BUILDINGENERGY BOSTON

Thermal Resilience as a Retrofit Metric

Al Mitchell (Phius)

Curated by Tristan Grant (MaGrann Associates)

Northeast Sustainable Energy Association (NESEA) | March 19, 2024

Thermal Resilience As A Retrofit Metric

Al Mitchell
NESEA
March 19, 2024

Outline

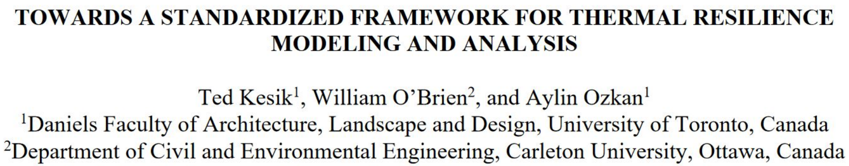
- Define Thermal Resilience
- Metrics
- Strategies
- Modeling protocol
- Graphs
- Conclusions

What is Thermal Resilience?

Literature Review

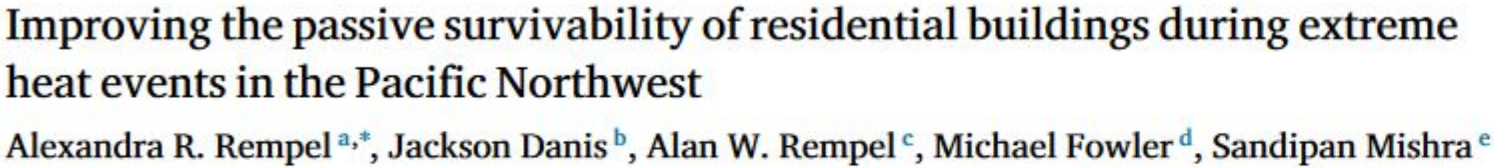
Evaluating thermal resilience of building designs using building performance simulation – A review of existing practices

Chun Yin Siu[a,*], William O'Brien[b], Marianne Touchie[a,c], Marianne Armstrong[d], Abdelaziz Laouadi[d], Abhishek Gaur[d], Zahra Jandaghian[d], Iain Macdonald[d]



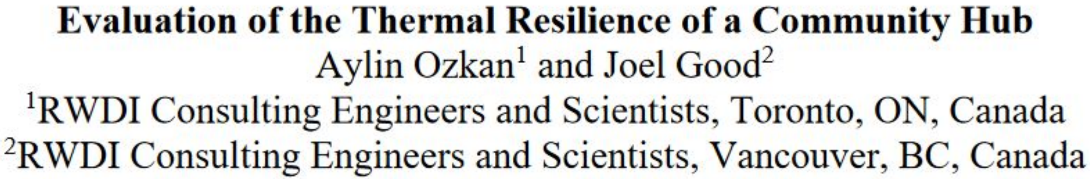
TOWARDS A STANDARDIZED FRAMEWORK FOR THERMAL RESILIENCE MODELING AND ANALYSIS

Ted Kesik[1], William O'Brien[2], and Aylin Ozkan[1]
[1]Daniels Faculty of Architecture, Landscape and Design, University of Toronto, Canada
[2]Department of Civil and Environmental Engineering, Carleton University, Ottawa, Canada



Improving the passive survivability of residential buildings during extreme heat events in the Pacific Northwest

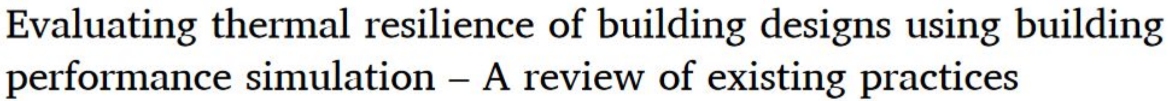
Alexandra R. Rempel[a,*], Jackson Danis[b], Alan W. Rempel[c], Michael Fowler[d], Sandipan Mishra[e]



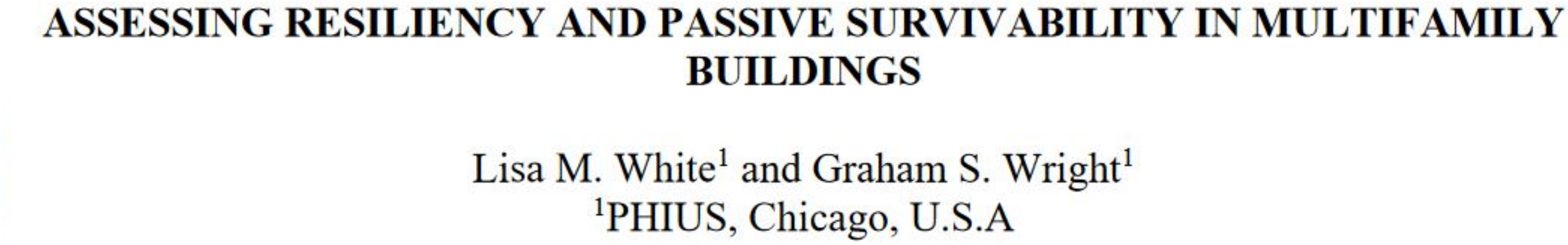
Evaluation of the Thermal Resilience of a Community Hub

Aylin Ozkan[1] and Joel Good[2]
[1]RWDI Consulting Engineers and Scientists, Toronto, ON, Canada
[2]RWDI Consulting Engineers and Scientists, Vancouver, BC, Canada

Literature Review

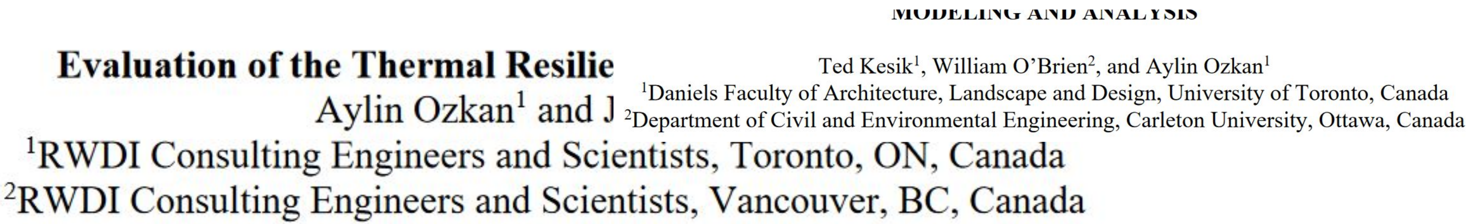


Evaluating thermal resilience of building designs using building performance simulation – A review of existing practices



ASSESSING RESILIENCY AND PASSIVE SURVIVABILITY IN MULTIFAMILY BUILDINGS

Lisa M. White[1] and Graham S. Wright[1]
[1]PHIUS, Chicago, U.S.A



MODELING AND ANALYSIS

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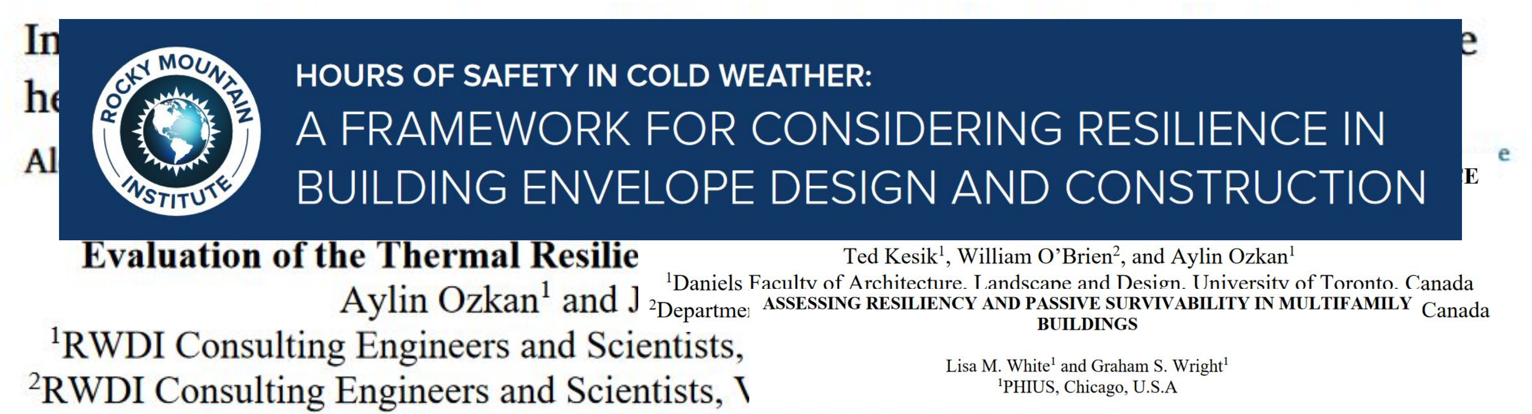

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HOURS OF SAFETY IN COLD WEATHER:

A FRAMEWORK FOR CONSIDERING RESILIENCE IN BUILDING ENVELOPE DESIGN AND CONSTRUCTION

Evaluation of the Thermal Resilie

Aylin Ozkan[1] and J

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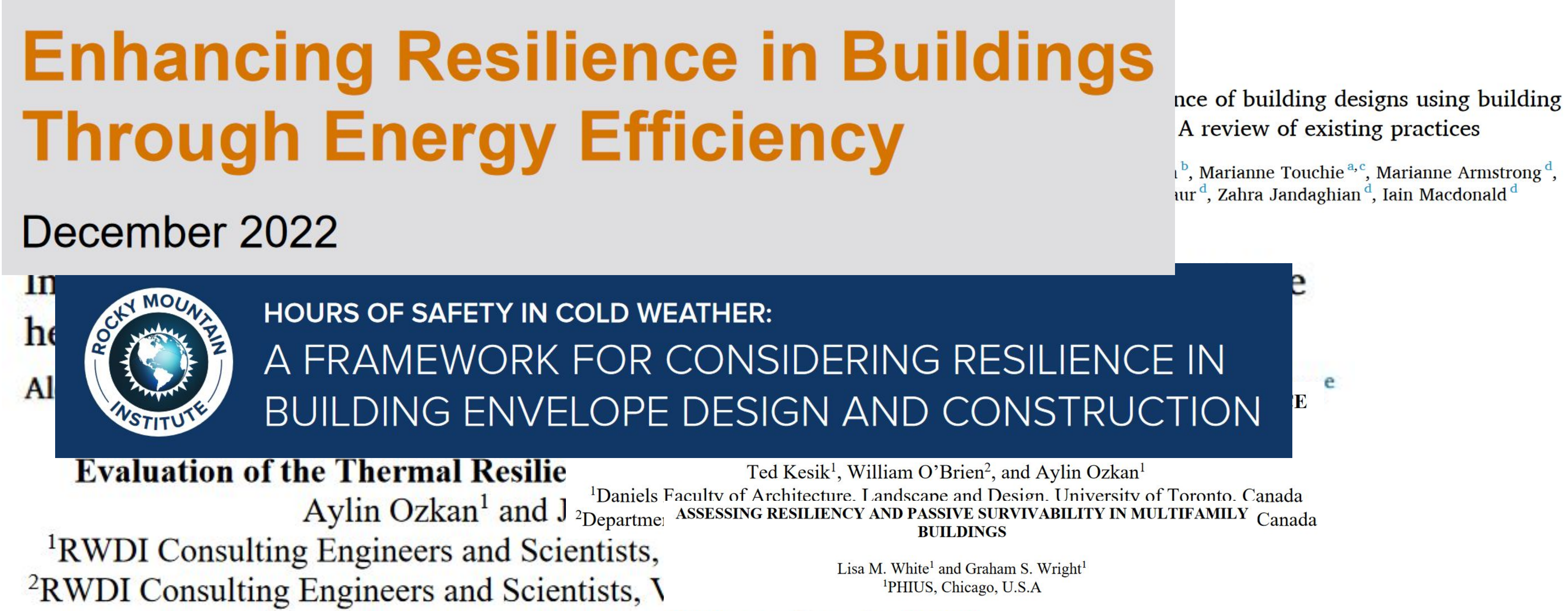

Enhancing Resilience in Buildings Through Energy Efficiency

December 2022

nce of building designs using building
A review of existing practices

b, Marianne Touchie[a,c], Marianne Armstrong[d],
aur[d], Zahra Jandaghian[d], Iain Macdonald[d]

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ROCKY MOUNTAIN INSTITUTE

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LEED

Pilot-Credits IPpc100: *Passive Survivability and Back-up Power During Disruptions*

1. Option 1: Provide for Passive Survivability (thermal safety) (1 point)
2. Path 2: Standard Effective Temperature (SET)
3. Path 3: Passive House certification

Thermal Resilience

A building’s ability to remain at and/or to recover to a habitable state after a disruptive event (such as power outage) where mechanical equipment is not providing heating, cooling or ventilation.” (Siu et al., 2023)

A building’s ability to remain at and/or to recover to a habitable state after a disruptive event (such as power outage) where mechanical equipment is not providing heating, cooling or ventilation, although some critical loads may be met with local renewable generation and battery backup.

How do we MeasureThermal Resilience?

The Goal: Protect Occupants

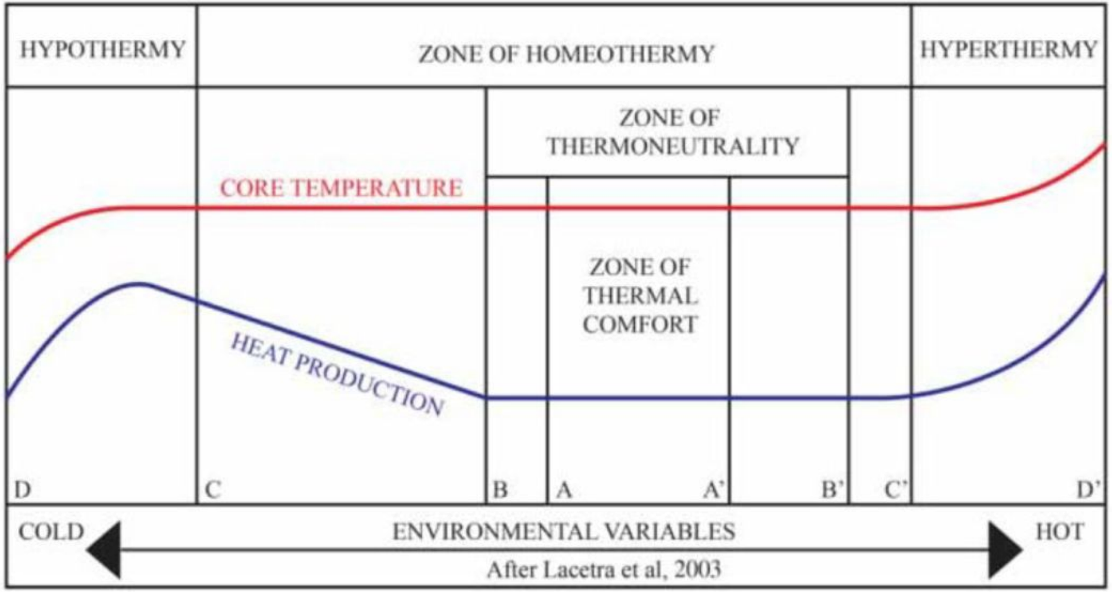


Figure 2a. Range of homeothermy (Holmes et al, 2016).

Winter Metrics

SET Hours [°F hr]

- Based on the Pierce Two Node comfort model
- Comprehensive of environmental conditions
  - Clo
  - Temperature (operative and DB)
  - Humidity
  - Wind speed
- Good for summer and winter

Limit: 216 °F hr

ASHRAE 55-2010 defines SET as “the temperature of an imaginary environment at 50% relative humidity, <0.1 m/s [0.33 ft/s] average air speed, and mean radiant temperature equal to average air temperature, in which total heat loss from the skin of an imaginary occupant with an activity level of 1.0 met and a clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level”

Winter Metrics

Hours below 2°C (35.6°F) [hr]

- Simple dry bulb calculation
- Limits freezing
  - Health risks
  - Infrastructure damage

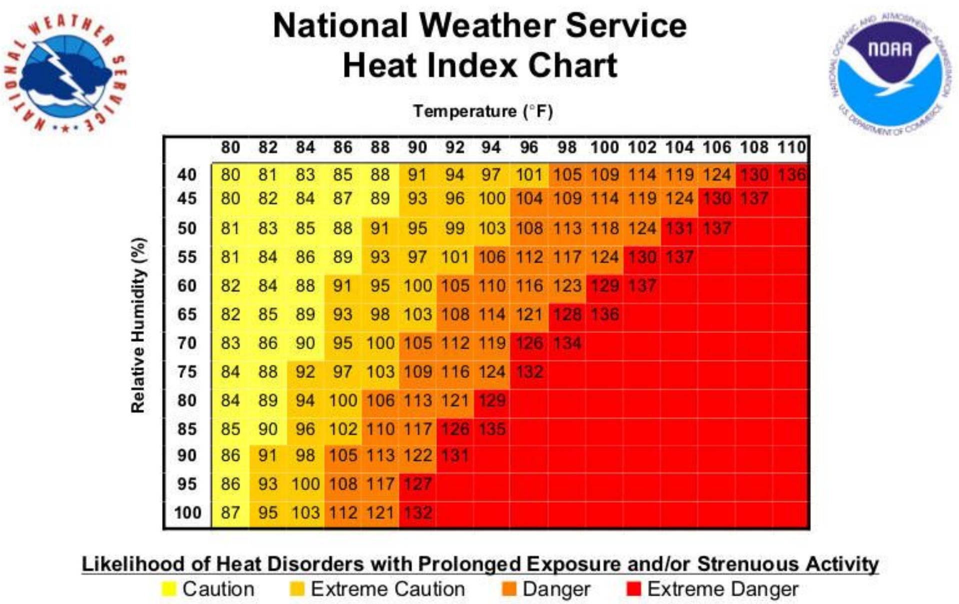
Limit: 0 hr

Summer Metrics

Heat Index [°F]

- Commonly recognized
- Dry bulb + Humidity

Limit: Advisory



National Weather Service
Heat Index Chart

Temperature (°F)

Relative Humidity (%)

	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure and/or Strenuous Activity

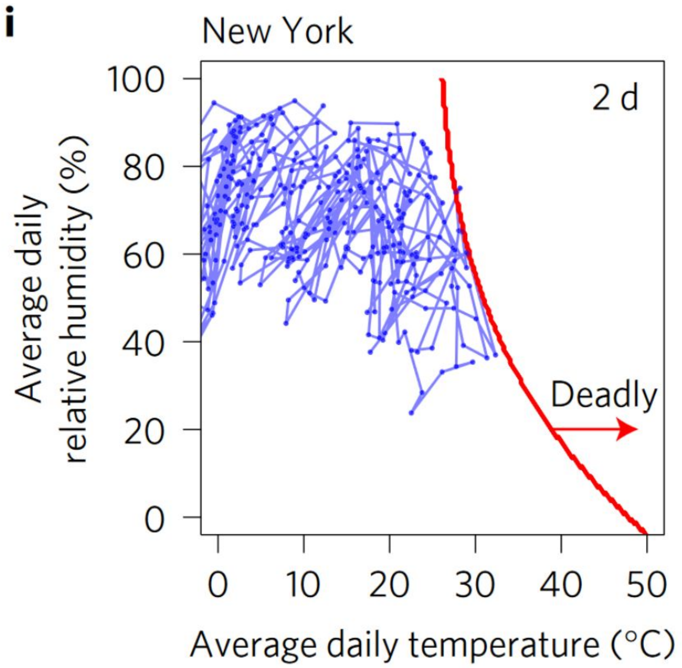
🟨 Caution 🟧 Extreme Caution 🟧 Danger 🟥 Extreme Danger

Summer Metrics

Mora Deadly Day [day]

