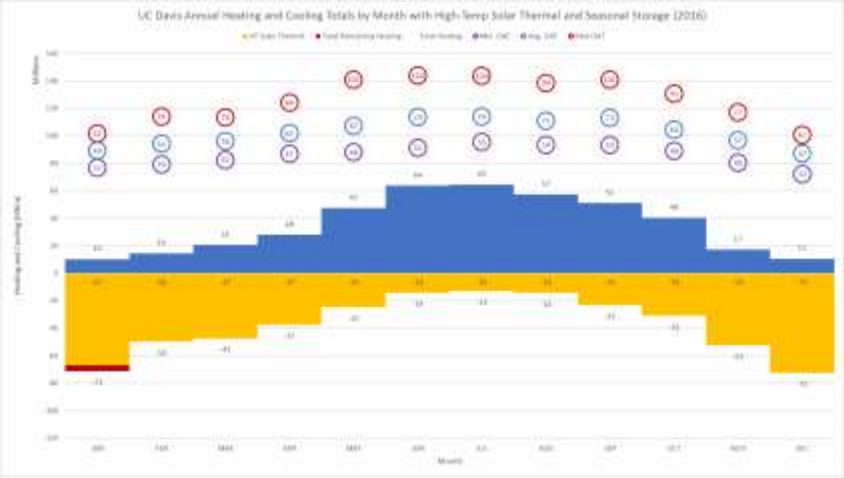
Hot Water Heat Sources

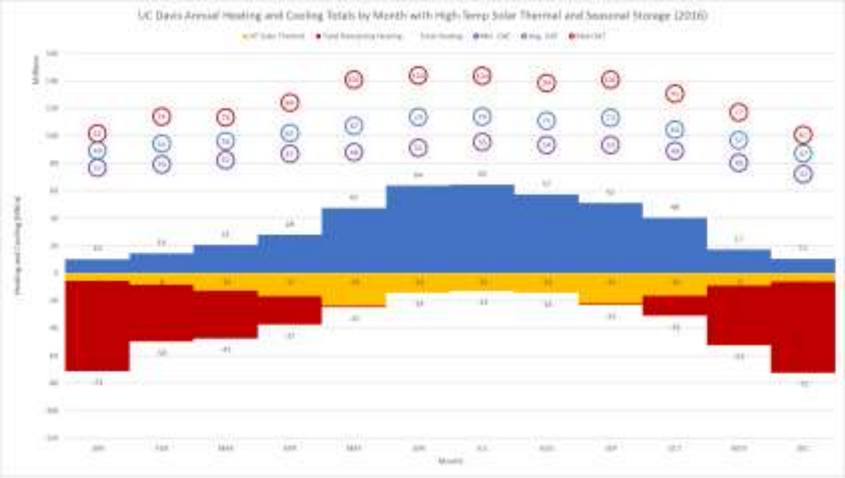
- These sources can be used directly for heating demand with hot water distribution
  - Natural gas combustion and carbon credits or biofuel
    - Boilers
    - Combined heat and power (30+ year payback)
  - Electric or electrode hot water generators
  - Solar thermal (evacuated tube collectors)



Hot Water Solar Summary

- 100% HW Solar is cost and size prohibitive
  - 180 acres
- 100% HW Solar via seasonal shifting is cost and size prohibitive
  - 34 acres and 1 billion gallon storage pit
- HW Solar sized for summer heating can only provide 40% of heat
  - 15 acres

