Supplemental information for: Unlocking demand response in commercial buildings: Empirical response of commercial buildings to daily cooling set point adjustments

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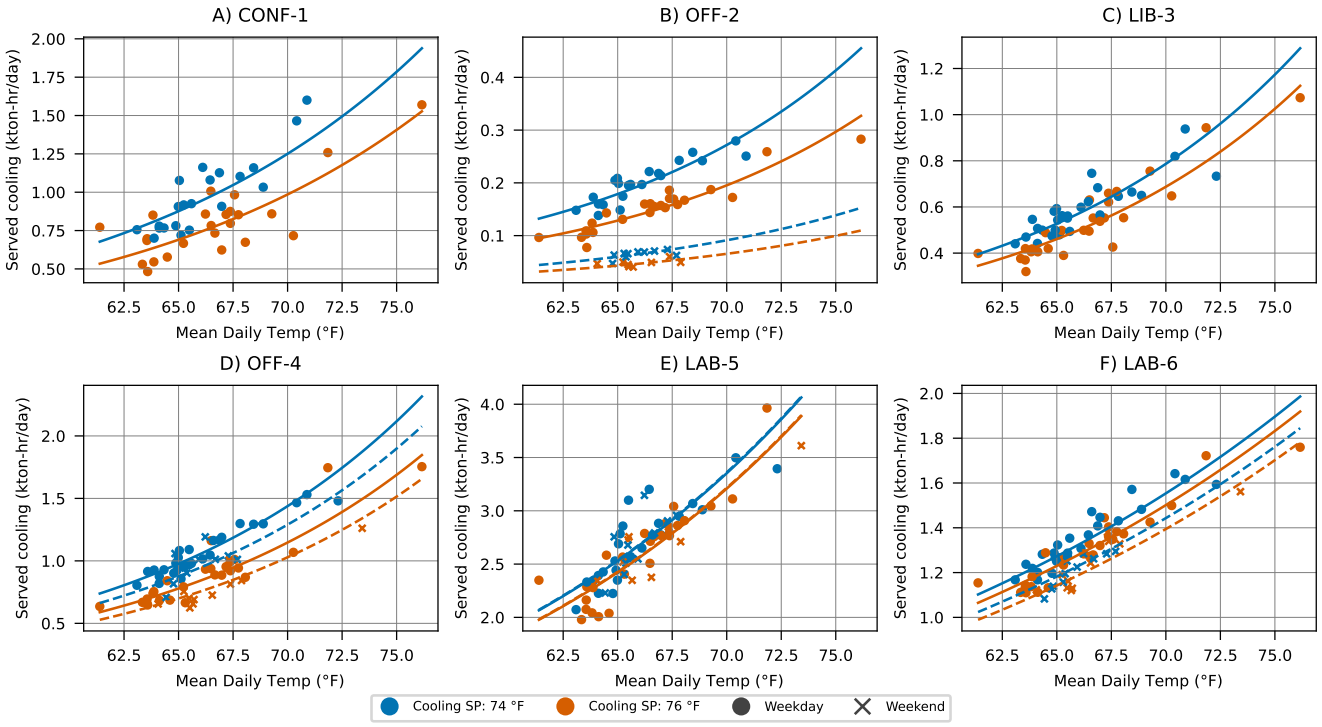
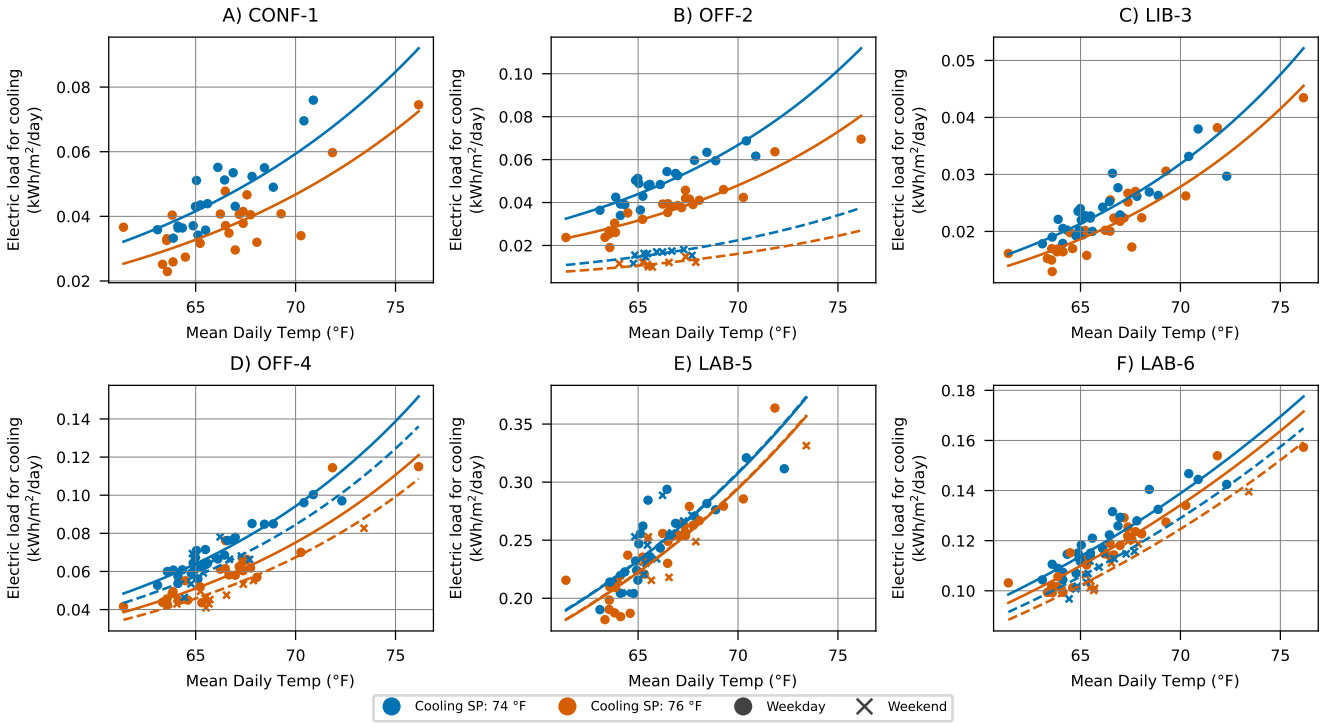
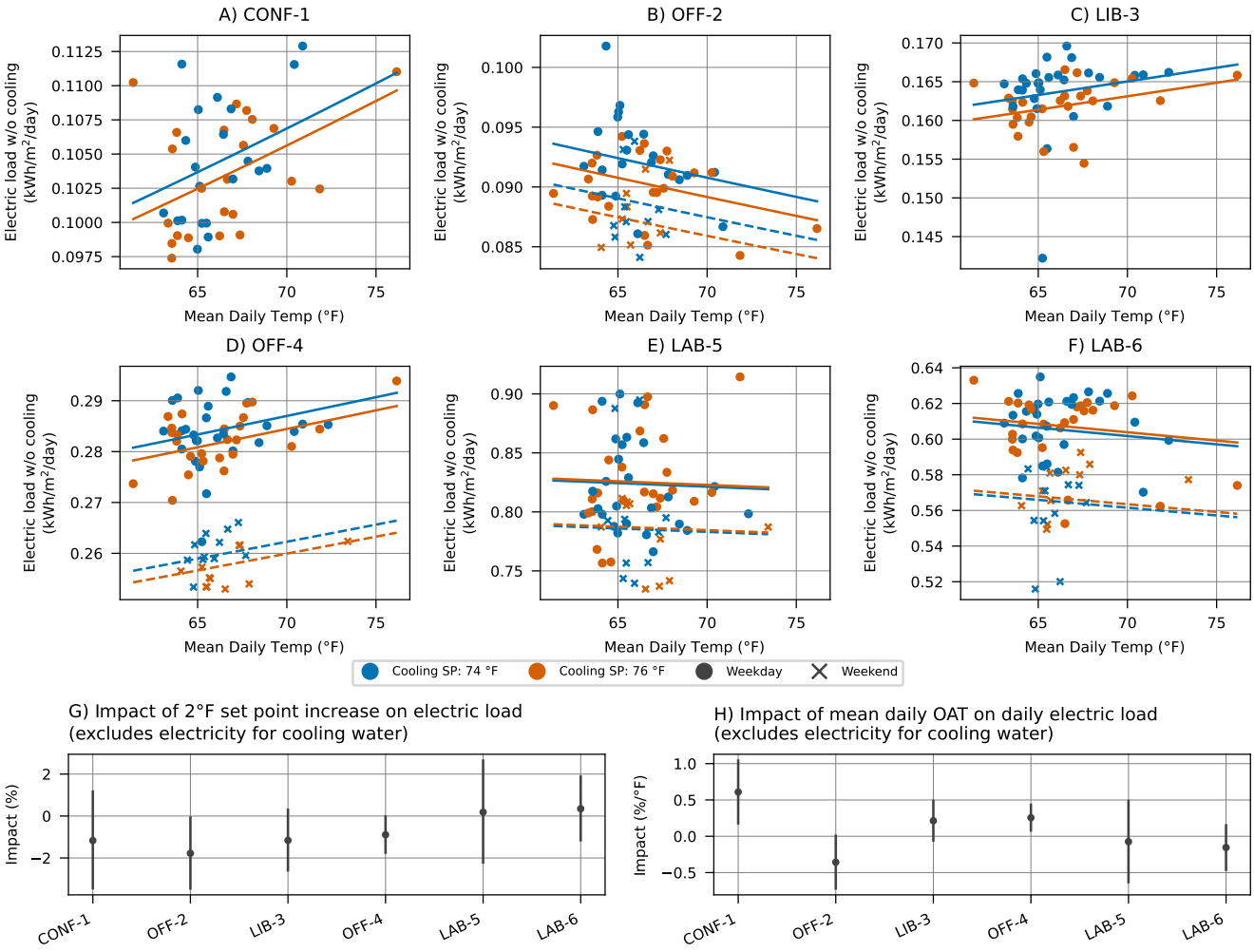
1 Supplemental tables and figures