- Based on epidemiological studies
- Dry bulb + Humidity

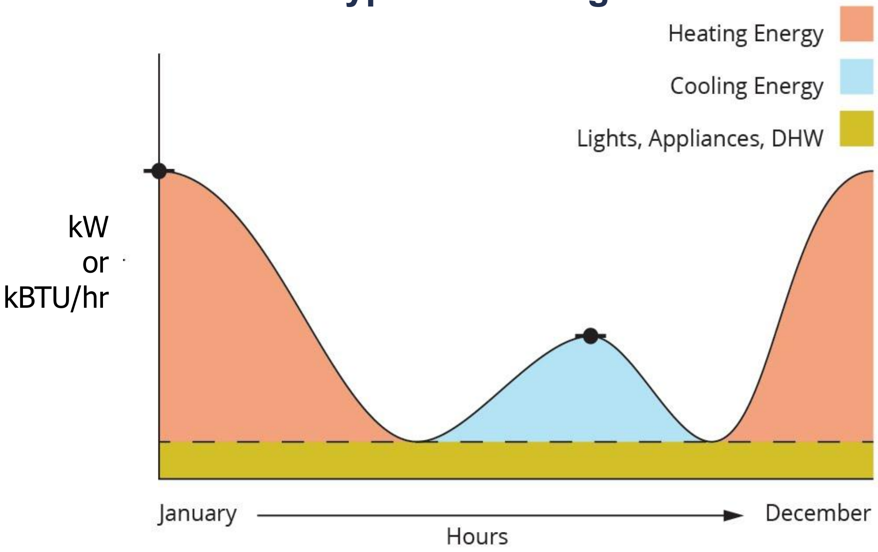
Limit: 0 Days



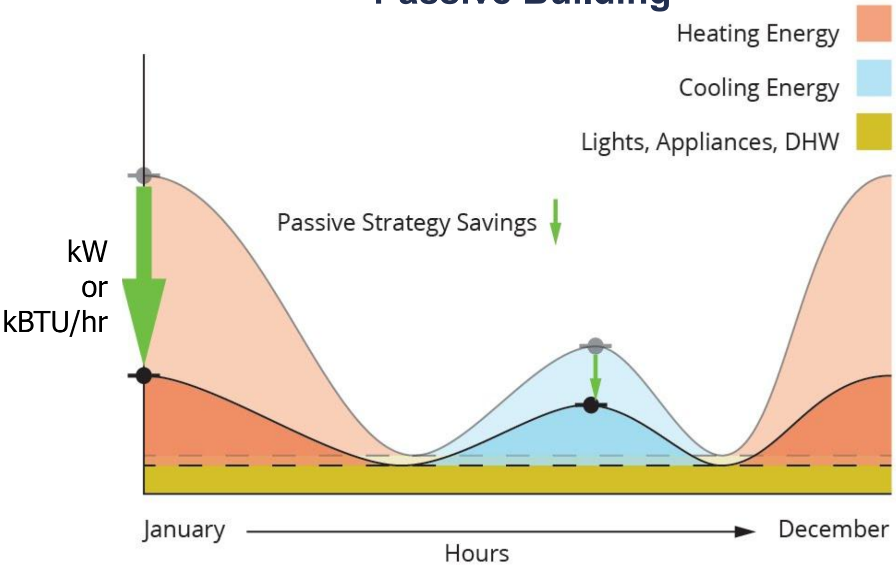
Strategies

Passive Building

Typical Building

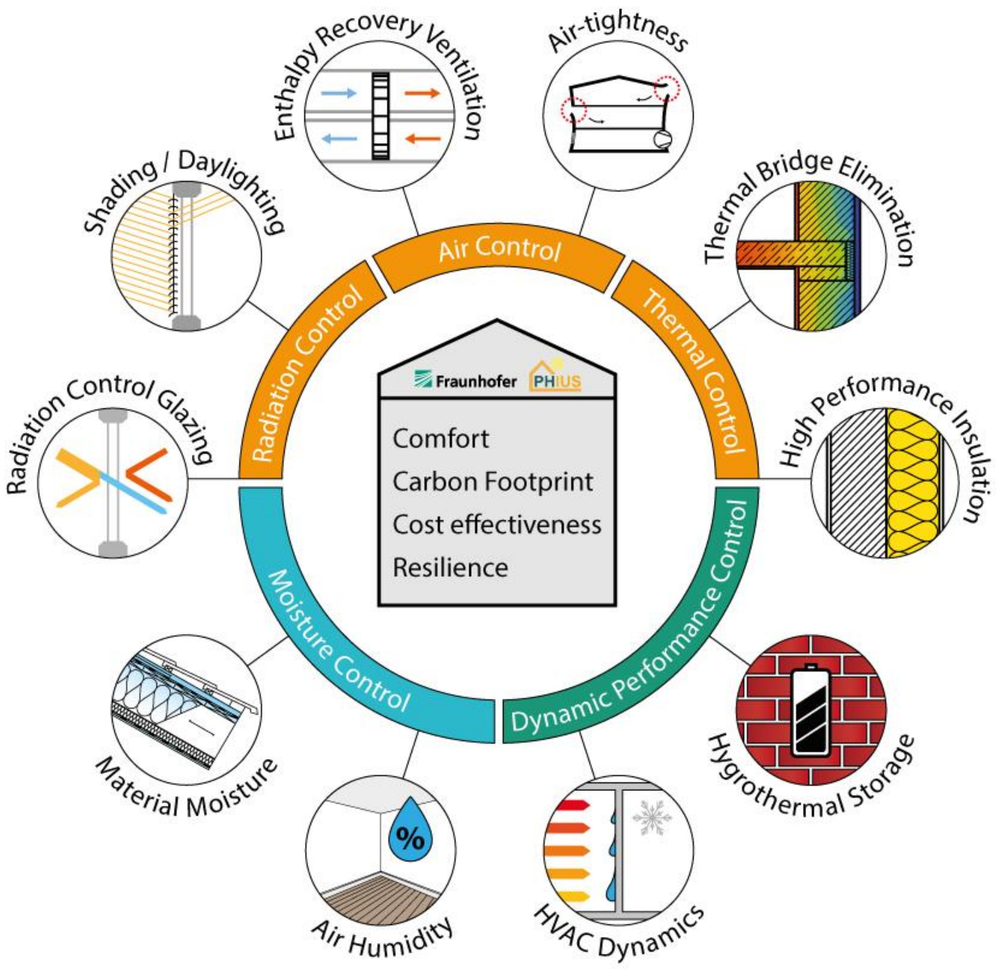


Passive Building



Annual Energy = kWh/yr (or kBTU/yr) □ area under the curve
Peak Power = kW (or kBTU/hr) □ point at top of curve

Passive Building Principles & Dynamics



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Passive Building Principles

THERMAL CONTROL

High Performance Insulation

Thermal Bridge Elimination

AIR CONTROL

Air-Tightness

Enthalpy Recovery Ventilation

RADIATION CONTROL

Shading / Daylighting

Climate Appropriate Glazing

© Phius 2021

Measures such as:

Resilience | Air sealing, insulation, seismic, PV, batteries…

+

Health | Radon, Carbon monoxide, mold…

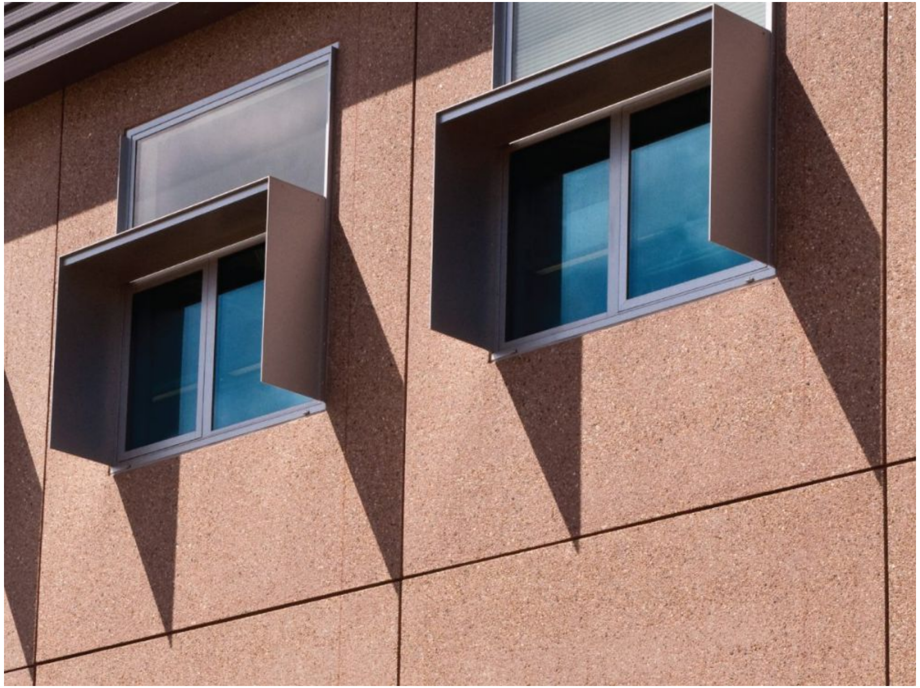
+

Decarbonization | Electrification, community solar, low-carbon choices…

Summer Responses

Passive Measures

- Natural Ventilation
- Scheduled Natural Ventilation
- Shades (preferably Exterior)



Summer Responses

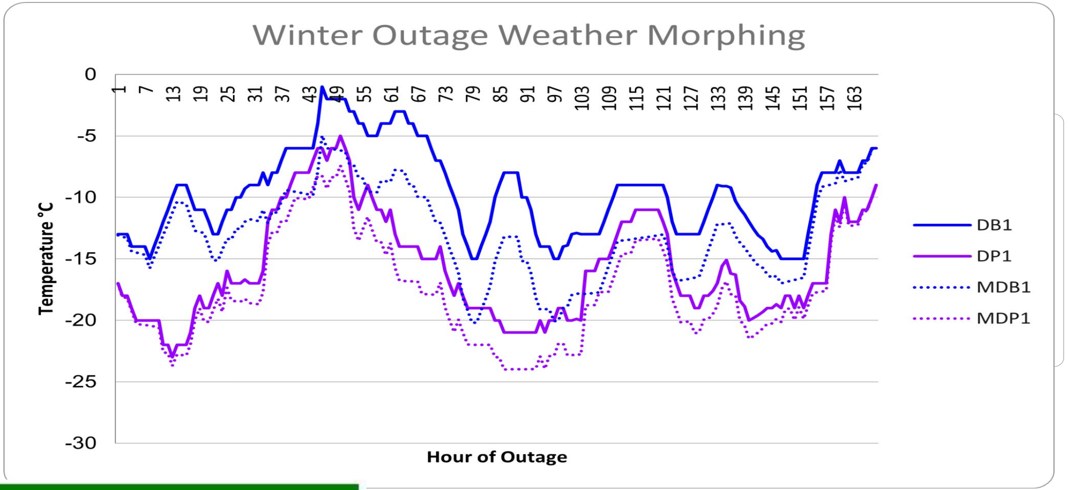
When Passive Measures Aren't Enough

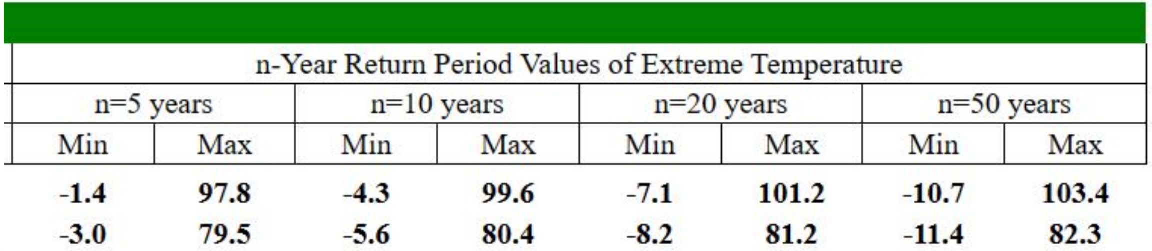
- Cooling on setback
- PV
- Batteries

Modeling

Stress Weather

- Limited physics based stress weather data
- Morphing to match ASHRAE statistical returns
- 10-Year winter returns