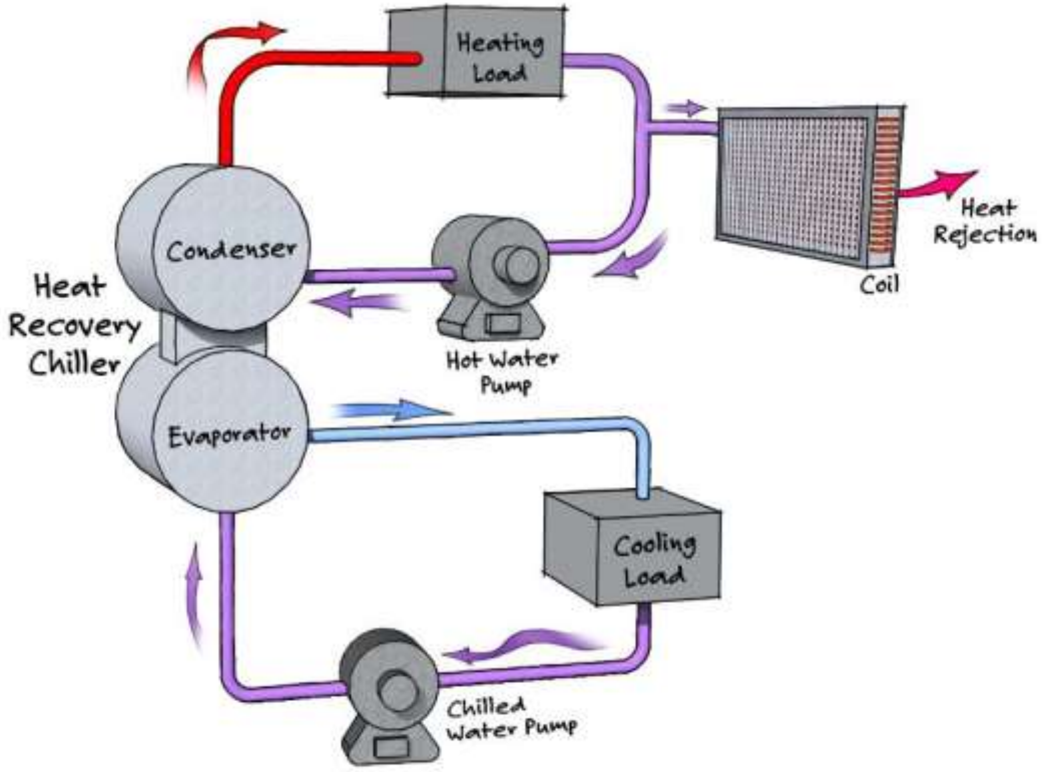


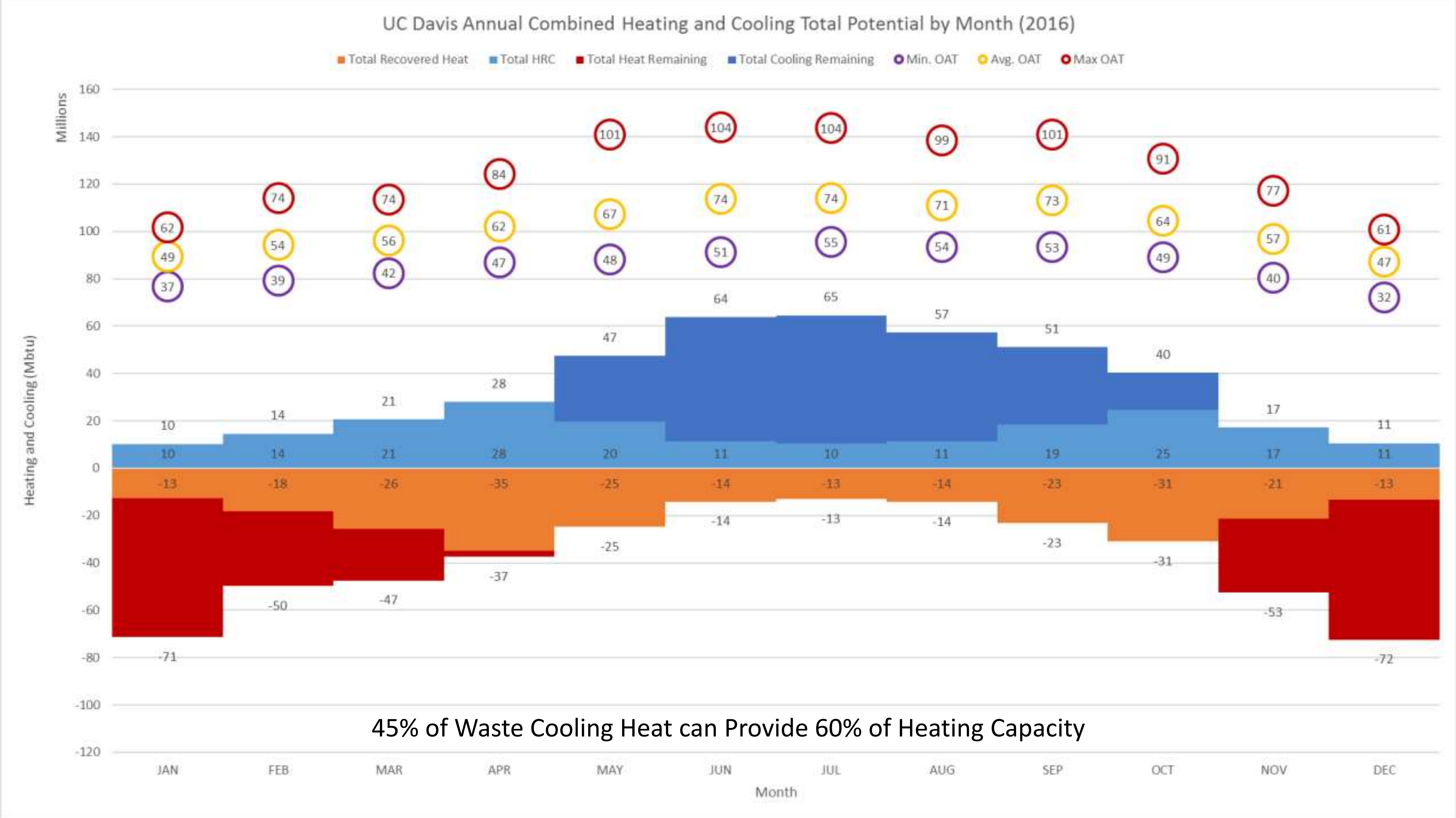


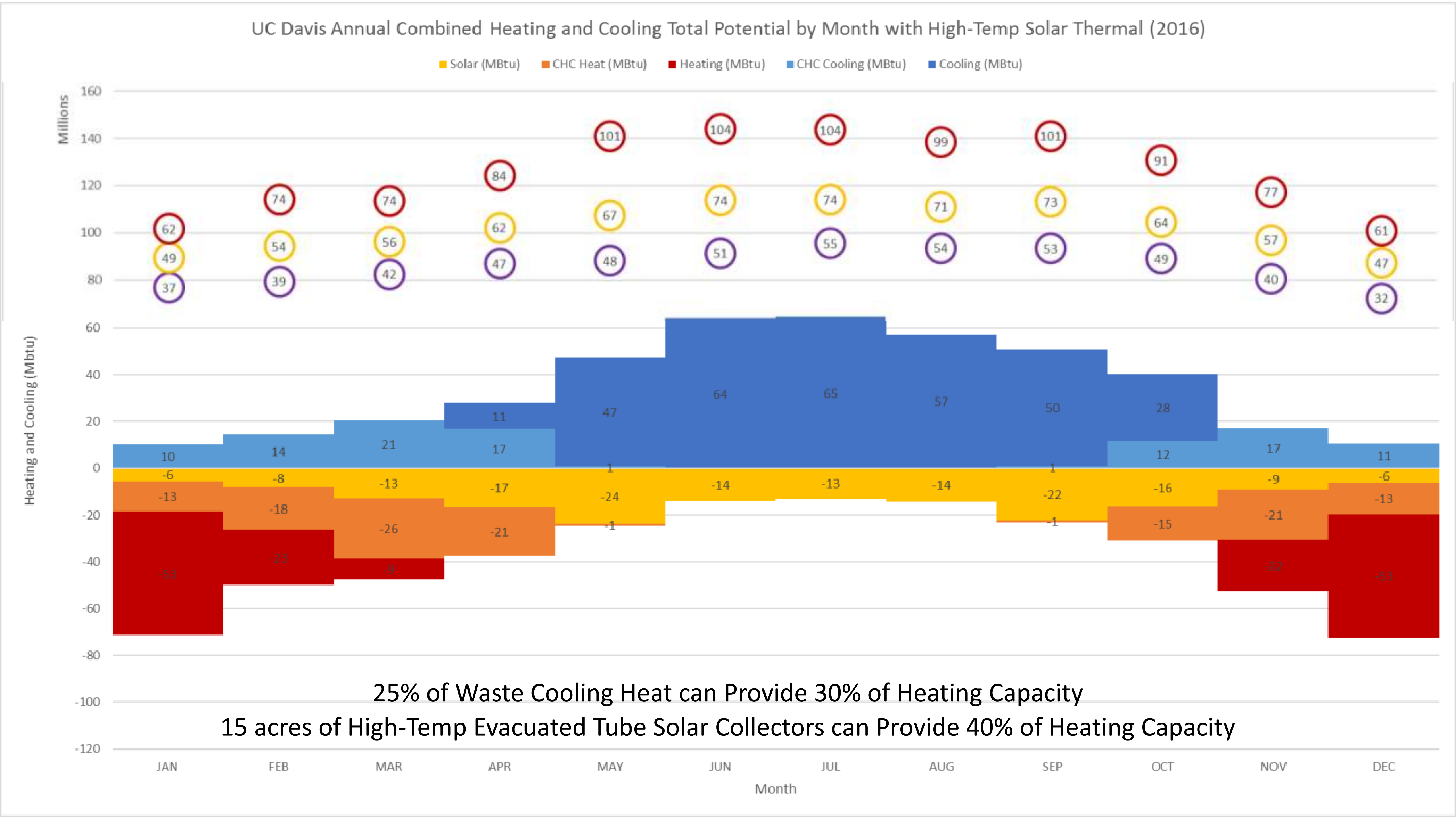
Combined Heating and Cooling (CHC)

- Simultaneous beneficial heating and cooling can deliver COP>10
- 45% of Waste Cooling Heat can Provide 60% of Heating Capacity

Centralized with hot water distribution
OR
Distributed with no hot water distribution



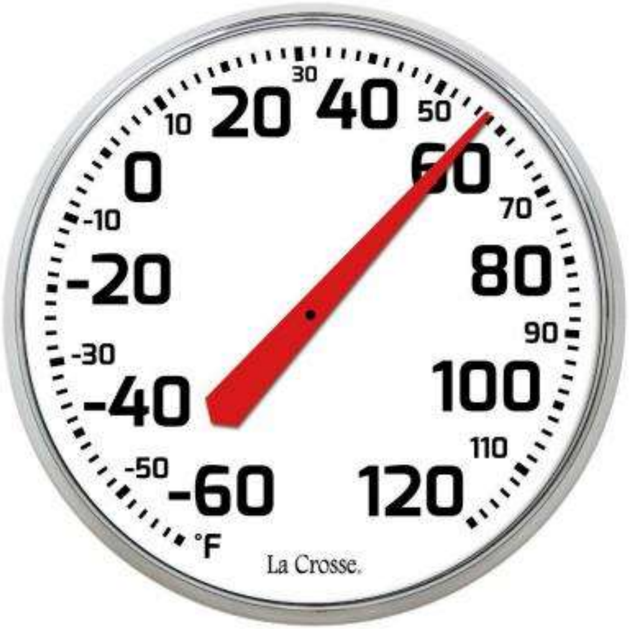

UC Davis Annual Combined Heating and Cooling Total Potential by Month (2016)
Total Recovered Heat
Total HRC
Total Heat Remaining
Total Cooling Remaining
Min. OAT
Avg. OAT
Max OAT
Millions
Heating and Cooling (Mbtu)
160
140
120
100
80
60
40
20
0
-20
-40
-60
-80
-100
-120
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
Month
45% of Waste Cooling Heat can Provide 60% of Heating Capacity



UC Davis Annual Combined Heating and Cooling Total Potential by Month with High-Temp Solar Thermal (2016)
Solar (MBtu)
CHC Heat (MBtu)
Heating (MBtu)
CHC Cooling (MBtu)
Cooling (MBtu)
Millions
Heating and Cooling (Mbtu)
Month
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC
25% of Waste Cooling Heat can Provide 30% of Heating Capacity
15 acres of High-Temp Evacuated Tube Solar Collectors can Provide 40% of Heating Capacity

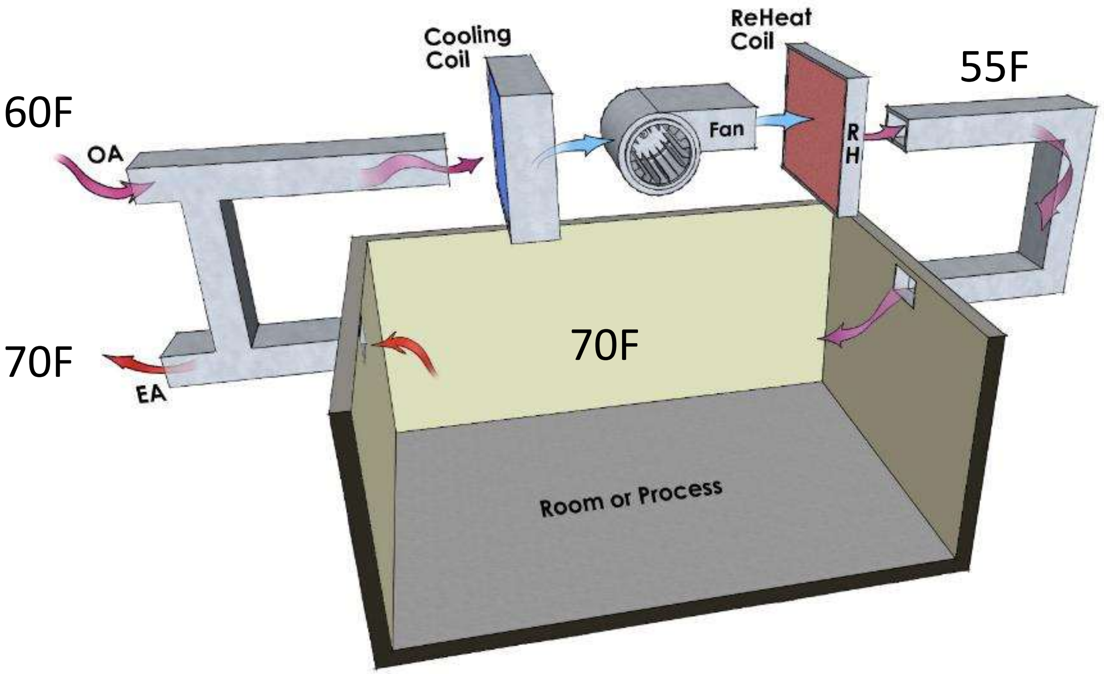
Chilled Water Heat Sources

- These sources require conversion to higher grade via heat pump
  - Building heat recovery: eliminate airside economizing to capture more heat
  - Geo-exchange
  - Solar thermal (fixed flat panel)
  - Irrigation flow
  - Domestic water flow
  - Wastewater influent
  - Wastewater effluent
  - Air-source heat pump
  - Any adjacent industry
  - Surface water