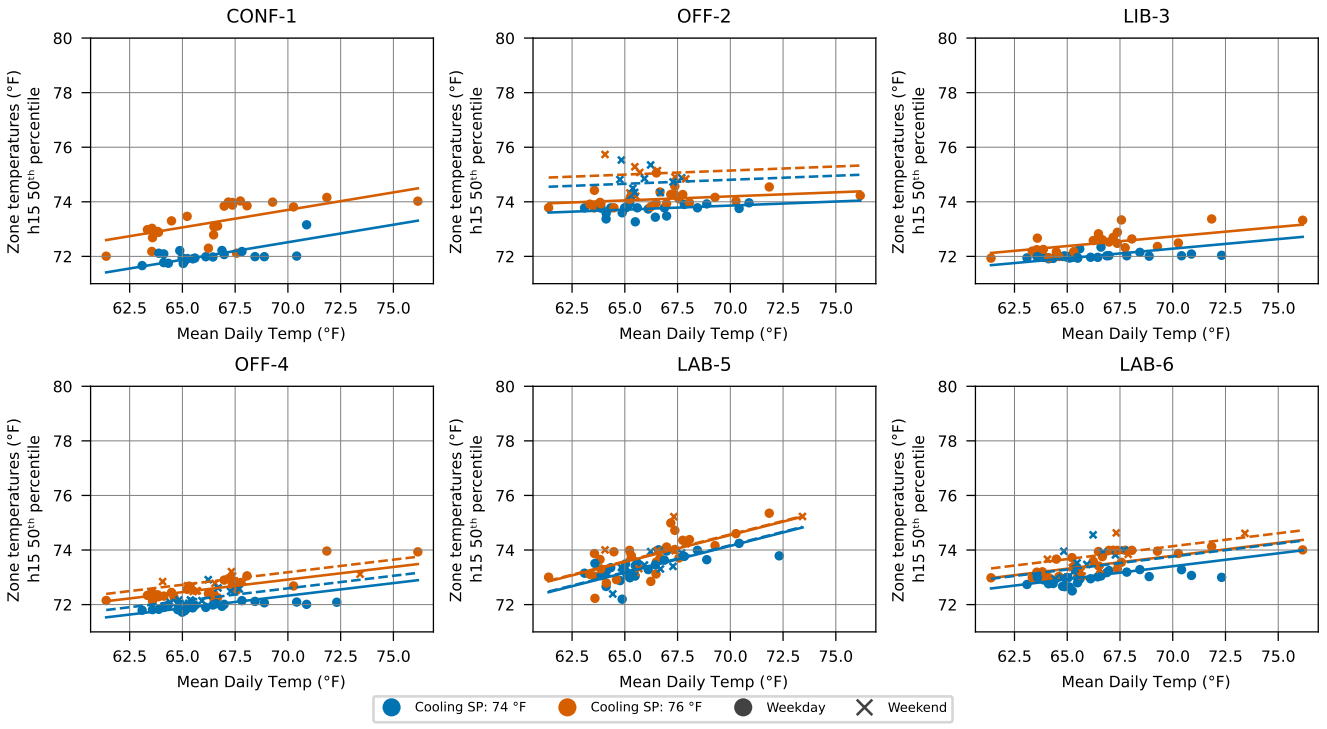
Supplementary Figure 1: Figure 2 in kton-hr/day. A ton-hour is a unit of energy commonly used in the HVAC industry, equivalent to 12.66 MJ.