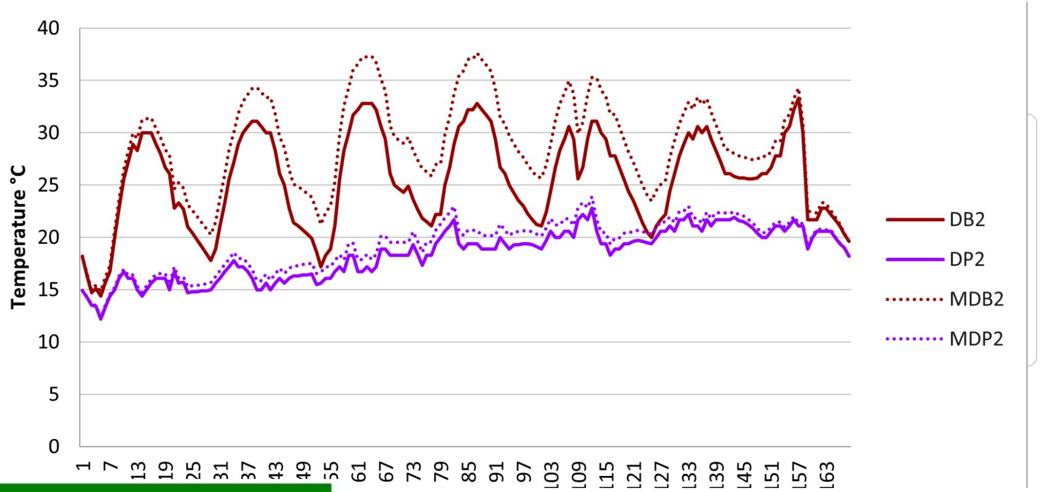


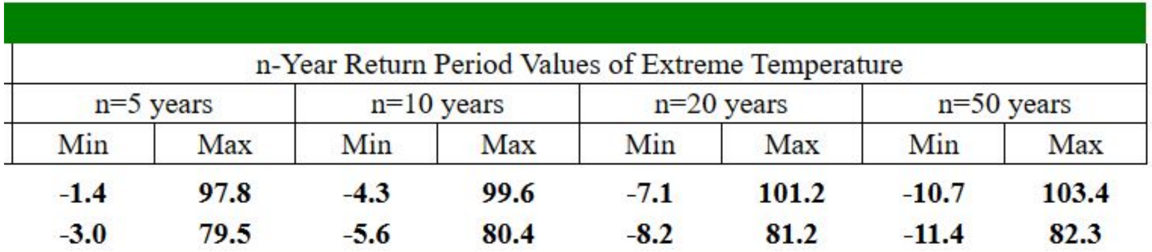


n-Year Return Period Values of Extreme Temperature							
n=5 years		n=10 years		n=20 years		n=50 years	
Min	Max	Min	Max	Min	Max	Min	Max
-1.4	**97.8**	**-4.3**	**99.6**	**-7.1**	**101.2**	**-10.7**	**103.4**
-3.0	**79.5**	**-5.6**	**80.4**	**-8.2**	**81.2**	**-11.4**	**82.3**

Stress Weather

- Limited physics based stress weather data
- Morphing to match ASHRAE statistical returns
- 20 - Year summer returns





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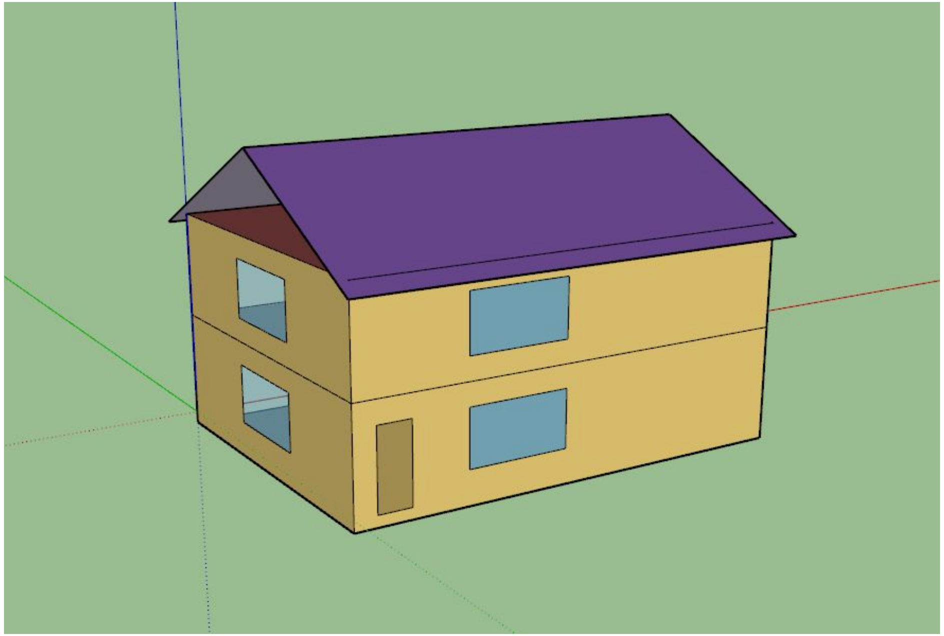
-3.0	**79.5**	**-5.6**	**80.4**	**-8.2**	**81.2**	**-11.4**	**82.3**

Test House

US DOE Prototypical Single Family House:

- 2 Stories
- 3 beds (4 occ)
- 2,128 sqft (198 sqm)
- 13.5% WWR
- slab on grade



Packages and Summer Modes

Retrofit Packages:

0. Baseline House

1. Electrification

2. DOE ‘Market Ready Envelope’

3. IECC 2021

3b. IECC 2021 @ 0.06cfm50

4. Phius CORE Prescriptive

Summer Modes:

NV - natural vent., temp control

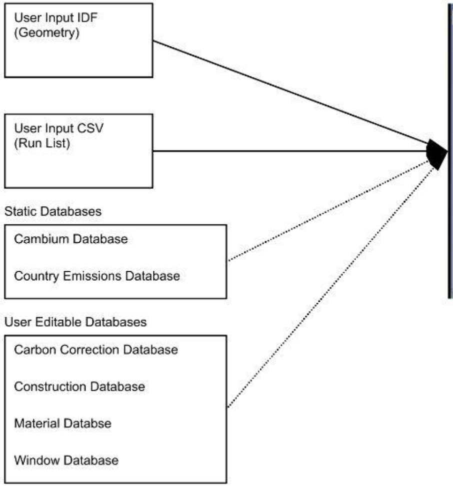
SchNV - scheduled nat. vent., temp ctrl.

ShcNV+Shd - add exterior blinds

DC - heat pump

DC+Shd - heat pump + ext. blinds

Inputs



User Input IDF (Geometry)

User Input CSV (Run List)

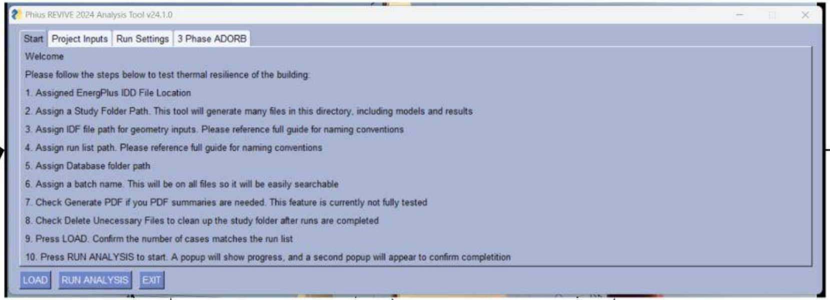
Static Databases

- Cambium Database
- Country Emissions Database

User Editable Databases

- Carbon Correction Database
- Construction Database
- Material Databse
- Window Database

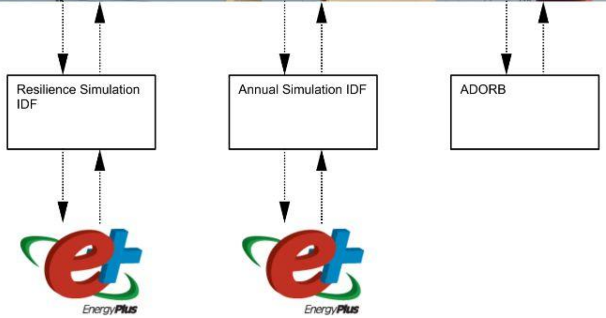
Analysis



Welcome

Please follow the steps below to test thermal resilience of the building:

1. Assigned EnergPlus IDD File Location
2. Assign a Study Folder Path. This tool will generate many files in this directory, including models and results
3. Assign IDF file path for geometry inputs. Please reference full guide for naming conventions
4. Assign run list path. Please reference full guide for naming conventions
5. Assign Database folder path
6. Assign a batch name. This will be on all files so it will be easily searchable
7. Check Generate PDF if you PDF summaries are needed. This feature is currently not fully tested
8. Check Delete Unecessary Files to clean up the study folder after runs are completed
9. Press LOAD. Confirm the number of cases matches the run list
10. Press RUN ANALYSIS to start. A popup will show progress, and a second popup will appear to confirm completition