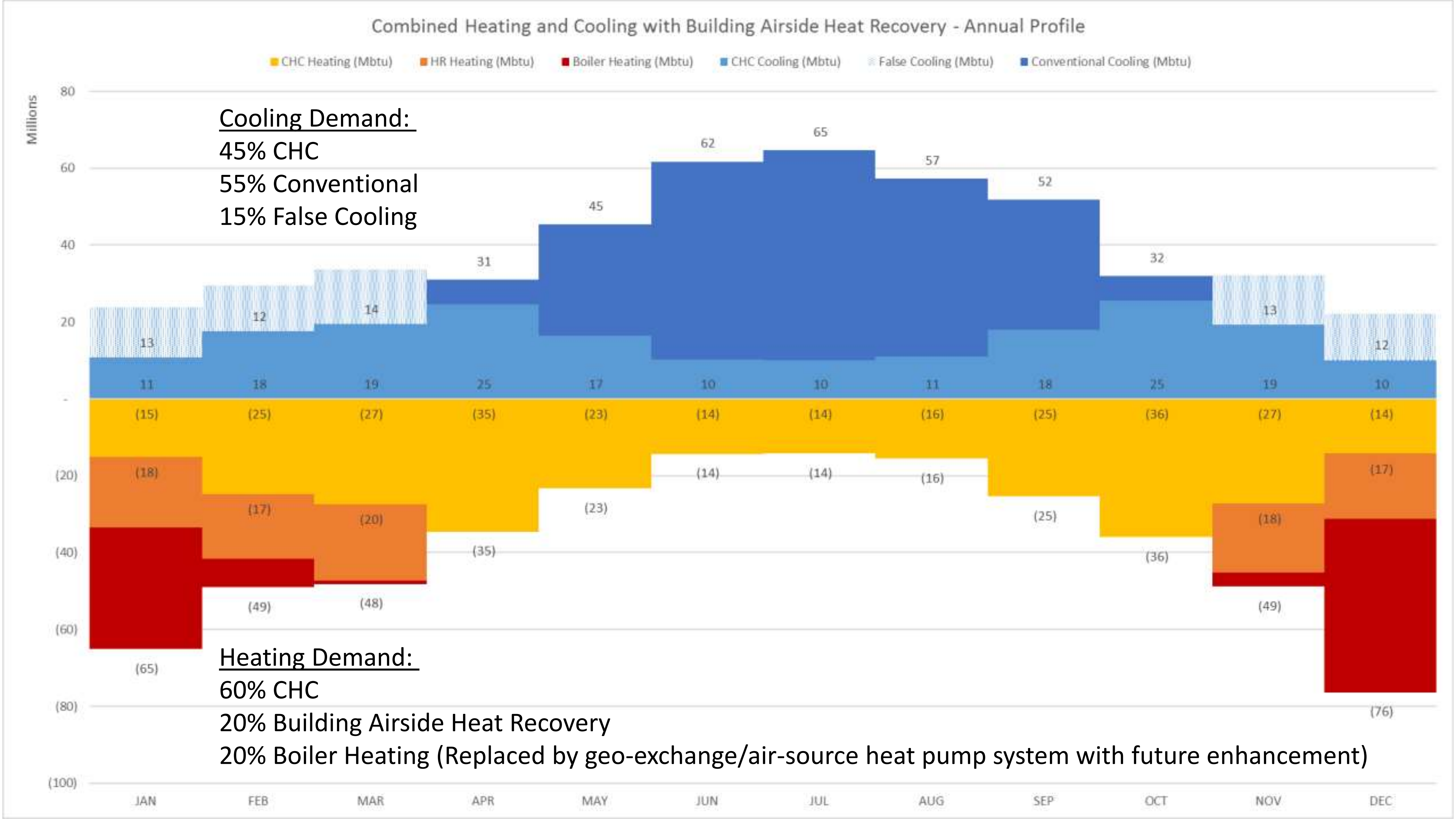


Building Heat Recovery

- Unlocks more hours per year of heat recovery potential
- Instead of exhausting warm air from buildings and using outdoor air for cooling, return the warm air to the cooling coil and extract heat, then store in campus chilled water tank
- 100% OA buildings can be fitted with CC on EA for more heat



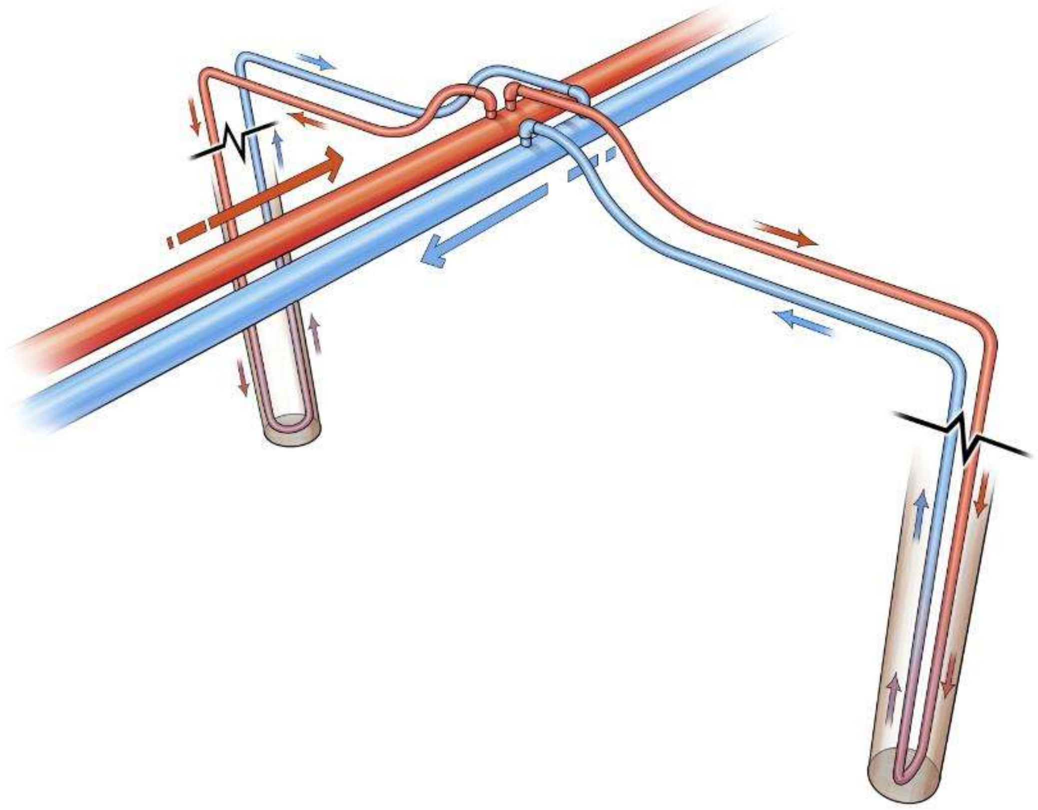
Normally at this conditions cooling is active but OA is used instead of RA (airside economizer). Disable this the triple the cooling load and enable more heat recovery.



Combined Heating and Cooling with Building Airside Heat Recovery - Annual Profile
CHC Heating (Mbtu)
HR Heating (Mbtu)
Boiler Heating (Mbtu)
CHC Cooling (Mbtu)
False Cooling (Mbtu)
Conventional Cooling (Mbtu)
Millions
Cooling Demand:
45% CHC
55% Conventional
15% False Cooling
Heating Demand:
60% CHC
20% Building Airside Heat Recovery
20% Boiler Heating (Replaced by geo-exchange/air-source heat pump system with future enhancement)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

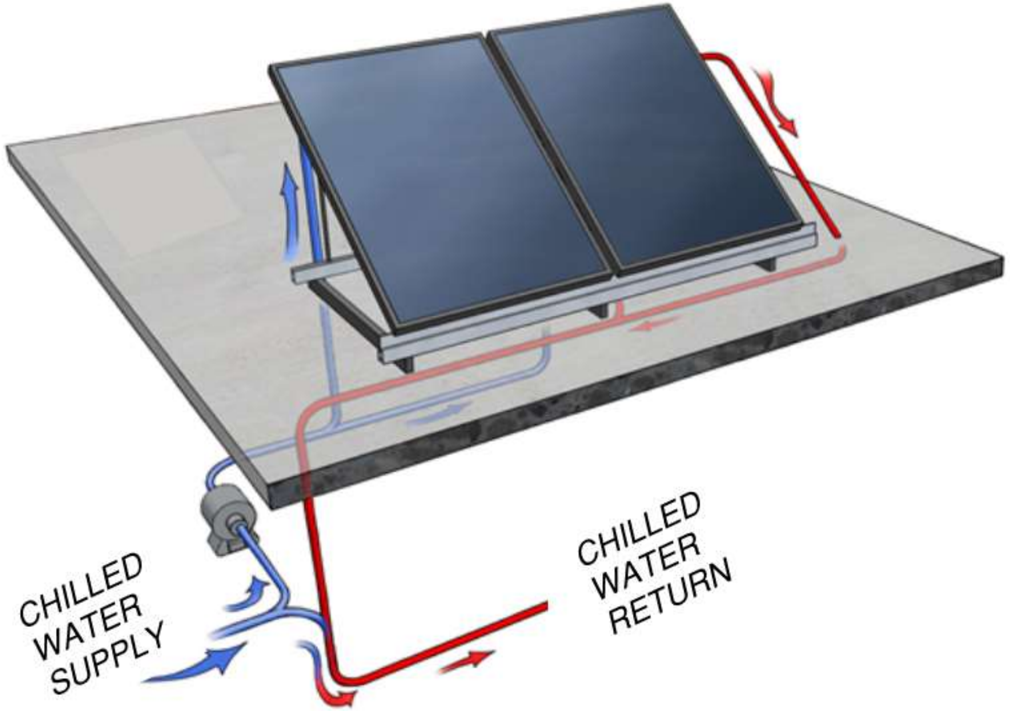
Geo-exchange

- Land area: 60-250 square foot land area per ton for vertical bores (need test boring)
  - 300-500 ft depth closed loop vertical 1-2 U-bend bores
- 53e6 MBtu per month would require up to 35 acre bore field
- Challenge – annual heat balance required to avoid saturation



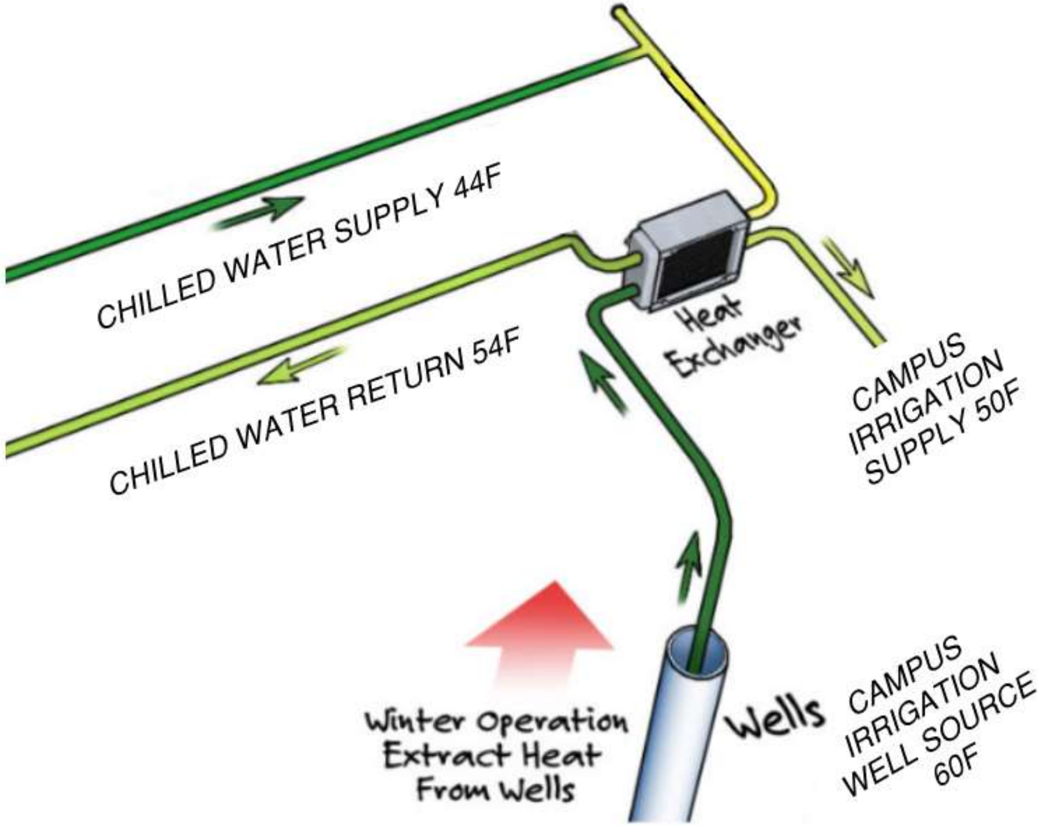
Chilled Water Solar

- Flat, fixed solar panels
- Provide 60F heating supply to chilled water system as false load
- 53e6 MBtu per month would require 120 acres
- 16e6 Mbtu per month would require 35 acres