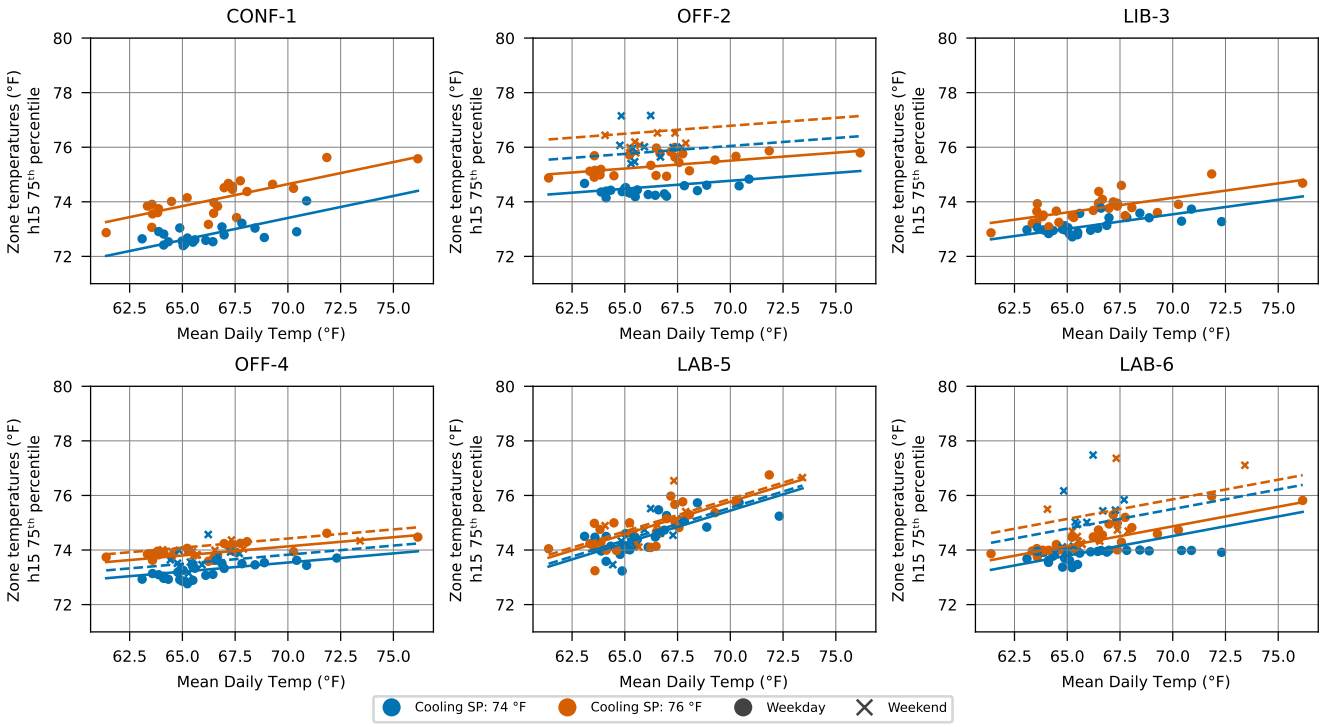
Supplementary Figure 2: Experiment results: electric load for cooling (kWh/m^2/day), assuming chillers with a COP of 5.5. Cooling data are shown in Figure 2.



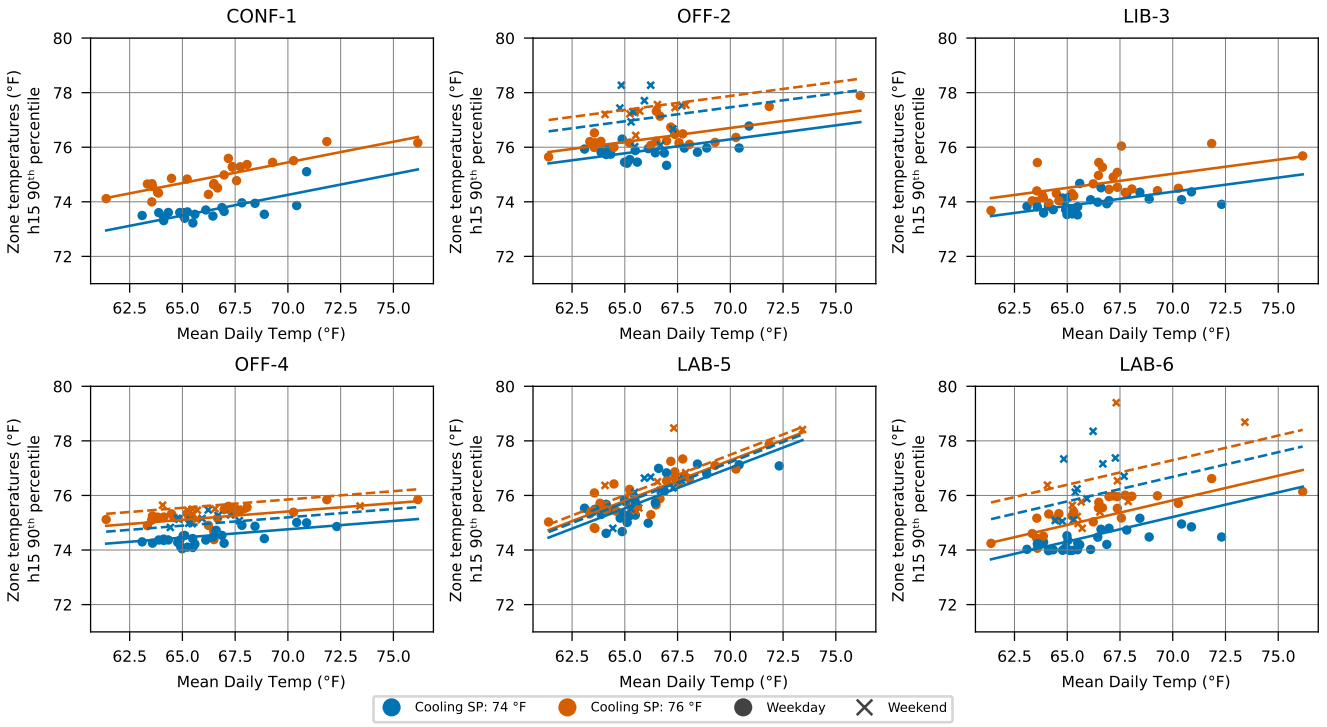
Supplementary Figure 3: Experiment results: electricity loads (excluding for cooling water). (a) Daily electricity as a function of mean daily temperatures of the cooling set points. Empirical data collected during the summer of 2021 and log model from equation 1. (b) Measured effect of OAT and set point change on electricity. Numerical results are reported in Table S2.