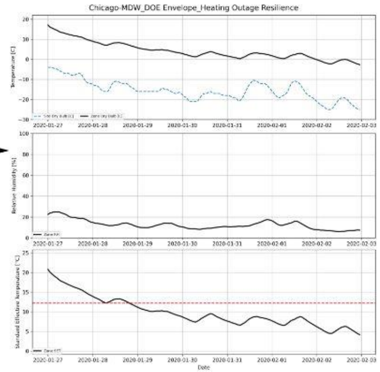


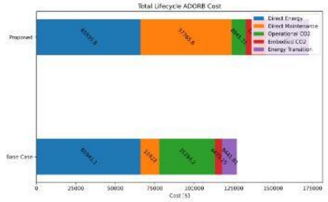
Resilience Simulation IDF

Annual Simulation IDF

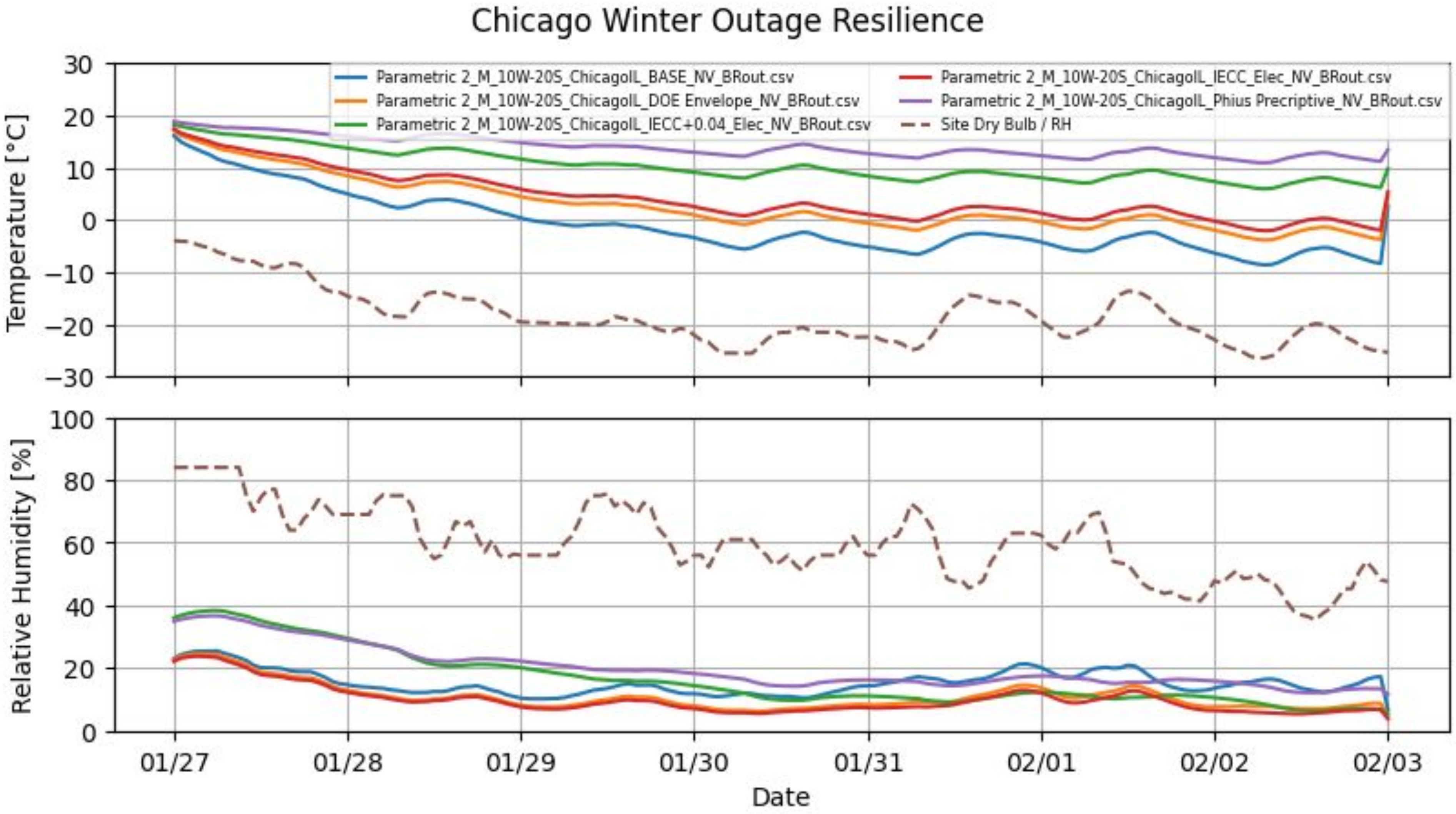
ADORB

Results





Graphs


Chicago Winter Outage Resilience
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Parametric 2_M_10W-20S_ChicagoIL_IECC+0.04_Elec_NV_BRout.csv