Heat from Irrigation Water Flow

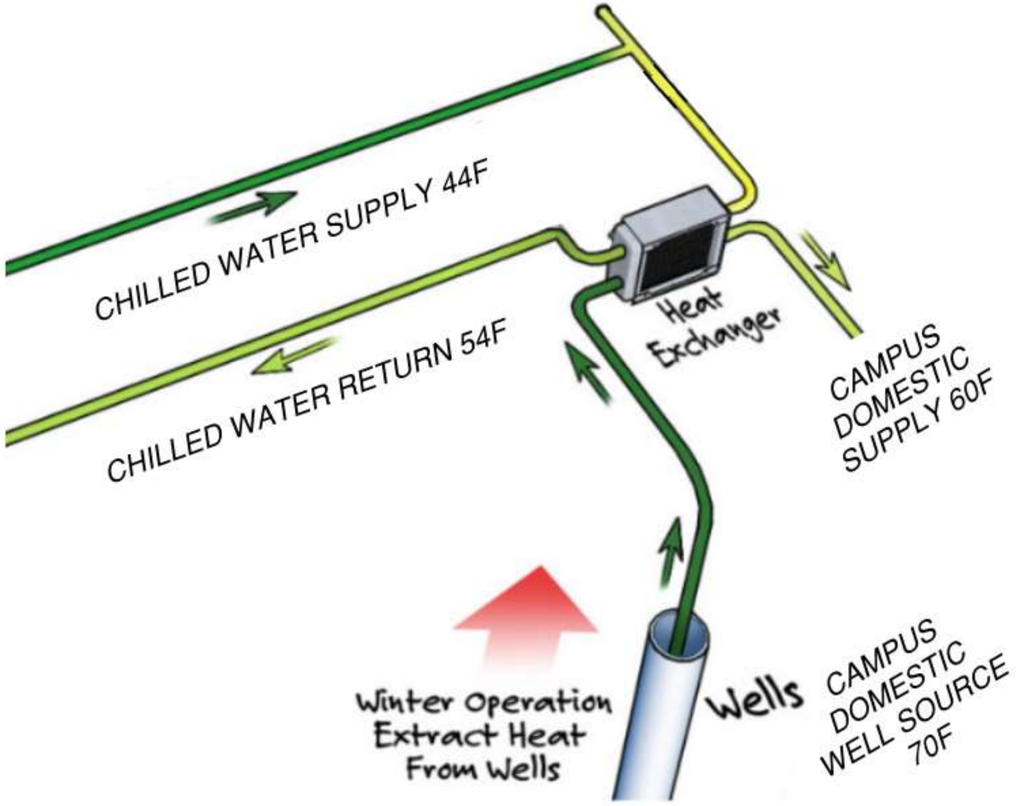
- Six wells draw water from shallow aquifer (300'-400' in depth)[1]
- 247Mgal in 2003[1]
  - 58% from UW6A (144Mgal)[1]
  - 13% from UW5 (32Mgal)[1]
- Cooling the UW6A flow by 14F can remove 1.4e6 MBtu per month
- Problem: Most of irrigation flow is in summer months when low grade heat sources are not needed.



[1]Source: Chiller System Alternative Cooling Options Evaluation, Stantec, March 2, 2011

Heat From Domestic Water Flow

- Six wells draw 5,300 gpm[1]
- Cooling the domestic flow by 10F can remove 19e6 MBtu per month
- Problem – this will increase DHW load (inefficient)



[1]Source: Chiller System Alternative Cooling Options Evaluation, Stantec, March 2, 2011

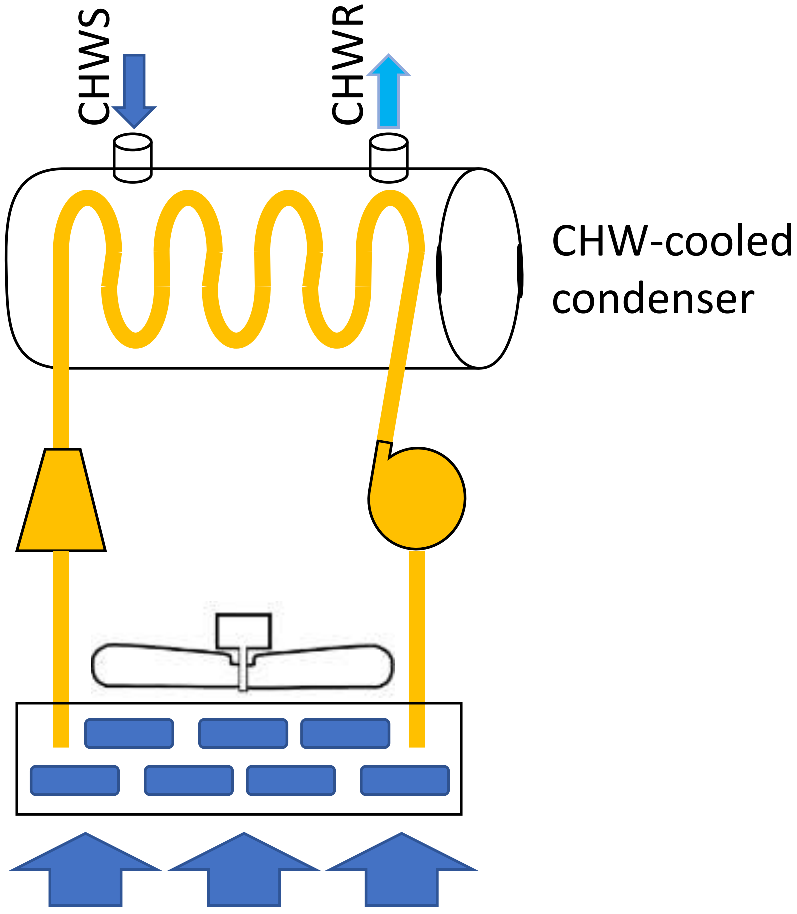
Heat from Wastewater Flow

- 2MGD flow
- Cooling flow by 10F can extract 5e6 Mbtu per month
- Influent to treatment plant
  - Lift station adjacent to TES plant
  - Problem – this could negatively impact the treatment plant
- Effluent from treatment plant
  - Requires further investigation

HUBER Wastewater Heat Exchanger RoWin as tank version, installed in a wastewater treatment plant effluent channel

Air-Source Heat Pump (ASHP)

- Extracts heat from outdoor air into chilled water system
- An alternate to gas combustion
- 170T module: 27ft x 18ft with clearances



Chilled Water Heat Sources Summary

- Building heat recovery is viable at low cost – analysis required to determine heat potential
- Geo-exchange is viable and scalable for majority of heat need
- CHW Solar is cost and size prohibitive
- Wastewater effluent heat is viable but scale limited
- ASHP is viable as Steam to CHW HX replacement

Independent System Components

- Boilers with credits or biogas
- CHP with credits or biogas
- Electric or Electrode boilers
- HW Solar Thermal
- Central CHC
- Distributed CHC
- Building Heat Recovery
- Geo-exchange
- CHW Solar Thermal
- Irrigation Water Heat Extraction
- Domestic Water Heat Extraction
- Waste Influent Heat Extraction
- Waste Effluent Heat Extraction
- Air-source Heat Pump

Constraints

A. Environmental Restrictions
B. Capability to Maintain Critical Loads
C. Refrigerant Restrictions (no CFC, no HCFC, no GWP>750)
    A. R-134a and R-410a cannot be installed after 2021
D. Phase-ability of concept
E. Can be complete by 2025
F. Requires Minimal System Shutdown

Criteria

	Criteria	Weighting Percent
1	Scope 1 Carbon Reduction	14
2	Site Water Consumption Reduction	1
3	Maintenance Intensity	12
4	Resiliency	3
5	Availability of Technology	2
6	Construction Cost	12
7	Campus Impact	2
8	Construction Challenges	2
9	Flexibility to Campus Growth	4
10	Phase-ability of Concept	16
11	Timely Reduction of Steam Loads	8
12	System Efficiency	15
13	Operational Complexity	9