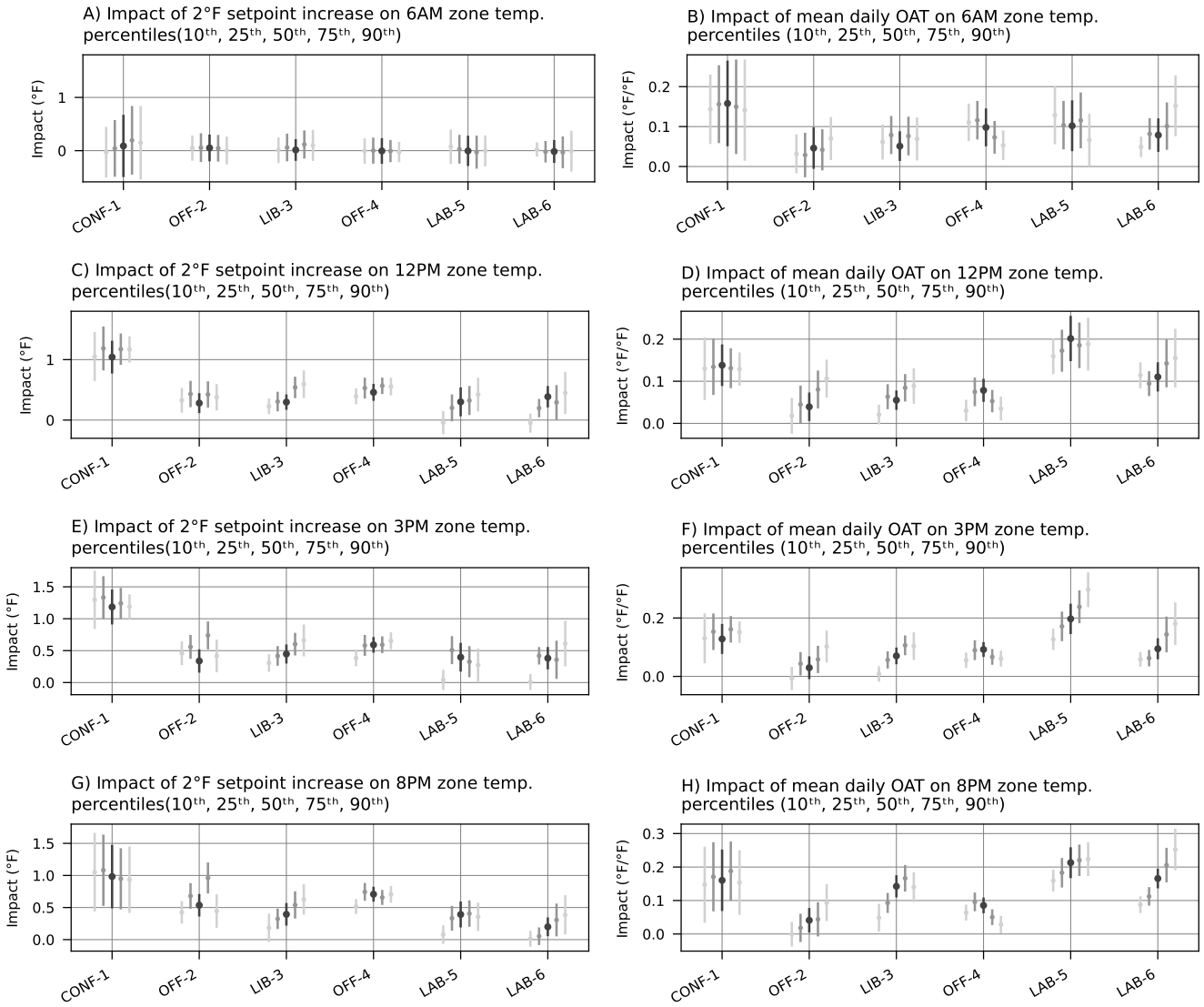
Supplementary Figure 4: Room temperature results: T_{50} at 3pm.



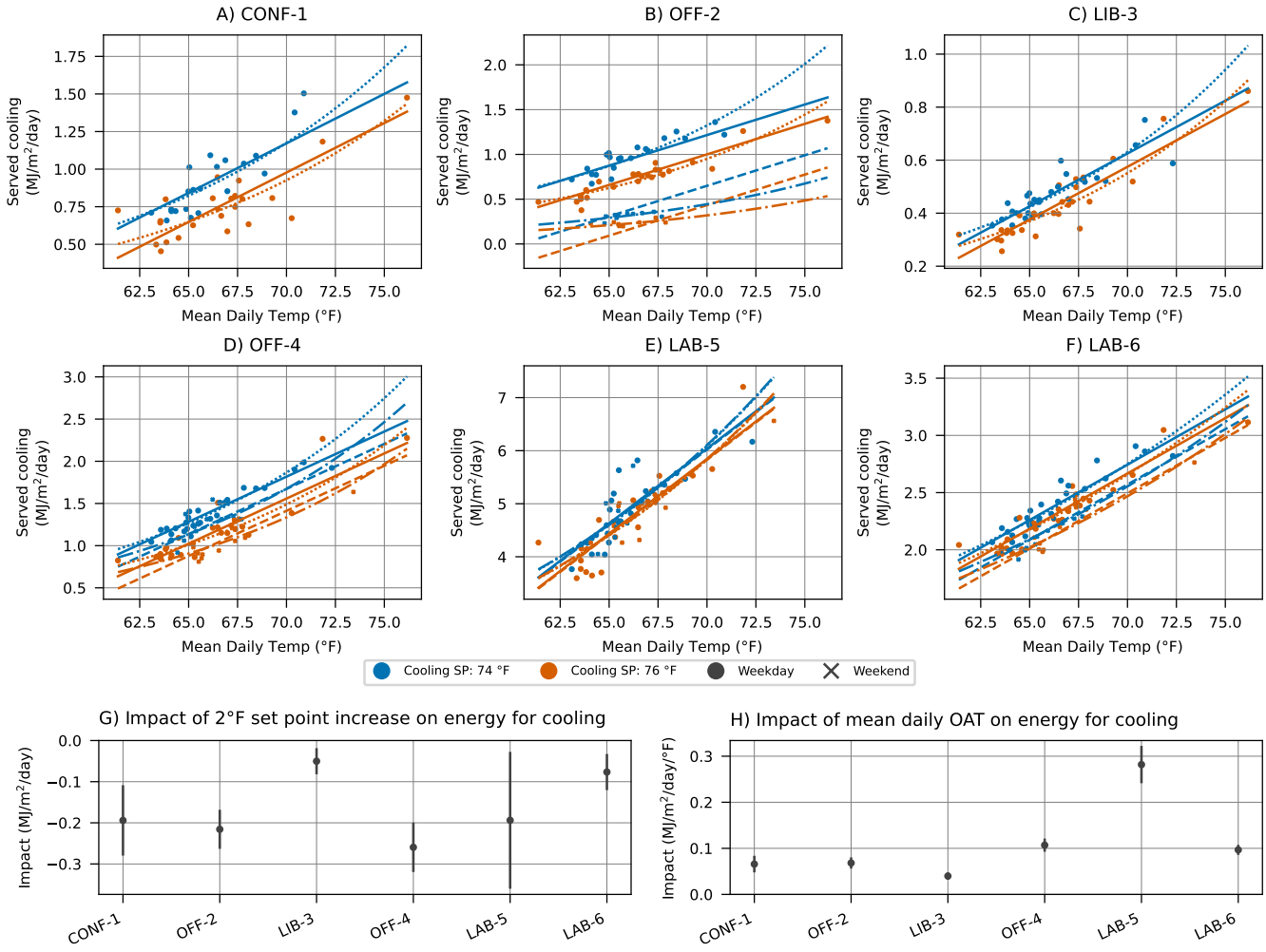
Supplementary Figure 5: Room temperature results: T_{75} at 3pm.