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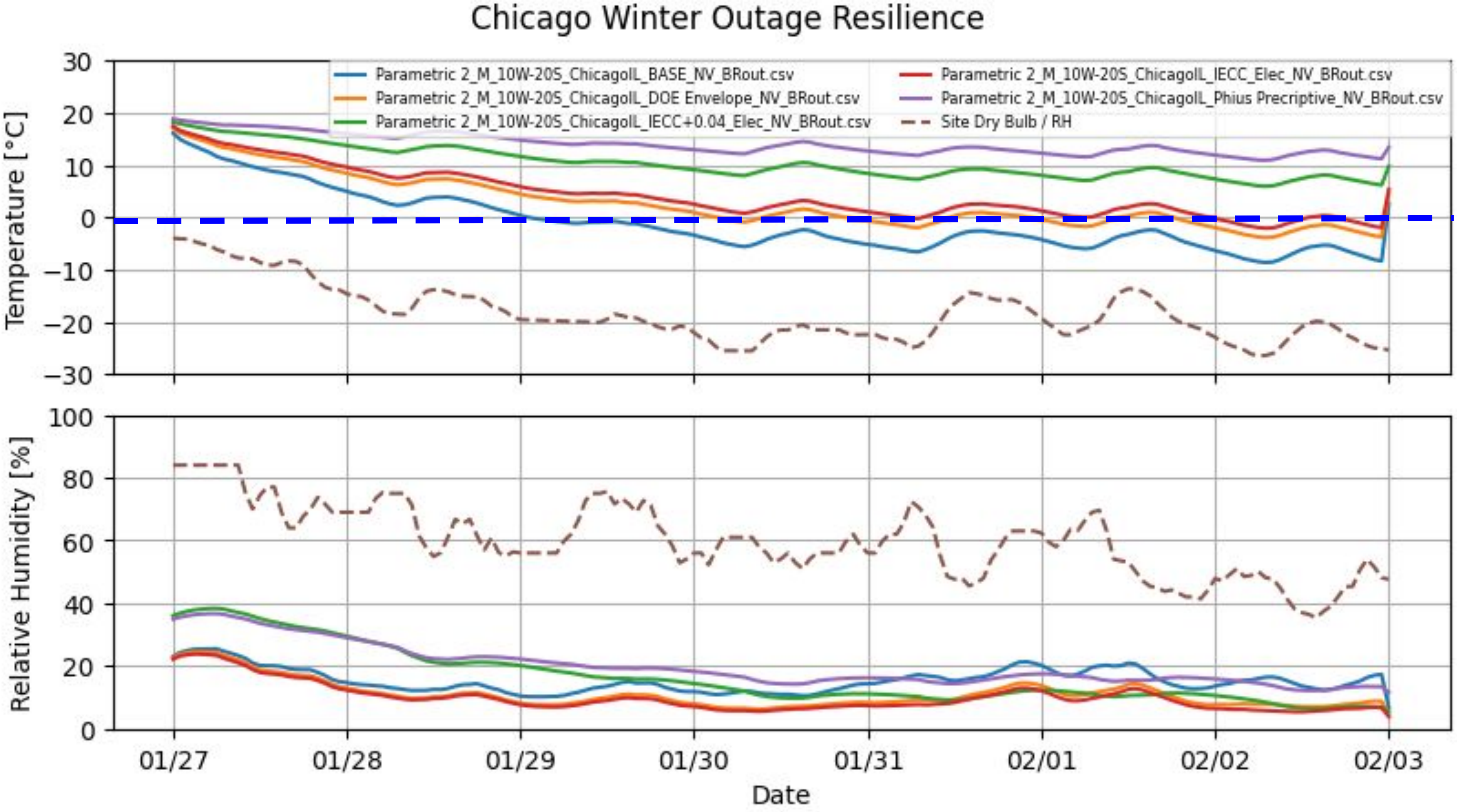
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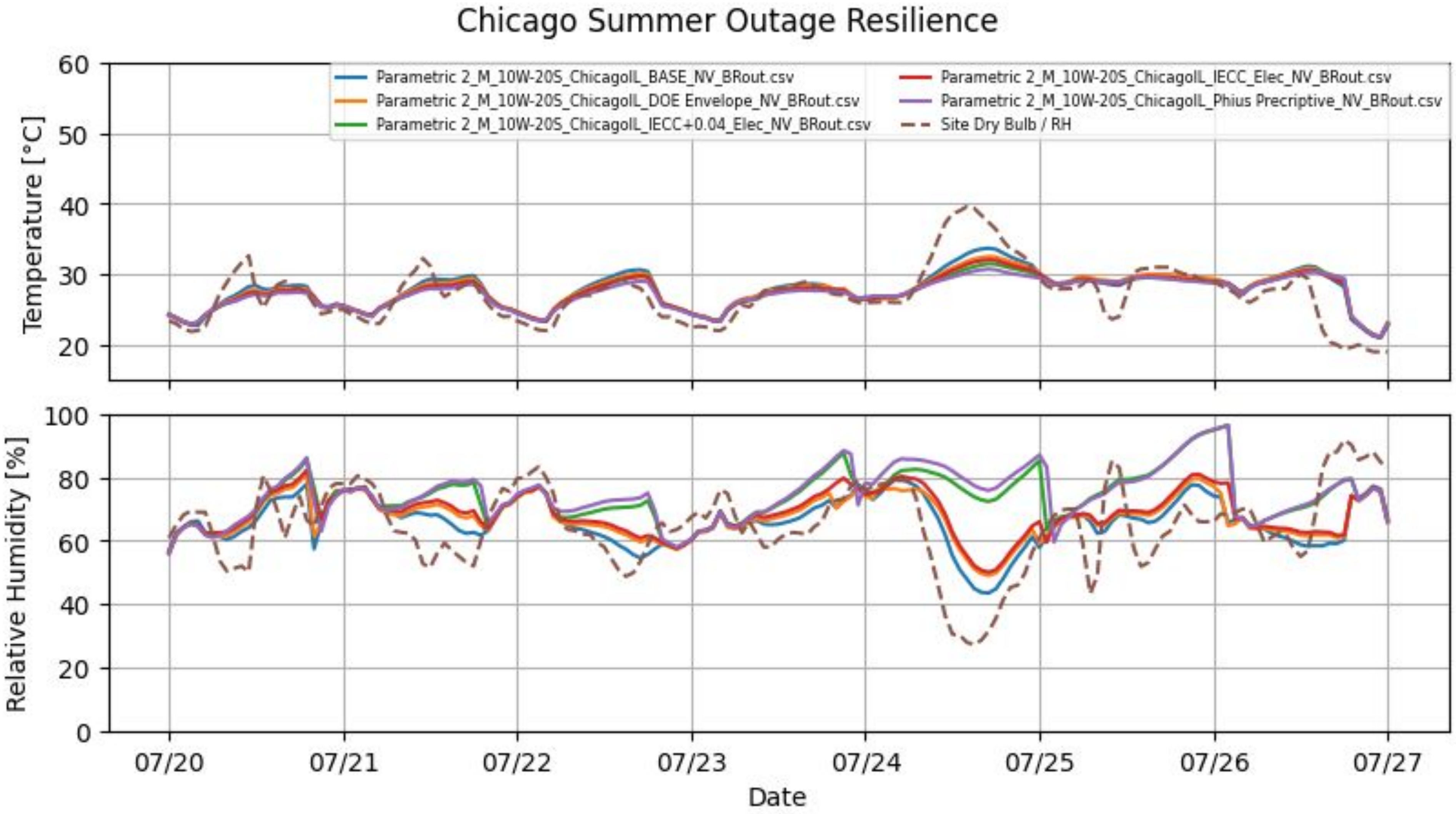
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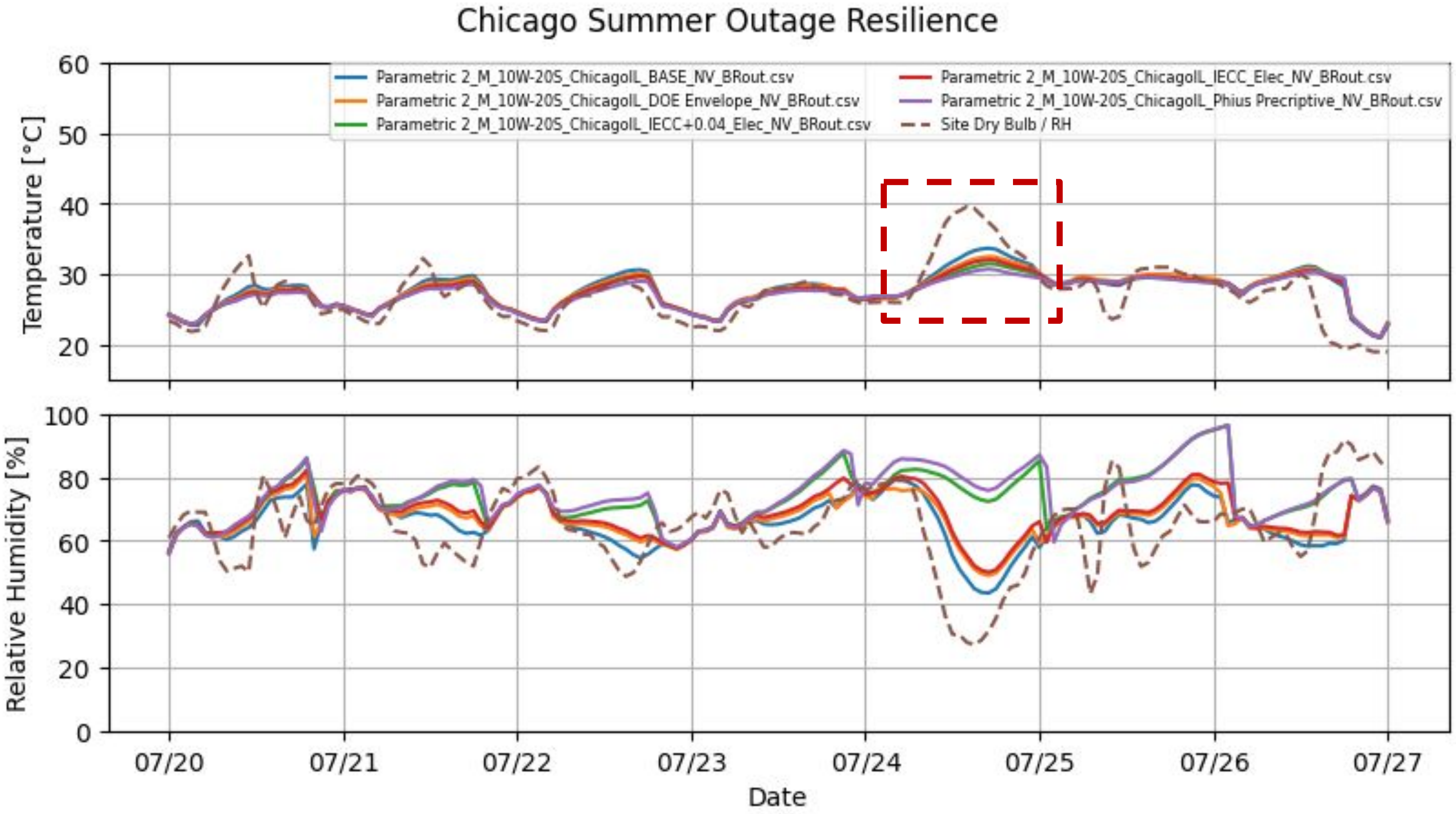
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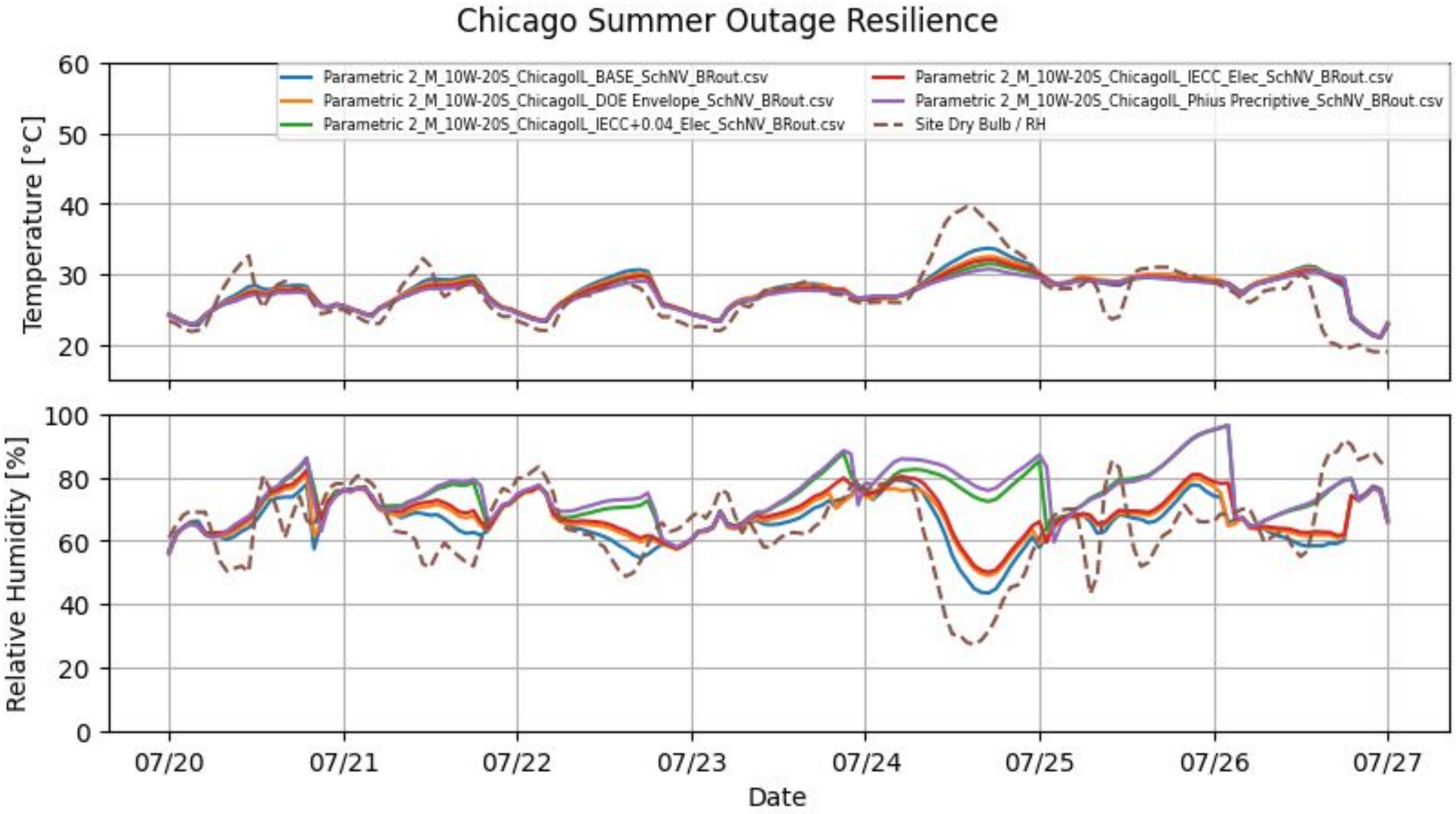