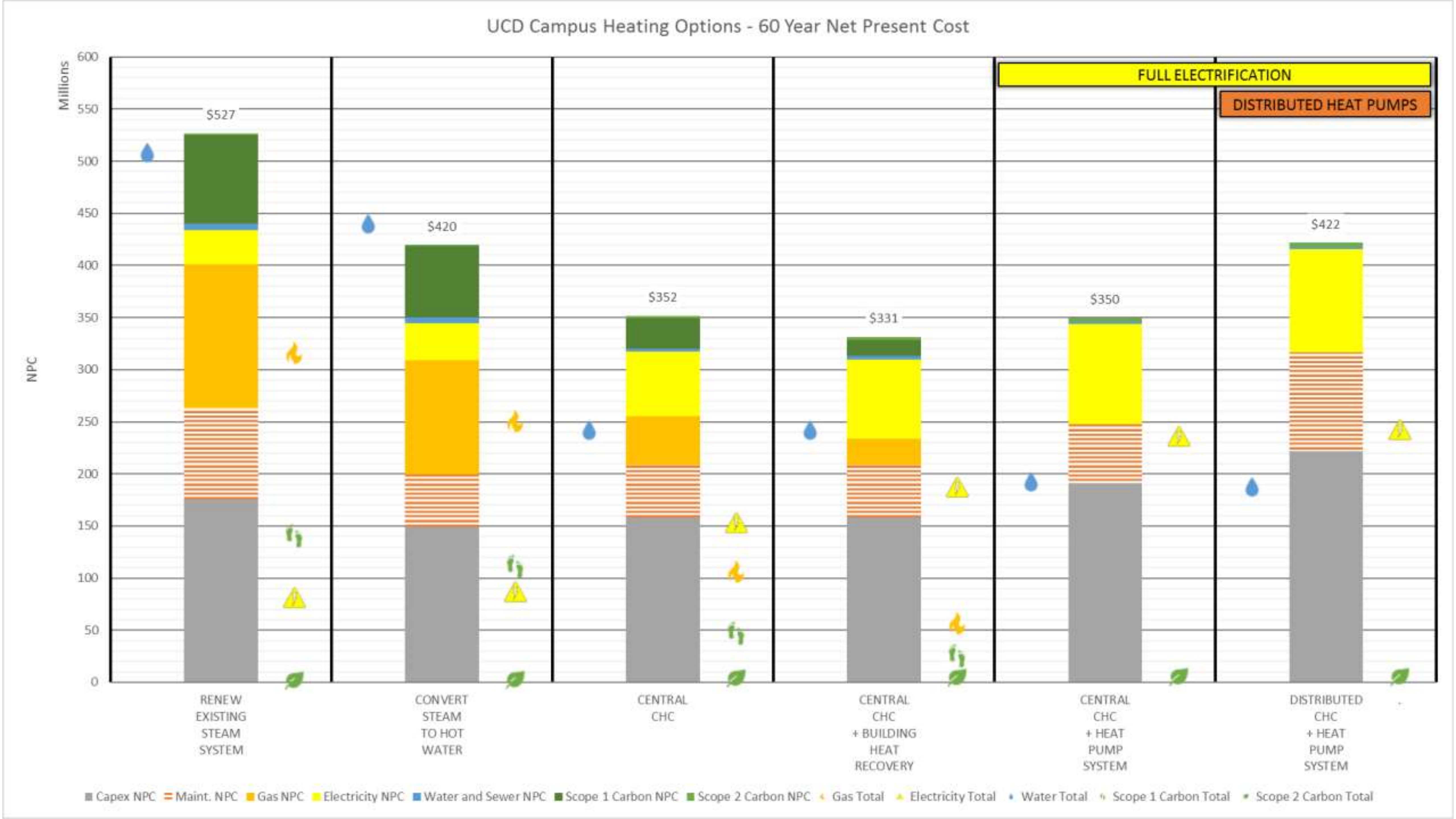
Qualitative Analysis

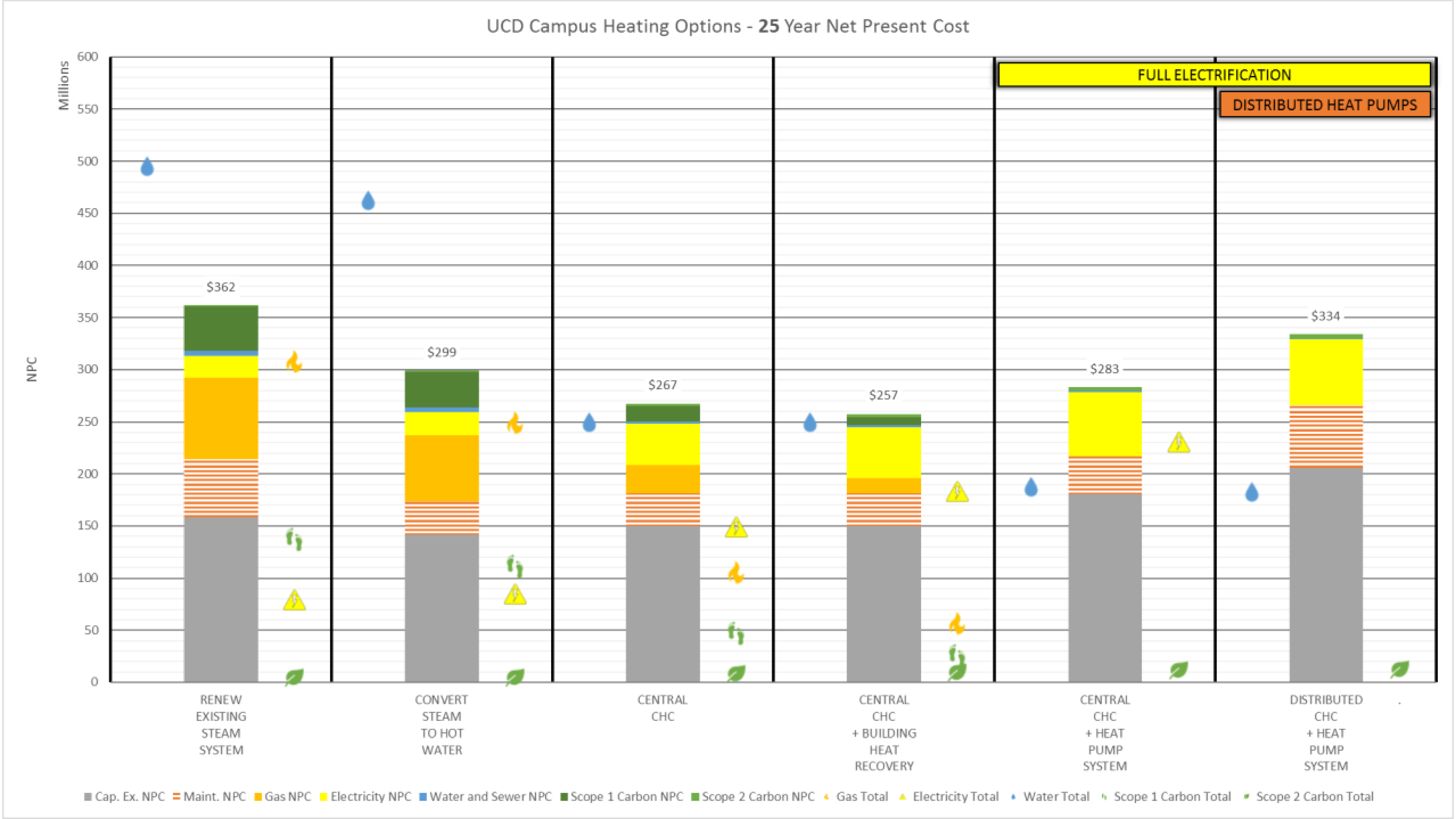
Rank	Option Description	Constraint A	Constraint B	Constraint C	Constraint D	Constraint E	Constraint F	PASS?	Criteria 1	Criteria 2	Criteria 3	Criteria 4	Criteria 5	Criteria 6	Criteria 7	Criteria 8	Criteria 9	Criteria 10	Criteria 11	Criteria 12	Criteria 13	TOTAL
	Weighting								14%	1%	12%	3%	2%	12%	2%	2%	4%	16%	8%	15%	9%	100%
3	Boilers with credits or biogas	Y	Y	Y	Y	Y	Y	Y	0	1	2	5	1	4	2	5	3	5	1	2	5	2.79
13	CHP with credits or biogas	Y	Y	Y	Y	Y	Y	Y	0	1	0	5	1	1	2	2	1	1	1	3	2	1.29
6	Electric or Electrode boilers	Y	Y	Y	Y	Y	Y	Y	5	2	2	2	2	1	1	2	3	2	4	0	4	2.36
7	HW Solar Thermal	Y	Y	Y	Y	Y	Y	Y	2	2	3	1	3	1	1	1	2	1	2	5	2	2.24
2	Central CHC	Y	Y	Y	Y	Y	Y	Y	3	3	4	4	3	4	2	2	2	2	2	4	2	3.01
5	Distributed CHC	Y	Y	Y	Y	Y	Y	Y	3	3	0	5	2	3	5	1	4	3	4	2	0	2.38
1	Building Heat Recovery	Y	Y	Y	Y	Y	Y	Y	1	1	5	0	3	5	5	5	3	4	2	5	5	3.73
4	Geo-exchange	Y	Y	Y	Y	Y	Y	Y	4	5	5	4	3	2	1	1	3	1	2	3	1	2.65
8	CHW Solar Thermal	Y	Y	Y	Y	Y	Y	Y	5	5	3	1	2	1	1	1	2	1	2	2	1	2.13
11	Irrigation Water Heat Extraction	Y	Y	Y	Y	Y	Y	Y	1	1	2	0	2	2	2	2	1	2	2	2	2	1.75
12	Domestic Water Heat Extraction	Y	Y	Y	Y	Y	Y	Y	0	0	2	0	2	2	2	2	1	2	2	0	2	1.30
14	Waste Influent Heat Extraction	Y	Y	Y	Y	Y	Y	Y	0	0	0	0	2	1	2	2	1	2	2	0	0	0.76
10	Waste Effluent Heat Extraction	Y	Y	Y	Y	Y	Y	Y	1	1	2	0	2	2	3	2	1	2	2	2	2	1.77
9	Air-source Heat Pump	Y	Y	Y	Y	Y	Y	Y	5	5	0	3	2	1	1	2	3	2	2	0	2	1.84