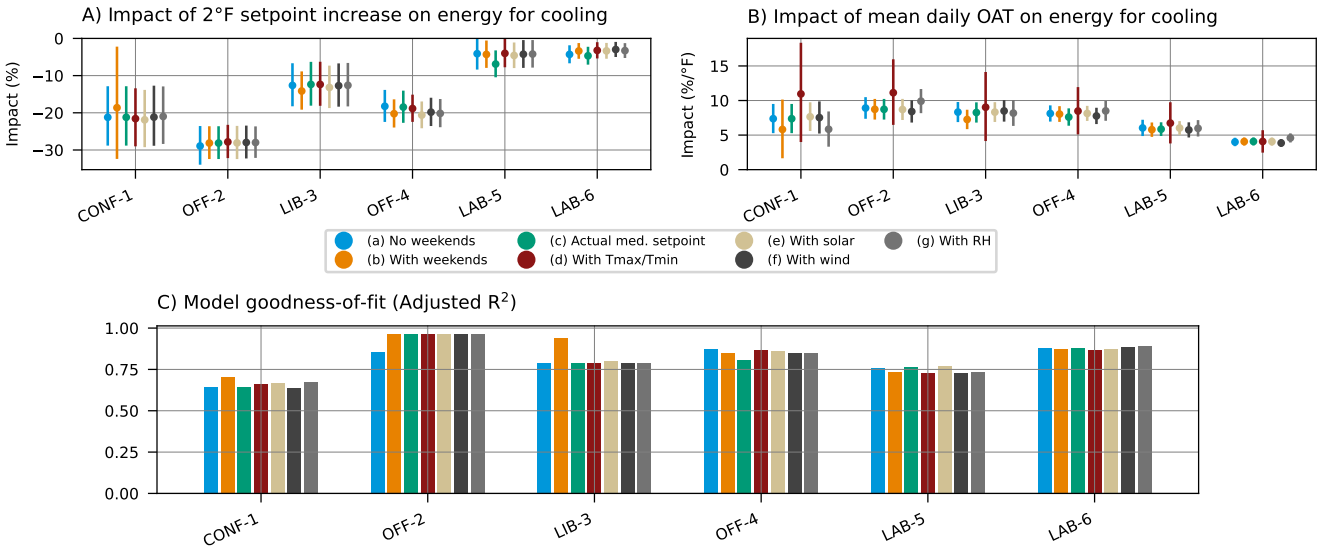
Supplementary Figure 6: Room temperature results: T_{90} at 3pm.



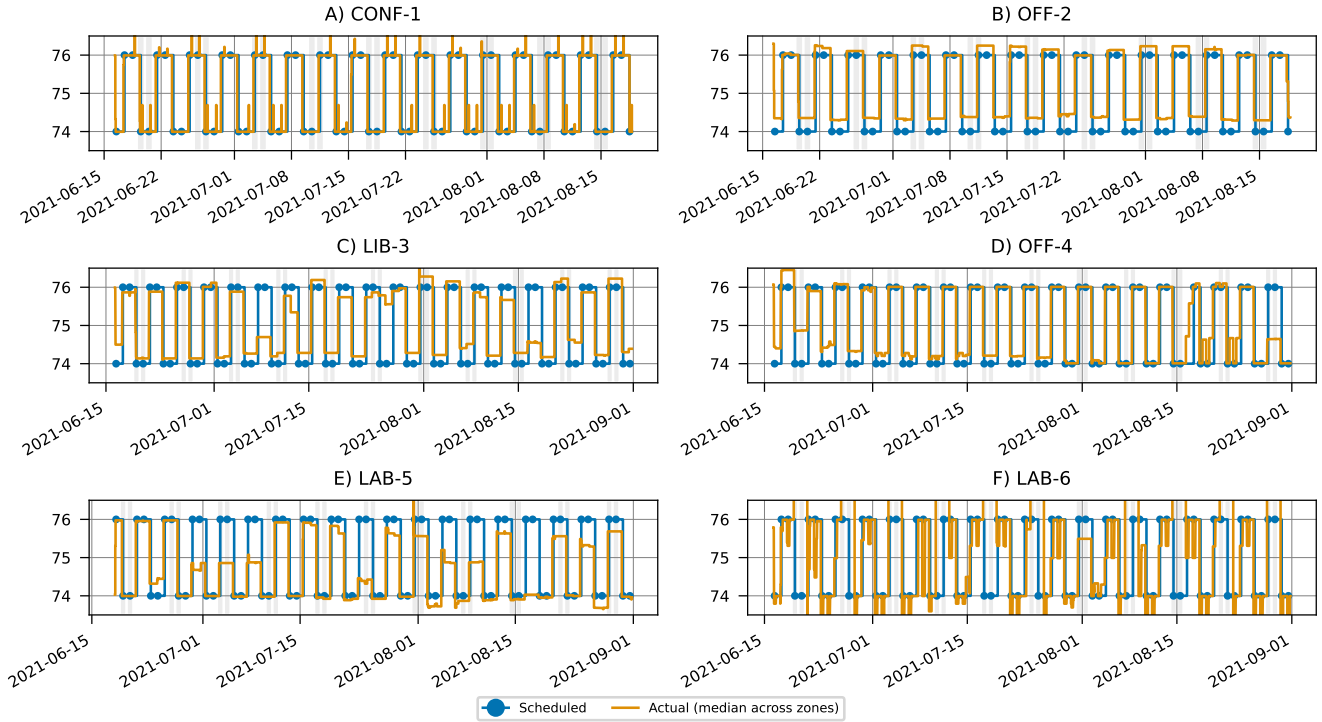
Supplementary Figure 7: The measured effects of OAT and set point change on zone temperature percentiles at different hours of the day.