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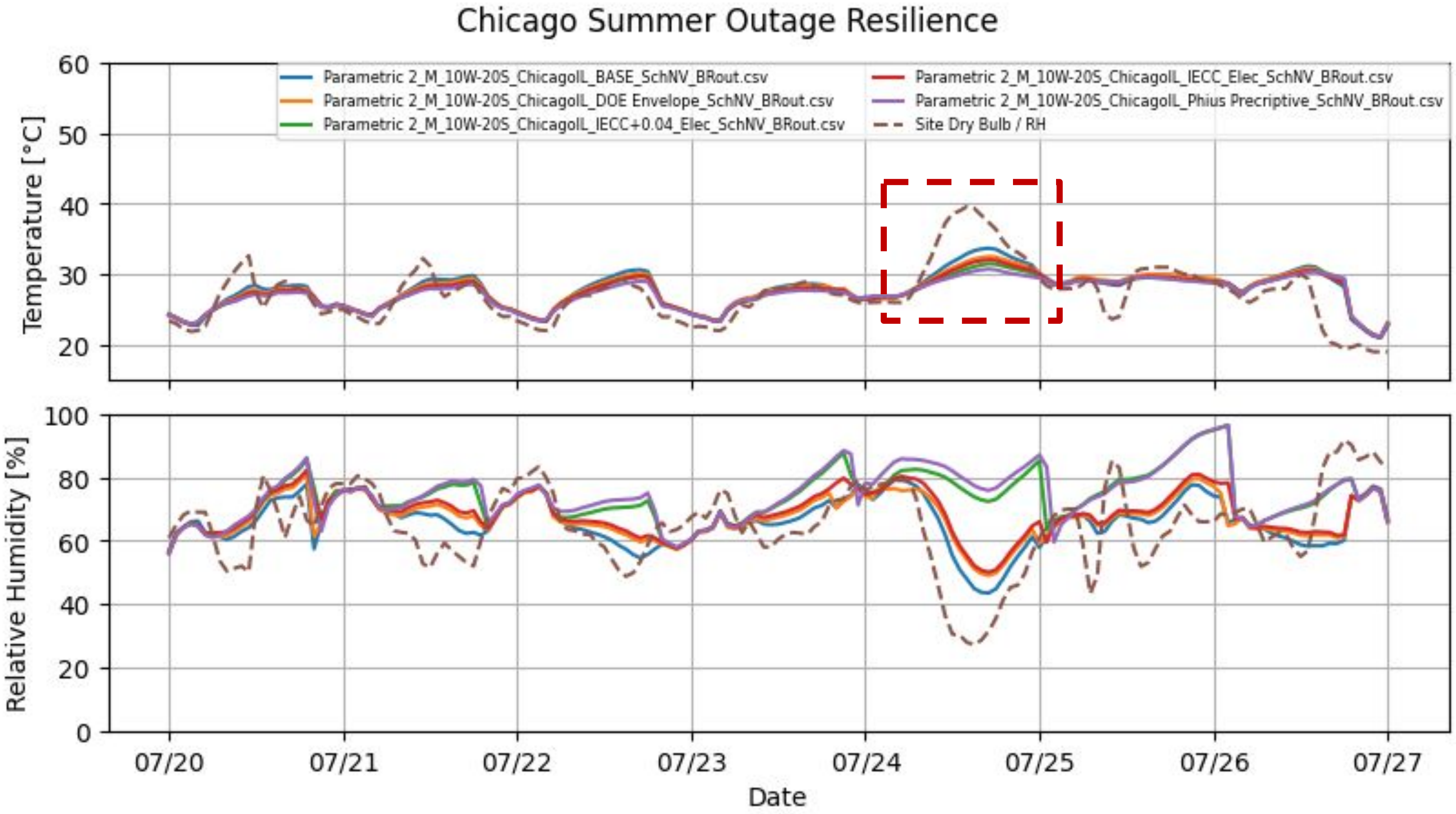
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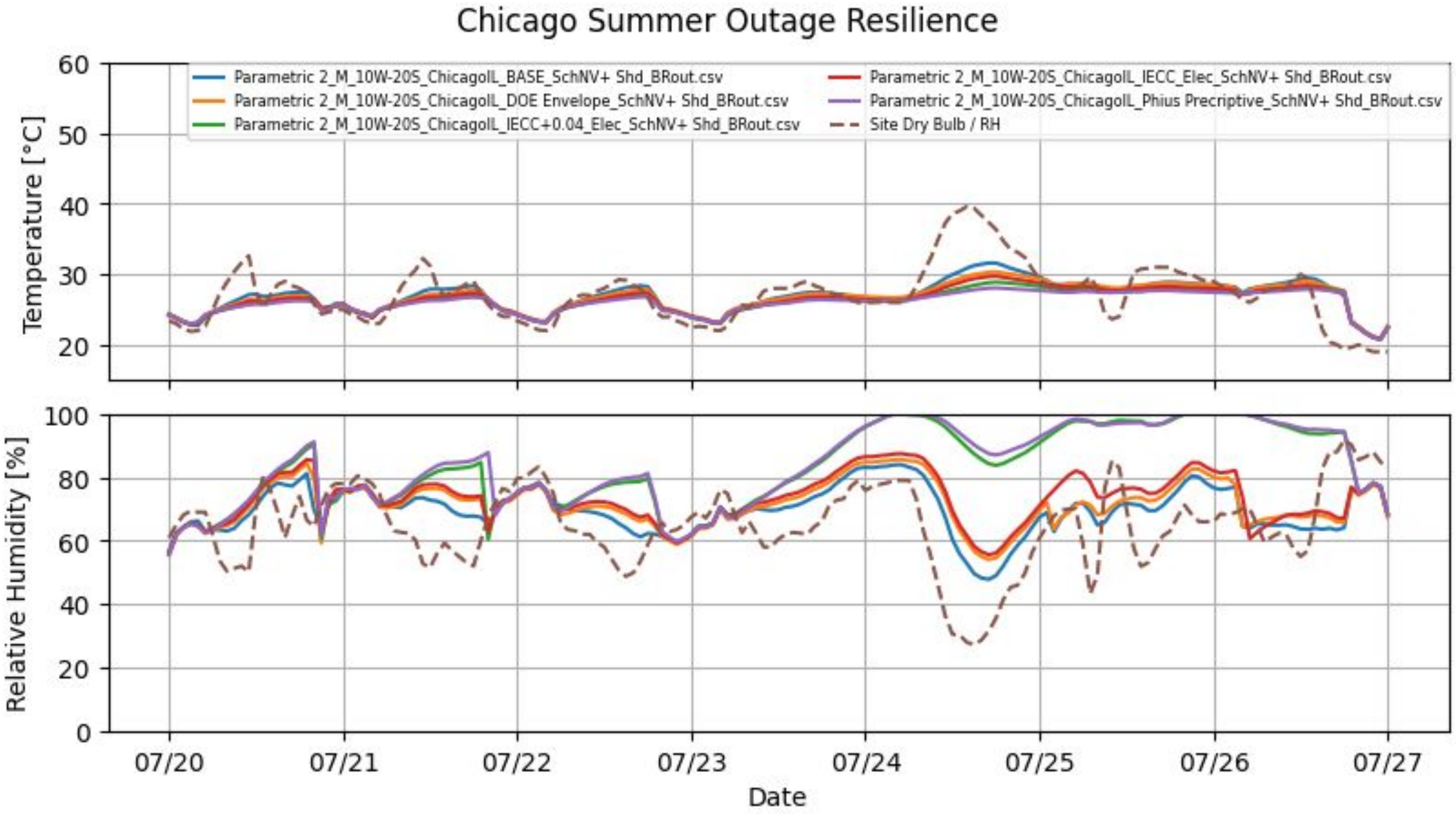
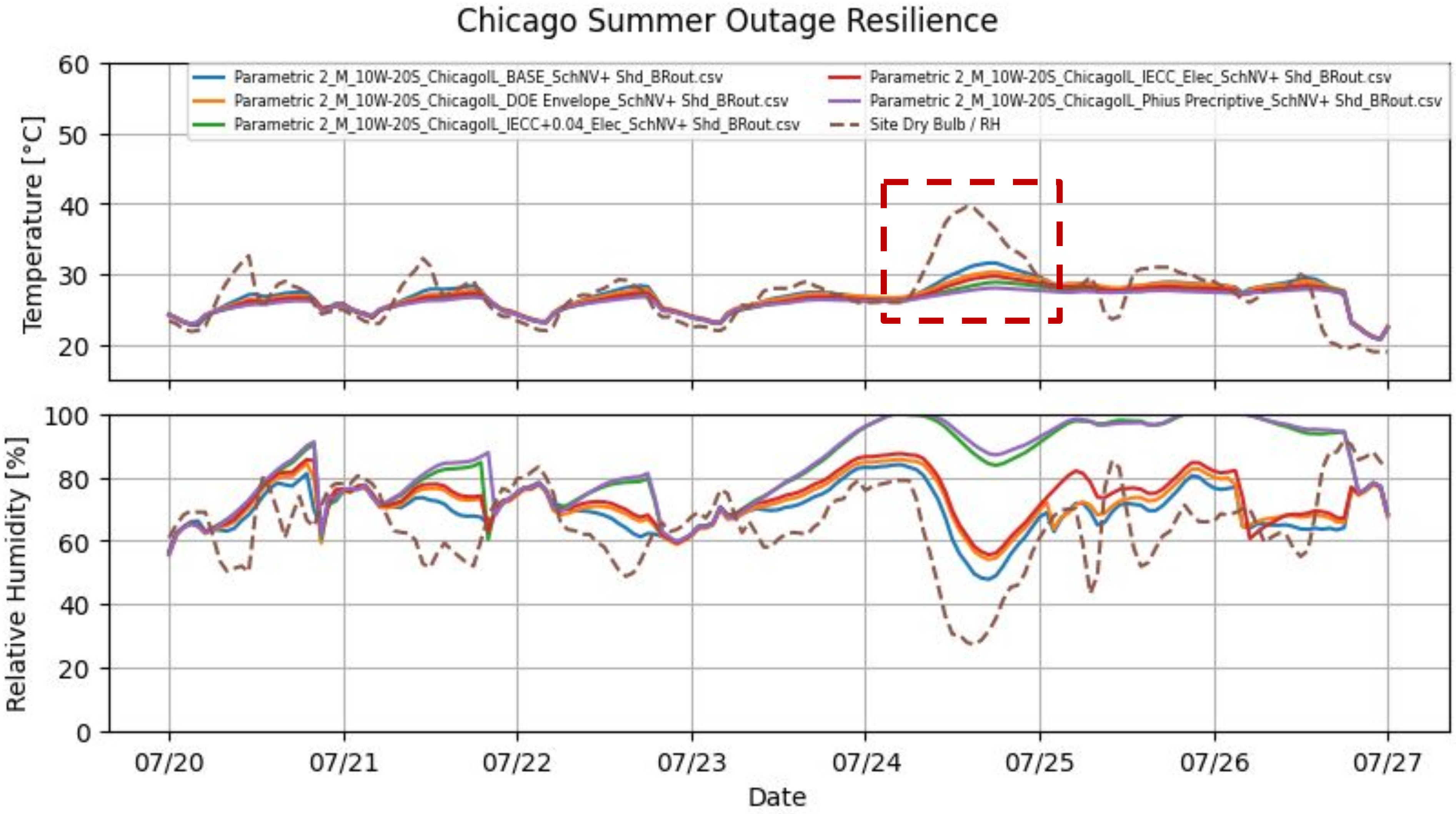
30
20
Relative Humidity [%]
100
80
60
40
20
0
07/20
07/21
07/22
07/23
07/24
07/25
07/26
07/27
Date