Microsoft Excel Worksheet

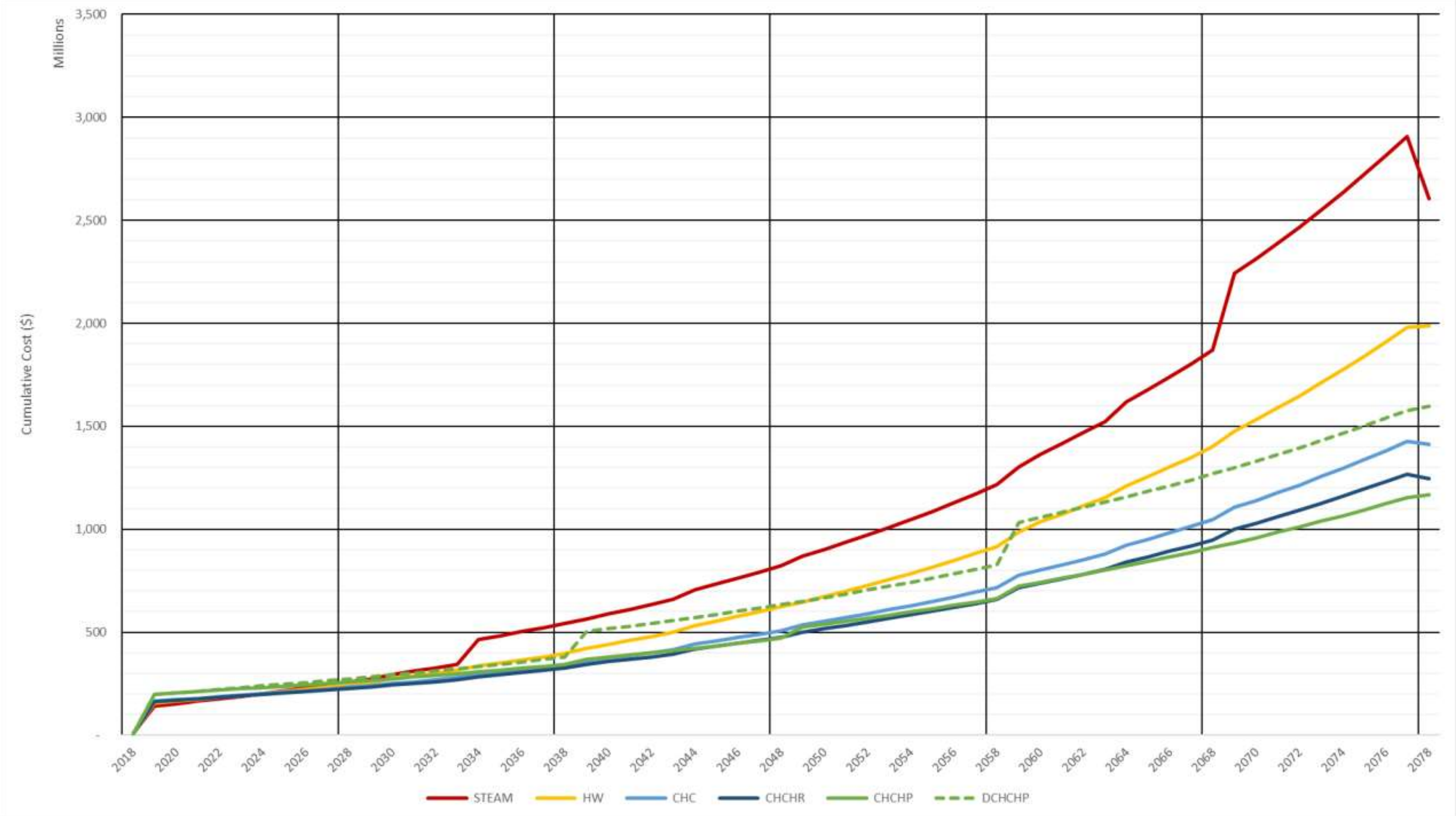
Options for Quantitative Analysis

Acronym	Description	Heat Sources
STEAM	Boilers and Steam Distribution (Baseline)	• Gas Combustion
HW	Boilers and HW Distribution	• Gas Combustion
CHC	Boilers and HW Distribution + Central CHC	• Gas Combustion • Chilled Water
CHCHR	Boilers and HW Distribution + Central CHC + Building Heat Recovery	• Gas Combustion • Chilled Water • Building Return Air
CHCHP	HW Distribution + Central CHC + Building Heat Recovery + Heat Pump System (no boilers)	• Chilled Water • Building Return Air • Geo-exchange • Ambient Air
DCHCHP	Distributed CHC (no HW Distribution) + Building Heat Recovery + Heat Pump System (no boilers)	• Chilled Water • Building Return Air • Geo-exchange • Ambient Air


UCD Campus Heating Options - 60 Year Net Present Cost
Millions
NPC
600
550
500
450
400
350
300
250
200
150
100
50
0
FULL ELECTRIFICATION
DISTRIBUTED HEAT PUMPS
$527
$420
$352
$331
$350
$422
RENEW EXISTING STEAM SYSTEM
CONVERT STEAM TO HOT WATER
CENTRAL CHC
CENTRAL CHC + BUILDING HEAT RECOVERY
CENTRAL CHC + HEAT PUMP SYSTEM
DISTRIBUTED CHC + HEAT PUMP SYSTEM
Capex NPC
Maint. NPC
Gas NPC
Electricity NPC
Water and Sewer NPC
Scope 1 Carbon NPC
Scope 2 Carbon NPC
Gas Total
Electricity Total
Water Total
Scope 1 Carbon Total
Scope 2 Carbon Total



UCD Campus Heating Options - 25 Year Net Present Cost
Millions
NPC
600
550
500
450
400
350
300
250
200
150
100
50
0
FULL ELECTRIFICATION
DISTRIBUTED HEAT PUMPS
$362
$299
$267
$257
$283
$334
RENEW EXISTING STEAM SYSTEM
CONVERT STEAM TO HOT WATER
CENTRAL CHC
CENTRAL CHC + BUILDING HEAT RECOVERY
CENTRAL CHC + HEAT PUMP SYSTEM
DISTRIBUTED CHC + HEAT PUMP SYSTEM
Cap. Ex. NPC
Maint. NPC
Gas NPC
Electricity NPC
Water and Sewer NPC
Scope 1 Carbon NPC
Scope 2 Carbon NPC
Gas Total
Electricity Total
Water Total
Scope 1 Carbon Total
Scope 2 Carbon Total



Millions
Cumulative Cost ($)
3,500
3,000
2,500
2,000
1,500
1,000
500
-
2018
2020
2022
2024
2026
2028
2030
2032
2034
2036
2038
2040
2042
2044
2046
2048
2050
2052
2054
2056
2058
2060
2062
2064
2066
2068
2070
2072
2074
2076
2078
STEAM
HW
CHC
CHCHR
CHCHP
DCHCHP

Sensitivity Analysis - Lowest NPC Option

Parameter	Level	Value	Electricity Cost Inflation (High, 4.0%)	Natural Gas Cost Inflation (High, 5.0%)	Cost of Carbon - Scope 1 ($/MTCDE) (High, 174)	Cost of Carbon - Scope 2 ($/MTCDE) (High, 174)	Carbon Cost Inflation (High, 8.5%)	Number of Years (Low, 30)	Discount rate (Low, 4.5%)	Discount rate (High, 7.5%)	O&M Cost Inflation Rate (High, 4.0%)	Material Cost Inflation Rate (High, 3.0%)	Steam Heat Loss (High, 40%)	Ratio of boiler replaced by HP (Low, 50%)	Process Steam Boiler EFLH (High, 1000)	Direct Buried HW Cost ($/in-ft) (Low, 35)	Direct Buried HW Cost ($/in-ft) (High, 65)	Central HRC Cost ($/ton) (Low, 1000)	Central HRC Cost ($/ton) (High, 1700)	Distributed HRC Cost ($/ton) (Low, 2500)	Distributed HRC Cost ($/ton) (High, 5000)
BASELINE			4	4	5	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Electricity Cost Inflation	High	4.0%		4	5	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Natural Gas Cost Inflation	High	5.0%			5	4	5	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Cost of Carbon - Scope 1 ($/MTCDE)	High	174				5	5	4	5	4	5	5	5	5	5	5	5	5	5	5	5
Cost of Carbon - Scope 2 ($/MTCDE)	High	174					5	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Carbon Cost Inflation	High	8.5%						4	5	4	5	5	5	5	5	5	5	5	5	5	5
Number of Years	Low	30							4	4	4	4	4	4	4	4	4	4	4	4	4
Discount rate	Low	4.5%									4	4	4	4	4	4	4	4	4	4	4
Discount rate	High	7.5%									4	4	4	4	4	4	4	4	4	4	4
O&M Cost Inflation rate	High	4.0%										4	4	4	4	4	4	4	4	4	4
Material Cost Inflation rate	High	3.0%											4	4	4	4	4	4	4	4	4
Steam Heat Loss	High	40%												4	4	4	4	4	4	4	4
Ratio of boiler replaced by HP	Low	50%													4	4	4	4	4	4	4
Process Steam Boiler EFLH	High	1000														4	4	4	4	4	4
Direct Buried HW Cost ($/in-ft)	Low	35																4	4	4	4
Direct Buried HW Cost ($/in-ft)	High	65																4	4	4	4
Central HRC Cost ($/ton)	Low	1000																		4	4
Central HRC Cost ($/ton)	High	1700																		4	4
Distributed HRC Cost ($/ton)	Low	2500																			
Distributed HRC Cost ($/ton)	High	5000																			

1	**RENEW EXISTING STEAM SYSTEM**	0%
2	**CONVERT STEAM TO HOT WATER**	0%
3	**CENTRAL CHC**	0%
4	**CENTRAL CHC + BUILDING HEAT RECOVERY**	82%
5	**CENTRAL CHC + HEAT PUMP SYSTEM**	18%
6	**DISTRIBUTED CHC + HEAT PUMP SYSTEM**	0%

Central Combined Heating and Cooling (CHC) with Building Heat Recovery (HR) is the lowest NPC option for 82% of the sensitivity testing.