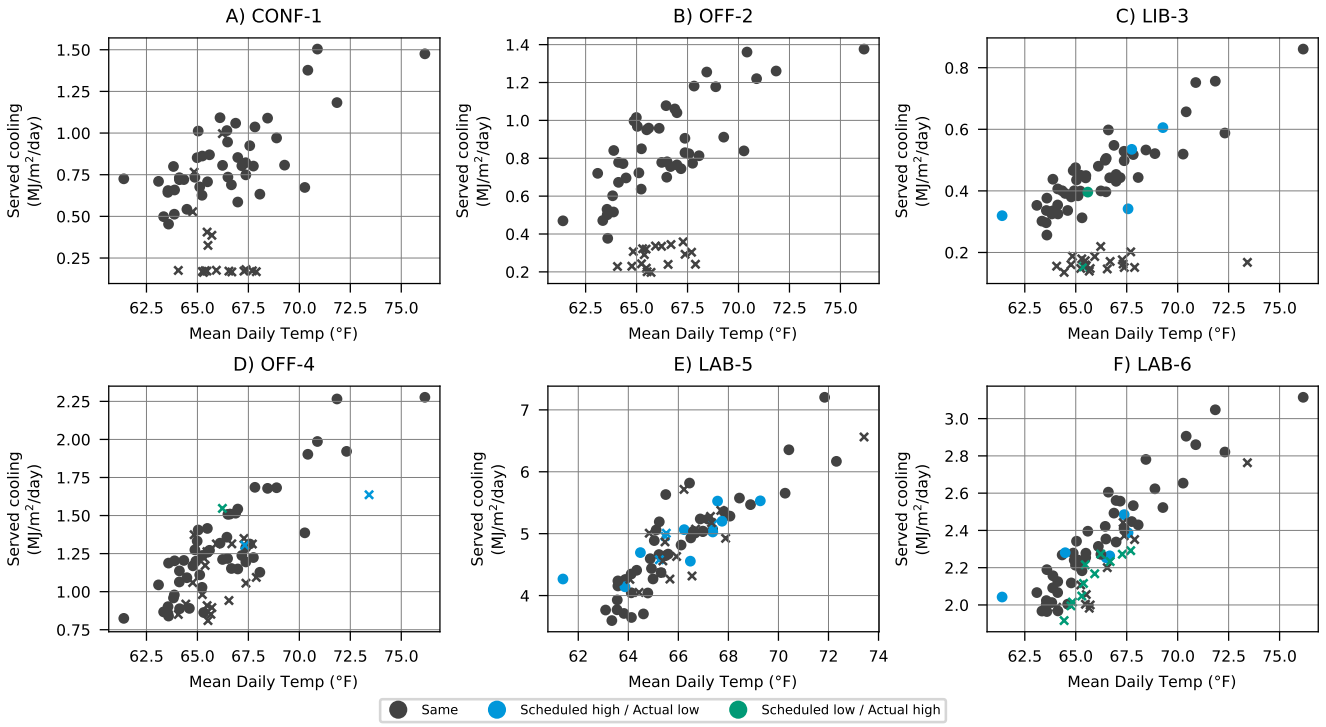
Supplementary Figure 8: Comparison of linear and logarithmic models for cooling loads (MJ/m^2/day). Numerical results for the linear models are presented in Table S6. Numerical results for the logarithmic models are presented in Table 2.



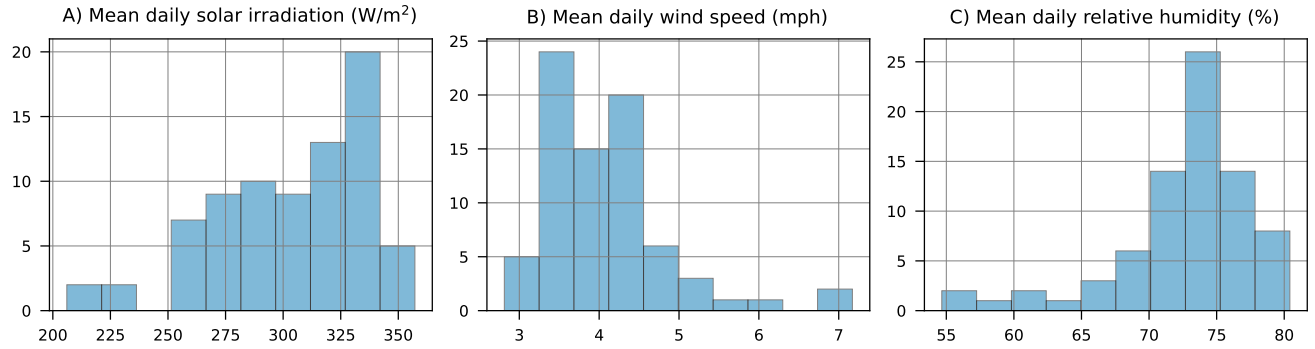
Supplementary Figure 9: Sensitivity of cooling load results to model specification.



Supplementary Figure 10: Comparison of actual and scheduled set points (timeseries data).



Supplementary Figure 11: Comparison of actual and scheduled set points during the experiments (scatterplot of cooling load as a function of mean daily OAT).



Supplementary Figure 12: Summary histograms for solar irradiation, wind speed and relative humidity during the experimentation period.

	CONF-1	**OFF-2**	**LIB-3**	**OFF-4**	**LAB-5**	**LAB-6**
CLASS LABS	0.0	11.8	6.1	20.2	19.6	29.7
CLASSROOMS	0.0	0.0	8.3	3.6	3.0	0.0
GENERAL USE FACILITIES	9.7	0.7	6.3	2.3	0.3	2.9
LIBRARY FACILITIES	0.5	0.0	30.7	0.0	0.0	0.0
OFFICES	26.7	42.3	13.3	31.4	36.1	30.5
SUPPORT FACILITIES	2.7	0.2	5.2	2.0	1.4	7.7
UNASSIGNABLE AREAS	60.4	44.9	29.9	39.5	39.6	29.2

Supplementary Table 1: Percentage of floor space in each building for different floor space types. The laboratory spaces in LAB-5 and LAB-6 contain equipment that is expected to draw significantly more cooling from process chilled water loops than those in OFF-4.