Quantitative Summary

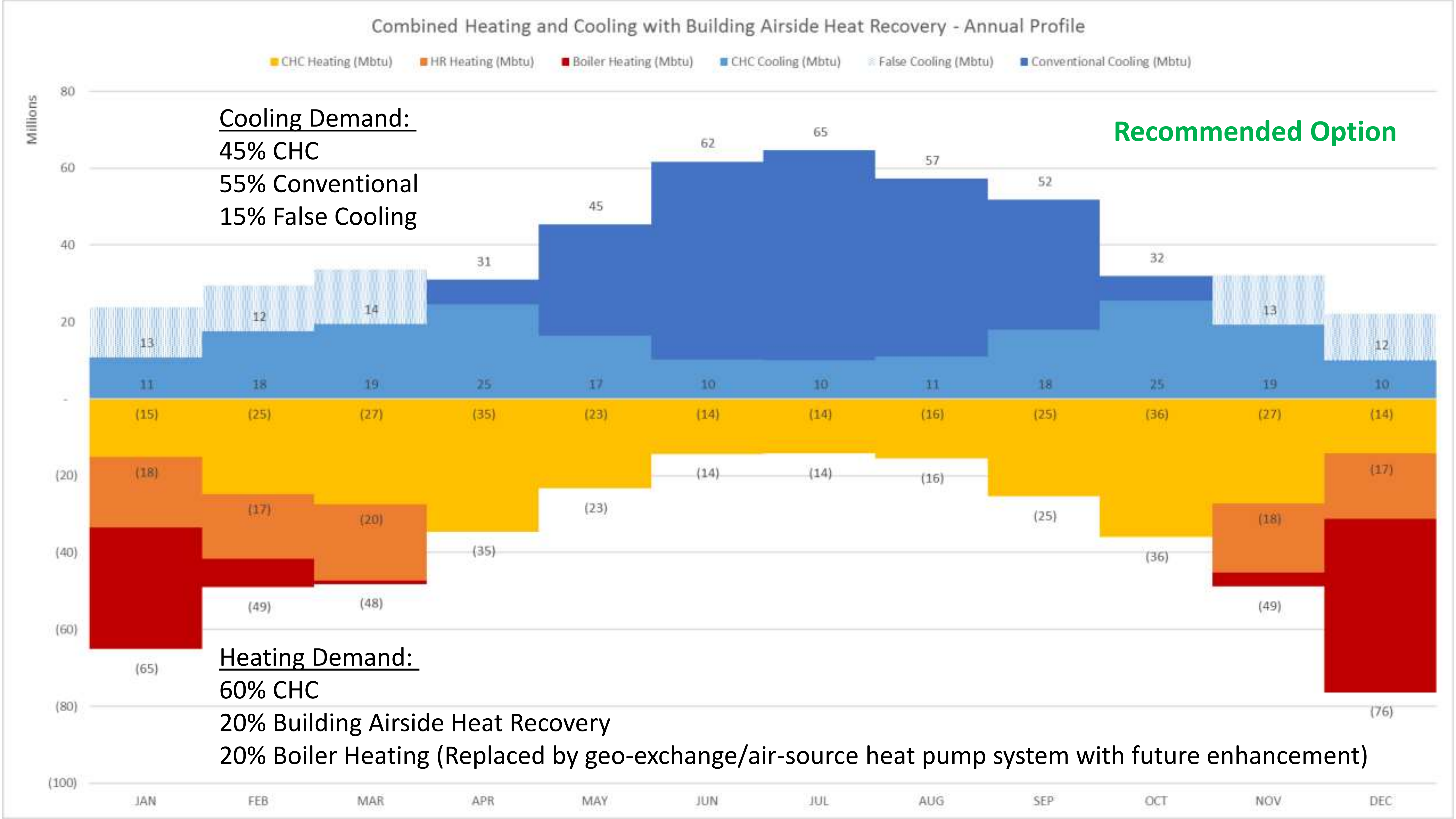
Acronym	Description	NPC	Best NPC % (Sensitivity)	Discounted Payback (years)	Total 60 Year Cost Avoided	Carbon Saved (MTCDE)	Water Saved (gallons)
STEAM	Boilers and Steam Distribution (Baseline)	$527M	0%	-	0	0	0
HW	Boilers and HW Distribution	$420M	0%	6.9	$0.62B	0.39M	0.7B
CHC	Boilers and HW Distribution + Central CHC	$352M	0%	6.6	$1.19B	1.22M	2.7B
CHCHR	Boilers and HW Distribution + Central CHC + Building Heat Recovery	**$331M**	**82%**	**6.2**	**$1.36B**	1.51M	2.7B
CHCHP	HW Distribution + Central CHC + Heat Pump System (no boilers)	$350M	18%	13.0	**$1.44B**	**1.83M**	**3.2B**
DCHCHP	Distributed CHC (no HW Distribution) + Heat Pump System (no boilers)	$422M	0%	15.2	$1.01B	**1.83M**	**3.2B**

Qualitative Summary

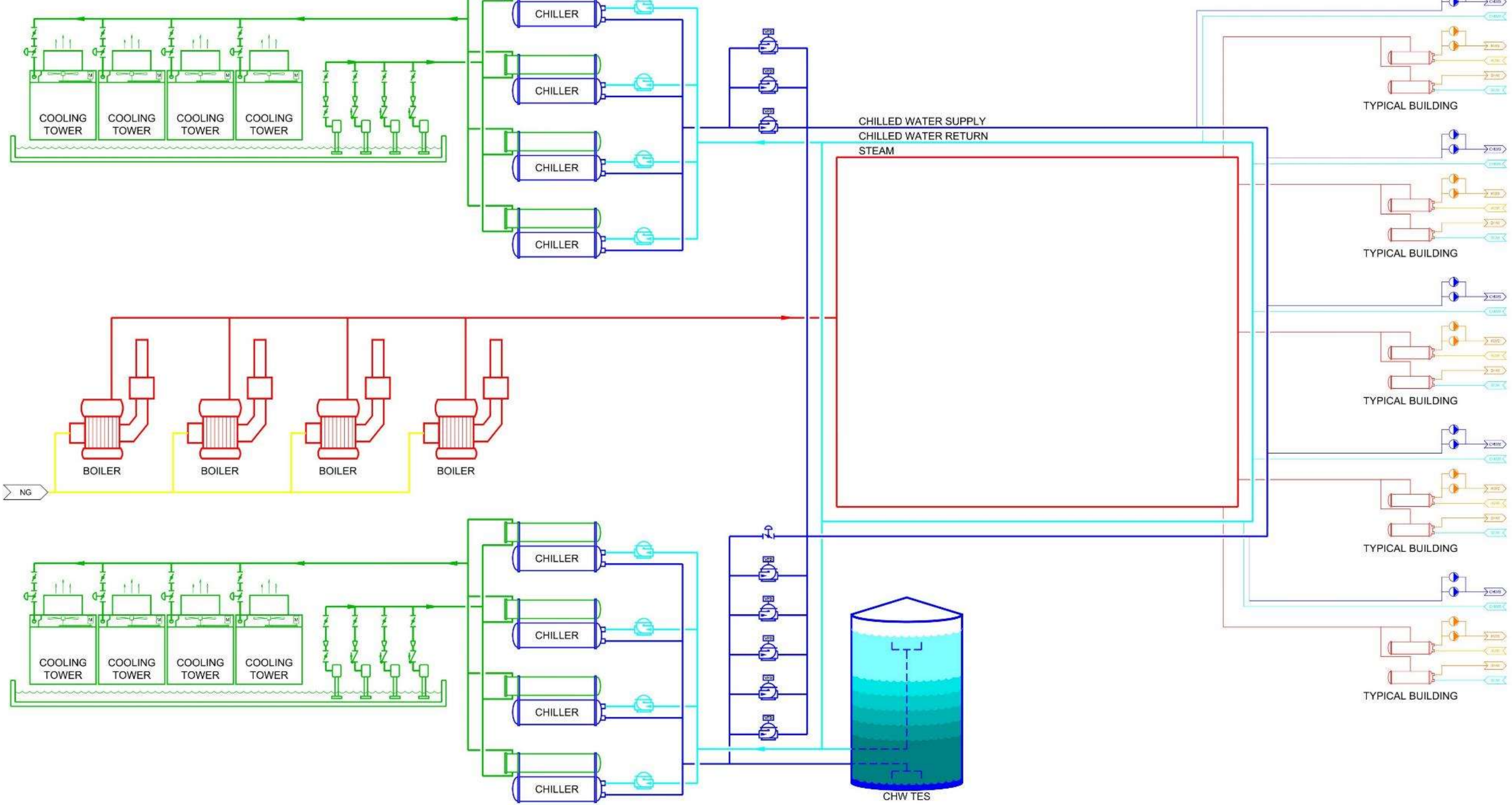
Acronym	Description	Campus Disruption	Building Disruption	Maintenance Intensity	High HW Boost Avail.?	Large Land Area Required?	Capital Cost Risk
STEAM	Boilers and Steam Distribution (Baseline)	High	Low	Mid	Yes	No	Mid
HW	Boilers and HW Distribution	High	Mid	Low	Yes	No	Low
CHC	Boilers and HW Distribution + Central CHC	High	Mid	Low	Yes	No	Low
CHCHR	Boilers and HW Distribution + Central CHC + Building Heat Recovery	High	Mid	Low	Yes	No	Low
CHCHP	HW Distribution + Central CHC + Heat Pump System (no boilers)	High	Mid	Mid	Yes	Yes	Mid
DCHCHP	Distributed CHC (no HW Distribution) + Heat Pump System (no boilers)	High	High	High	No	Yes	High

Recommendation

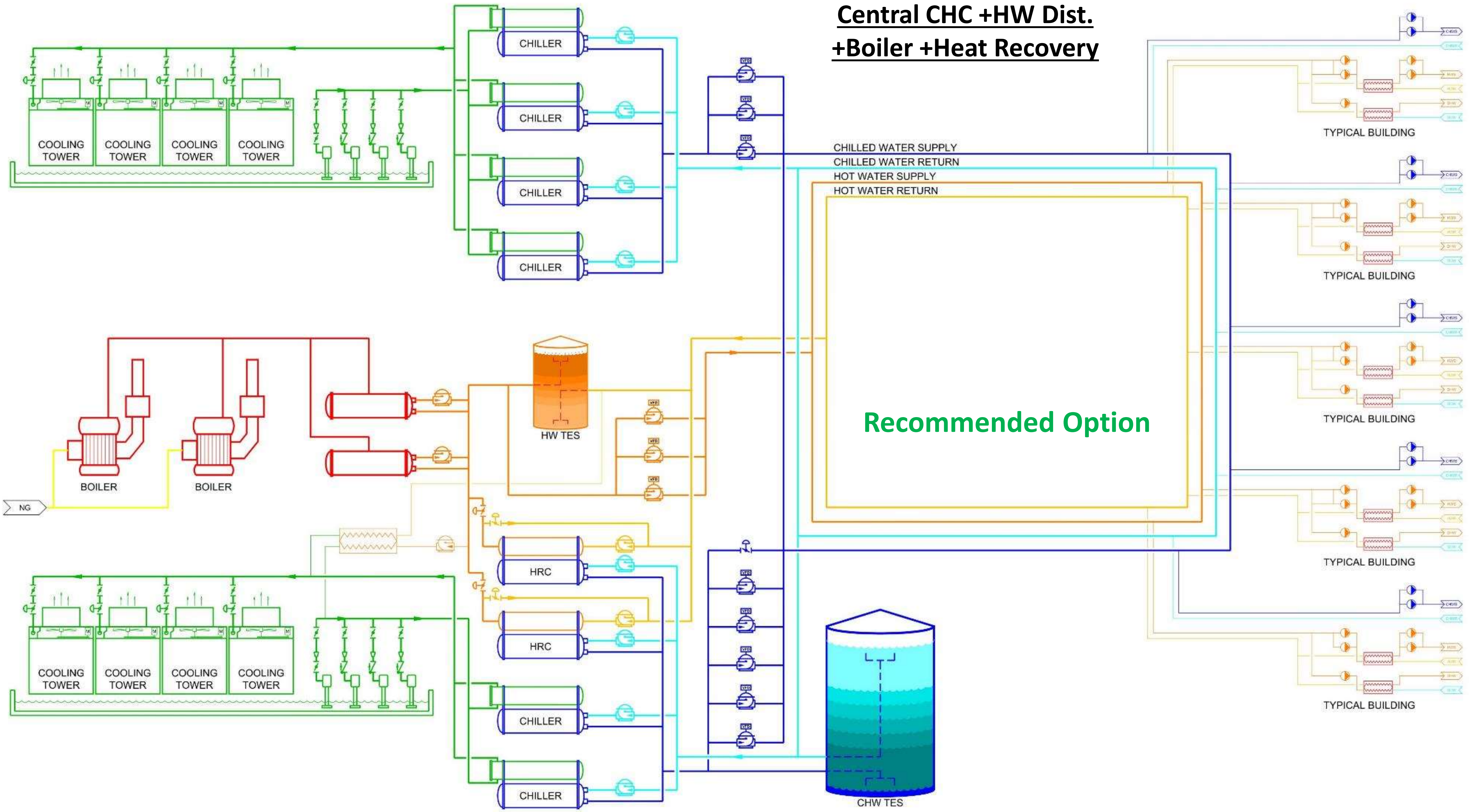
- Central Combined Heating and Cooling system with Hot Water distribution and Building Airside Heat Recovery
    - Lowest total net present cost
    - Most efficient
    - Most flexibility of heating sources
        - Option to add geo-exchange or air-source heat pumps later for full electrification
    - Less cost risk than distributed system
    - Less maintenance intensive than distributed system
    - Less impact to the existing electrical infrastructure
    - More robust equipment than distributed system