	CONF-1	OFF-2	LIB-3	OFF-4	LAB-5	LAB-6
Number of observations	45	63	54	75	72	76
R^2	0.662	0.964	0.799	0.853	0.744	0.878
Prob (F-statistic)	1.25e-10	2.30e-42	1.63e-18	1.63e-29	4.59e-20	9.23e-33

	CONF-1			OFF-2			LIB-3		
	Value	Std. Err	P-Value	Value	Std. Err	P-Value	Value	Std. Err	P-Value
SP (Treatment)	-0.24	0.048	1.2e-05	-0.33	0.028	5.1e-17	-0.14	0.031	6.4e-05
OAT	0.071	0.0089	5.5e-10	0.084	0.006	2.6e-20	0.08	0.0058	8.9e-19
Weekend	-	-	-	-1.1	0.031	3.9e-41	-	-	-
Intercept	-4.8	0.59	3.1e-10	-5.6	0.4	2e-20	-6.1	0.39	3.5e-21

	OFF-4			LAB-5			LAB-6		
	Value	Std. Err	P-Value	Value	Std. Err	P-Value	Value	Std. Err	P-Value
SP (Treatment)	-0.23	0.022	5.1e-16	-0.044	0.017	0.014	-0.034	0.0092	0.00035
OAT	0.077	0.0044	1.6e-27	0.056	0.004	1.5e-21	0.04	0.0019	5.7e-33
Weekend	-0.11	0.024	1.9e-05	0.0023	0.019	0.91	-0.074	0.01	2.6e-10
Intercept	-4.8	0.29	6.9e-26	-2.1	0.27	2.4e-11	-1.8	0.12	5.6e-23

Supplementary Table 2: Additional numerical data for the models shown in Figure 2 (cooling).

	CONF-1	OFF-2	LIB-3	OFF-4	LAB-5	LAB-6
Number of observations	44	62	53	74	71	75
R^2	0.177	0.276	0.089	0.841	0.161	0.499
Prob (F-statistic)	0.0185	0.000291	0.0973	6.96e-28	0.00803	1.10e-10

	CONF-1			OFF-2			LIB-3		
	Value	Std. Err	P-Value	Value	Std. Err	P-Value	Value	Std. Err	P-Value
SP (Treatment)	-0.012	0.012	0.32	-0.018	0.0086	0.041	-0.012	0.0073	0.12
OAT	0.0061	0.0021	0.0066	-0.0036	0.0018	0.054	0.0021	0.0014	0.12
Weekend	-	-	-	-0.037	0.0095	0.00024	-	-	-
Intercept	-2.7	0.14	7.1e-22	-2.1	0.12	3.2e-25	-2	0.09	3.9e-27

	OFF-4			LAB-5			LAB-6		
	Value	Std. Err	P-Value	Value	Std. Err	P-Value	Value	Std. Err	P-Value
SP (Treatment)	-0.0089	0.0044	0.044	0.0019	0.012	0.88	0.0035	0.0076	0.65
OAT	0.0026	0.00088	0.0051	-0.00074	0.0028	0.79	-0.0016	0.0015	0.31
Weekend	-0.09	0.0048	3e-29	-0.048	0.014	0.00075	-0.069	0.0083	4e-12
Intercept	-1.4	0.058	5.8e-36	-0.15	0.18	0.43	-0.4	0.1	0.00019

Supplementary Table 3: Additional numerical results for models shown in Figure S3 (electricity excluding for cooling water).

	CONF-1	OFF-2	LIB-3	OFF-4	LAB-5	LAB-6
Number of observations	44	62	53	74	71	75
R^2	0.615	0.928	0.588	0.864	0.271	0.593
Prob (F-statistic)	3.20e-09	5.19e-33	2.38e-10	2.98e-30	9.00e-05	7.14e-14

	CONF-1			OFF-2			LIB-3		
	Value	Std. Err	P-Value	Value	Std. Err	P-Value	Value	Std. Err	P-Value
SP (Treatment)	-0.075	0.019	0.00029	-0.098	0.01	2.8e-13	-0.025	0.0083	0.0041
OAT	0.026	0.0035	5.2e-09	0.023	0.0022	3.4e-15	0.012	0.0015	1.7e-10
Weekend	-	-	-	-0.27	0.012	4e-31	-	-	-
Intercept	-3.6	0.23	8.7e-19	-3.5	0.15	8.6e-32	-2.5	0.1	2.4e-29

	OFF-4			LAB-5			LAB-6		
	Value	Std. Err	P-Value	Value	Std. Err	P-Value	Value	Std. Err	P-Value
SP (Treatment)	-0.047	0.0061	7.2e-11	-0.0082	0.012	0.51	-0.0024	0.0069	0.73
OAT	0.017	0.0012	5.3e-22	0.013	0.0029	3.8e-05	0.0055	0.0014	0.00016
Weekend	-0.095	0.0066	1.8e-22	-0.037	0.014	0.0098	-0.07	0.0075	4.8e-14
Intercept	-2.2	0.082	2e-38	-0.77	0.19	0.00013	-0.69	0.092	1.4e-10

Supplementary Table 4: Additional numerical data for models shown in Figure 3 (electricity results with cooling).

	CONF-1	OFF-2	LIB-3	OFF-4	LAB-5	LAB-6
Number of observations	45	63	54	75	72	76
R^2	0.712	0.693	0.657	0.723	0.533	0.572
Prob (F-statistic)	4.42e-12	3.83e-15	1.43e-12	9.17e-20	2.84e-11	2.83e-13

	CONF-1			OFF-2			LIB-3		
	Value	Std. Err	P-Value	Value	Std. Err	P-Value	Value	Std. Err	P-Value
SP (Treatment)	1	0.13	4.8e-10	0.35	0.075	1.9e-05	0.37	0.054	1.1e-08
OAT	0.13	0.024	1.9e-06	0.04	0.016	0.015	0.07	0.01	8.7e-09
Weekend	-	-	-	0.88	0.083	2e-15	-	-	-
Intercept	63	1.6	8.1e-35	71	1.1	1.7e-57	67	0.67	3.4e-60

	OFF-4			LAB-5			LAB-6		
	Value	Std. Err	P-Value	Value	Std. Err	P-Value	Value	Std. Err	P-Value
SP (Treatment)	0.5	0.054	7e-14	0.32	0.099	0.0019	0.33	0.073	1.9e-05
OAT	0.087	0.011	2e-11	0.18	0.023	4e-11	0.11	0.015	4.5e-10
Weekend	0.28	0.059	9.8e-06	0.078	0.11	0.49	0.33	0.08	0.00011
Intercept	66	0.72	2e-75	61	1.5	5.3e-49	66	0.98	1.1e-66

Supplementary Table 5: Additional numerical data for models shown in Figure 4 (room temperatures).