Combined Heating and Cooling with Building Airside Heat Recovery - Annual Profile
CHC Heating (Mbtu)
HR Heating (Mbtu)
Boiler Heating (Mbtu)
CHC Cooling (Mbtu)
False Cooling (Mbtu)
Conventional Cooling (Mbtu)
Millions
80
60
40
20
-
(20)
(40)
(60)
(80)
(100)
Cooling Demand:
45% CHC
55% Conventional
15% False Cooling
Recommended Option
13
11
(15)
(18)
(65)
12
18
(25)
(17)
(49)
14
19
(27)
(20)
(48)
31
25
(35)
(35)
45
17
(23)
(23)
62
10
(14)
(14)
65
10
(14)
(14)
57
11
(16)
(16)
52
18
(25)
(25)
32
25
(36)
(36)
13
19
(27)
(18)
(49)
12
10
(14)
(17)
(76)
Heating Demand:
60% CHC
20% Building Airside Heat Recovery
20% Boiler Heating (Replaced by geo-exchange/air-source heat pump system with future enhancement)
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
DEC

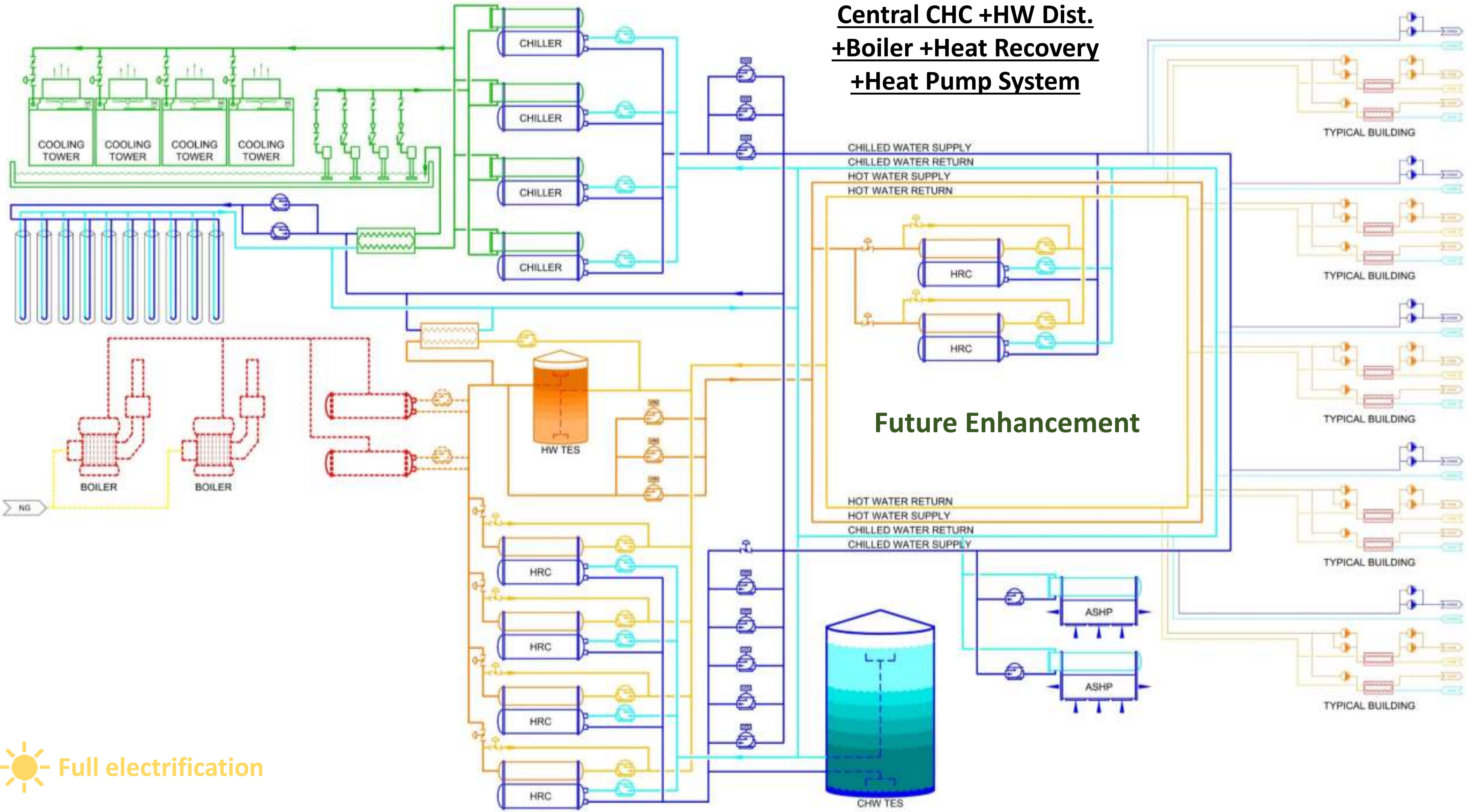
Existing Steam



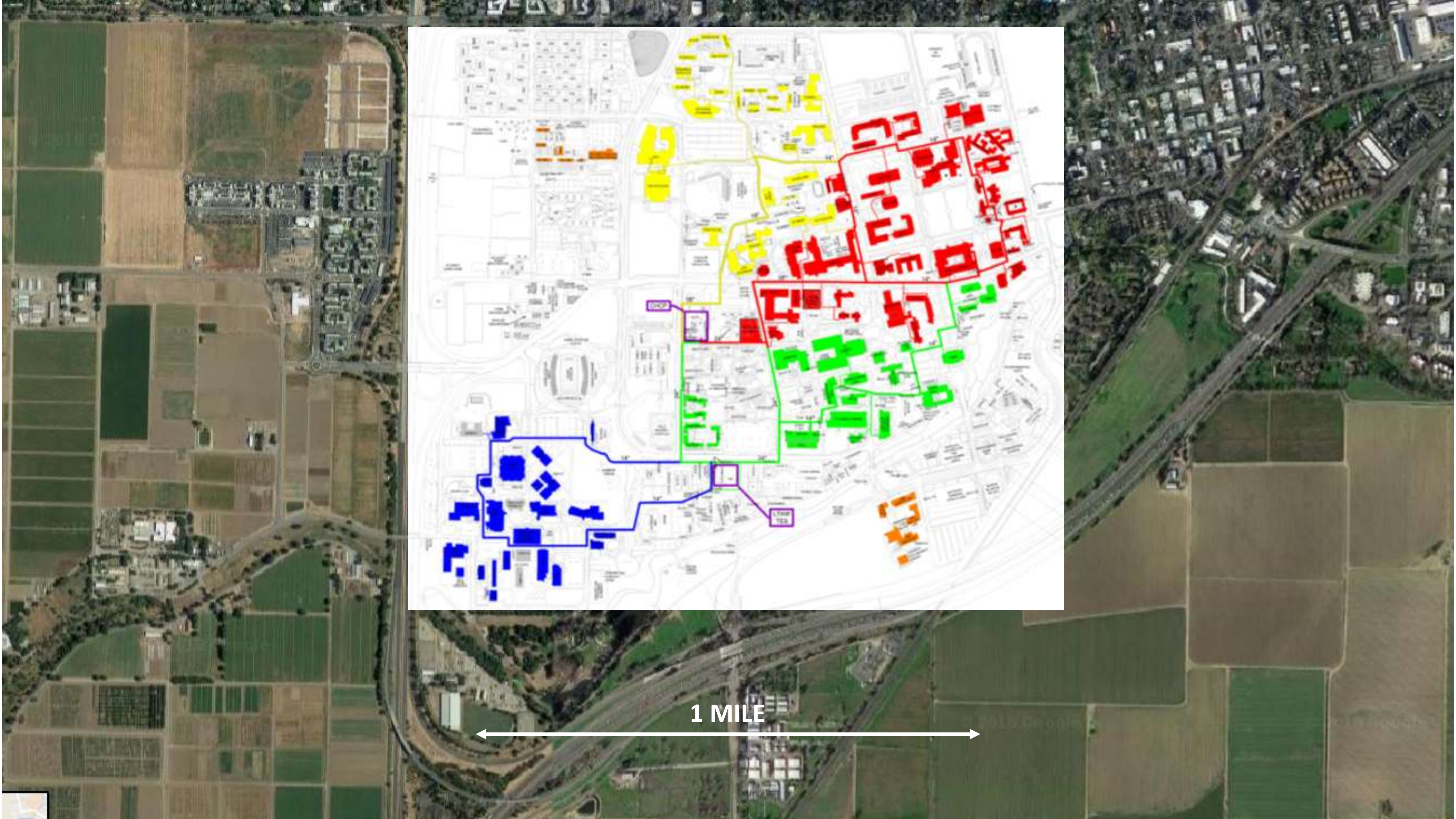
Central CHC +HW Dist. +Boiler +Heat Recovery



Central CHC +HW Dist. +Boiler +Heat Recovery +Heat Pump System



Full electrification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Questions?

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