	CONF-1	OFF-2	LIB-3	OFF-4	LAB-5	LAB-6
Number of observations	45	63	54	75	72	76
R^2	0.685	0.934	0.816	0.854	0.767	0.893
Prob (F-statistic)	3.00e-11	8.42e-35	1.67e-19	1.24e-29	1.90e-21	7.81e-35

	CONF-1			OFF-2			LIB-3		
	Value	Std. Err	P-Value	Value	Std. Err	P-Value	Value	Std. Err	P-Value
SP (Treatment)	-0.19	0.041	2.4e-05	-0.22	0.022	7.8e-14	-0.05	0.014	0.00097
OAT	0.066	0.0076	6.6e-11	0.068	0.0047	5.5e-21	0.04	0.0027	4.4e-20
Weekend	-	-	-	-0.57	0.025	3.6e-31	-	-	-
Intercept	-3.4	0.5	2.5e-08	-3.6	0.31	1.9e-16	-2.2	0.18	1.2e-16

	OFF-4			LAB-5			LAB-6		
	Value	Std. Err	P-Value	Value	Std. Err	P-Value	Value	Std. Err	P-Value
SP (Treatment)	-0.26	0.029	1.8e-13	-0.19	0.082	0.021	-0.077	0.021	0.00038
OAT	0.11	0.0058	1.3e-28	0.28	0.019	5.1e-23	0.097	0.0042	3.8e-35
Weekend	-0.15	0.031	1.5e-05	-0.017	0.091	0.85	-0.17	0.023	6.3e-11
Intercept	-5.7	0.39	3.3e-23	-14	1.3	1.2e-16	-4	0.28	3.3e-23

Supplementary Table 6: Additional numerical data for models shown in Figure S8 (alternate linear model for cooling).

Column name	Description	Unit
cooling	Whole building daily cooling consumption	MJ/m2
electricity	Whole building daily electricity consumption	kWh/m2
Tmean, Tmax, Tmin	Mean, maximum and minimum of daily outside air temperature	Fahrenheit
scheduled_sp	Scheduled setpoint (74 or 76)	Fahrenheit
actual_med_sp	We first compute the hourly median of the actual setpoint across zones. actual_med_sp is then the daily average value of median hourly setpoint between 8 am and 8pm	Fahrenheit
scheduled_sp_bin	Binary version of scheduled_sp (True when 76)	None
mean_zone_temp	We first compute the hourly average of the zone temperature across zones. mean_zone_temp is then the daily average value of this average zone temperature between 8 am and 8pm.	Fahrenheit
"{quantile}-h{hour}", "{quantile}-mean", "{quantile}-max"	We first compute the hourly percentiles of zone temperatures across zones (10th, 25th, 50th, 75th, 90th). Column 0.1-h0 is the value of the 10th percentile at hour 0. Column 0.1-mean is the average value of the 10th percentile taken between 8 am and 8 pm. Column 0.1-max is the maximum value of the 10th percentile taken between 8 am and 8 pm.	Fahrenheit

Supplementary Table 7: Data columns.

2 Code and data

A zip folder containing all code and data to reproduce the figures and tables listed in the following table is published with this paper. The zip folder contains one code folder and one data folder.

Data The data folder contains one CSV file per building, with daily data for that building. Data columns described in Table 7.

Code For each figure, see the corresponding Jupyter notebook referenced in Table 8. Running these figures requires a Python installation (Python 3.8 was used to develop the code) and the packages listed in the requirements.txt file. The packages can be installed using pip with the command "pip install -r requirements.txt".

3 Key energy statistics for the buildings sector

The numbers in Table S9 were used in the abstract and introduction and are all for 2018.

	Short title	**Notebook to regenerate**
Figure 2	Experiment results: energy for cooling.	Figure 2 Cooling results
Figure 3	Experiment results: electricity loads (including for cooling water).	Figure 3 Electricity results w cooling
Figure 4	Experiment results: zone temperatures.	Figure 4 Temperature results
Figure 5	Impact of growing number of observations on quality of estimates.	Figure 5 Expanding train set
Figure S1	Figure 2 in kton-hr/day.	Figure 2 Cooling results
Figure S2	Experiment results: electric load for cooling.	Figure 2 Cooling results
Figure S3	Experiment results: electricity loads (excluding for cooling water).	Figure S3 Electricity results wo cooling
Figure S3	Impacts on zone temperature percentiles at different hours of the day.	Figure S3 Hourly temperature impacts
Figure S4	Sensitivity of cooling results to model specification.	Figure 2 Cooling results
Figure S5	Comparison of linear and logarithmic models for cooling loads.	Figure 2 Cooling results
Table S2	Additional numerical results for Figure 2.	Figure 2 Cooling results
Table S3	Additional numerical results for Figure S3.	Figure S3 Electricity results wo cooling
Table S4	Additional numerical results for Figure 3.	Figure 3 Electricity results w cooling
Table S5	Additional numerical results for Figure 4.	Figure 4 Temperature results
Table S6	Additional numerical results for Figure S8.	Figure 2 Cooling results

Supplementary Table 8: Jupyter notebook needed to regenerate each figure and table.

Final energy consumption	414.5 EJ	[1]
Non residential buildings as share of total final energy use	8%	[2]
Residential buildings as share of total final energy use	22%	[2]
Buildings energy use	124.4 EJ	Calculated
Buildings electricity use	42.7 EJ	[3]
Cooling as share of energy use in buildings	6%	[4]
Cooling energy use in buildings	7.5 EJ	Almost all electricity according to Fig 1.8 in [4]
Cooling electricity use as share of building electricity	17.5%	Calculated
Cooling electricity use as share of building electricity	18.5%	[4]
Space heating and cooling	50 EJ	Fig 4 in [2]
Space heating and cooling as share of total energy use	12.1%	Calculated
Commercial space heating and cooling as share of total energy use	3.22%	Calculated (assumes commercial has same breakdown as residential)
Electricity consumption	80.9 EJ	[1]
Building electricity use as share of total	52.8%	Calculated
Cooling electricity use as share of total electricity use	9.2%	Calculated
Commercial cooling as share of total electricity use	2%	Calculated

Supplementary Table 9: Key building energy statistics.

References

[1] International Energy Agency, IEA Sankey diagram - World Final Consumption, available at: https://www.iea.org/sankey/ (2022).

[2] IEA, Global status report for buildings and construction 2019, Tech. rep., IEA, Paris (2019).

[3] International Energy Agency, Tracking Buildings 2021, available at: https://www.iea.org/reports/tracking-buildings-2 (2021).

[4] IEA, The future of cooling - opportunities for energy-efficient air conditioning, Tech. rep., IEA, Paris (2018).