Chicago Summer Outage Resilience
Parametric 2_M_10W-20S_ChicagoIL_BASE_SchNV+ Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_DOE Envelope_SchNV+ Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC+0.04_Elec_SchNV+ Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC_Elec_SchNV+ Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_Phius Precriptive_SchNV+ Shd_BRout.csv
Site Dry Bulb / RH
Temperature [°C]
60
50
40
30
20
Relative Humidity [%]
100
80
60
40
20
0
07/20
07/21
07/22
07/23
07/24
07/25
07/26
07/27
Date


Chicago Summer Outage Resilience
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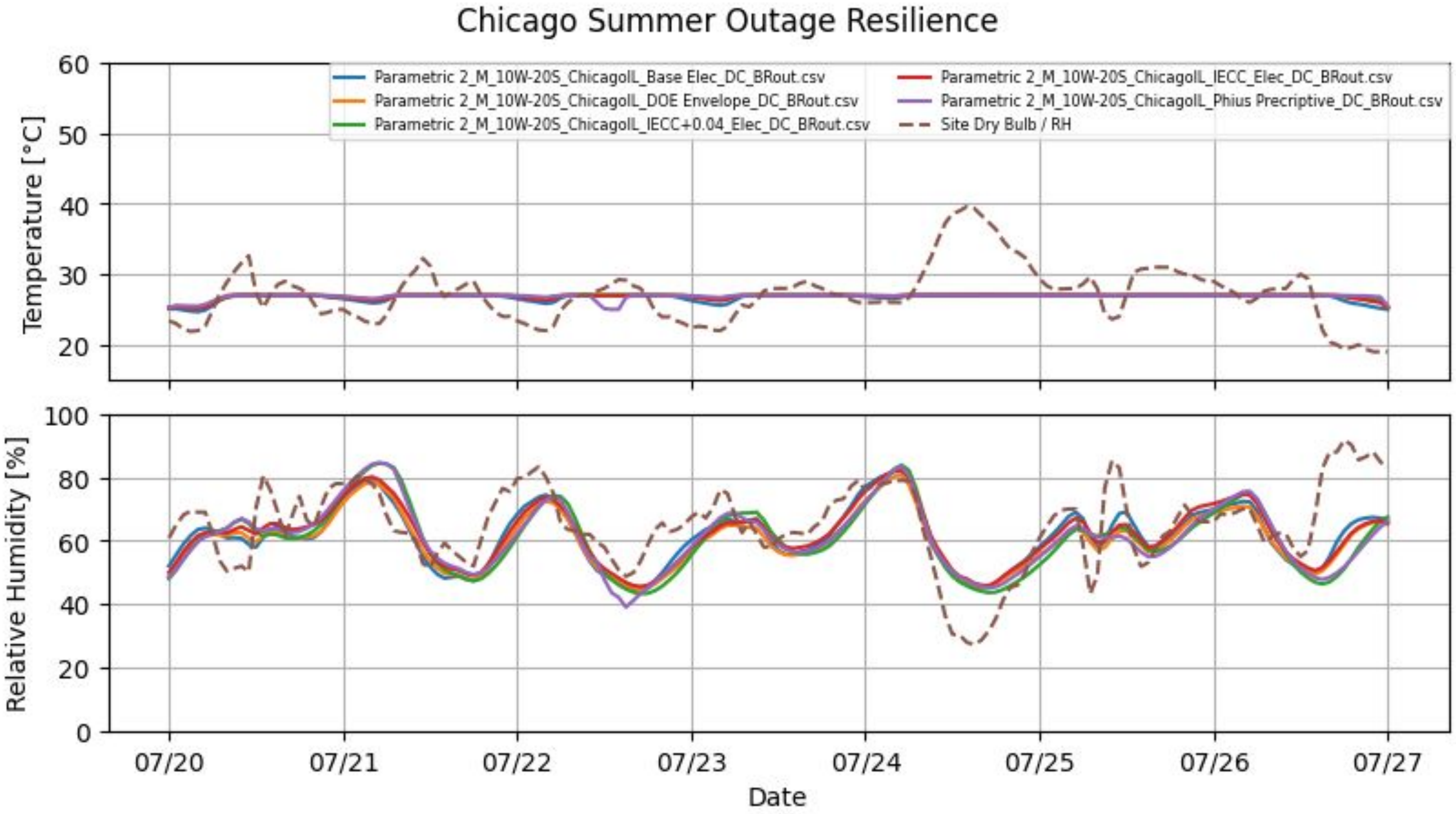
Parametric 2_M_10W-20S_ChicagoIL_DOE Envelope_SchNV+ Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC+0.04_Elec_SchNV+ Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC_Elec_SchNV+ Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_Phius Precriptive_SchNV+ Shd_BRout.csv
Site Dry Bulb / RH
Temperature [°C]
60
50
40
30
20
Relative Humidity [%]
100
80
60
40
20
0
07/20
07/21
07/22
07/23
07/24
07/25
07/26
07/27
Date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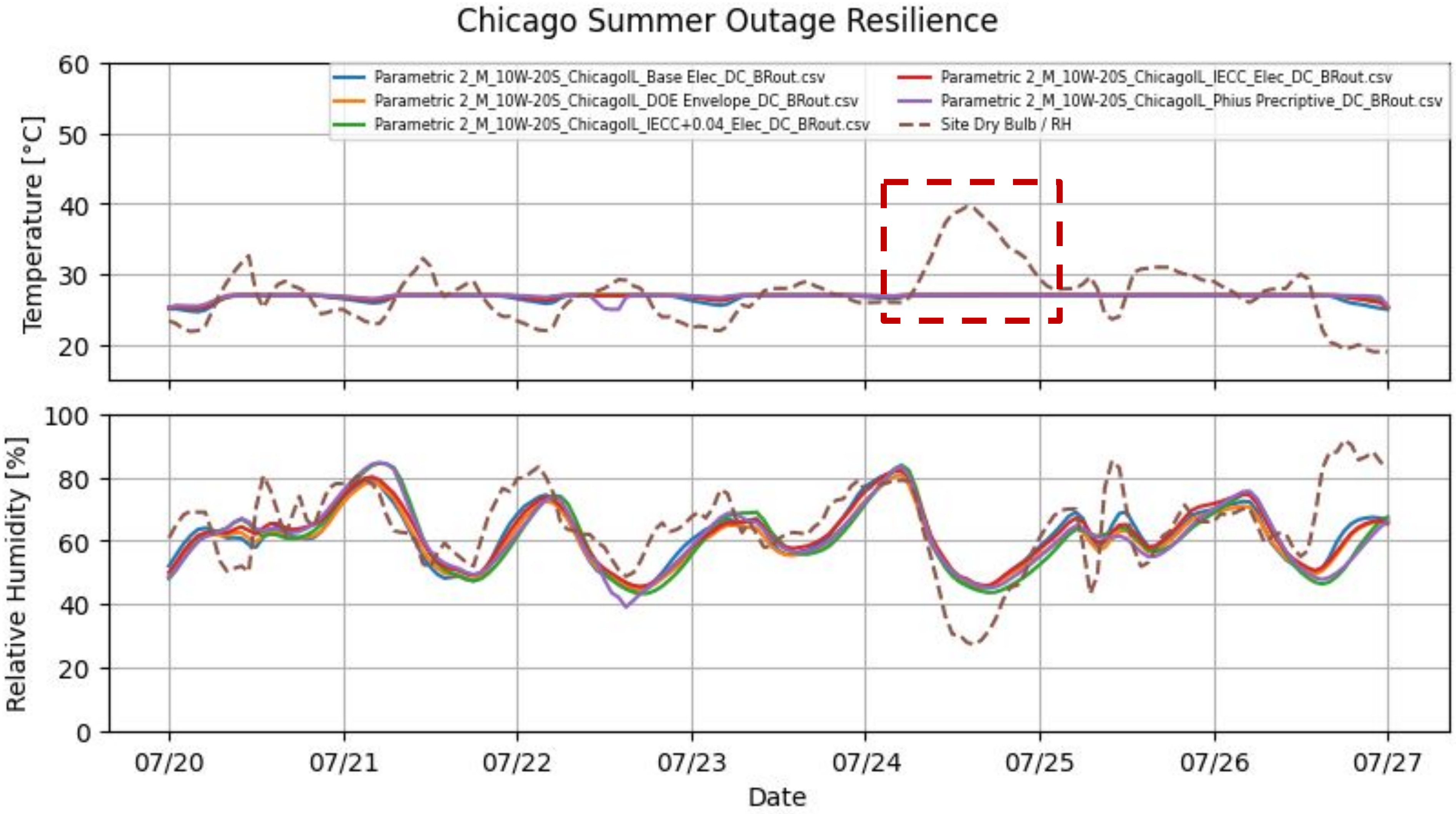
Parametric 2_M_10W-20S_ChicagoIL_DOE Envelope_DC_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC+0.04_Elec_DC_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC_Elec_DC_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_Phius Precriptive_DC_BRout.csv
Site Dry Bulb / RH
Temperature [°C]
60
50
40
30
20
Relative Humidity [%]
100
80
60
40
20
0
07/20
07/21
07/22
07/23
07/24
07/25
07/26
07/27
Date


Chicago Summer Outage Resilience
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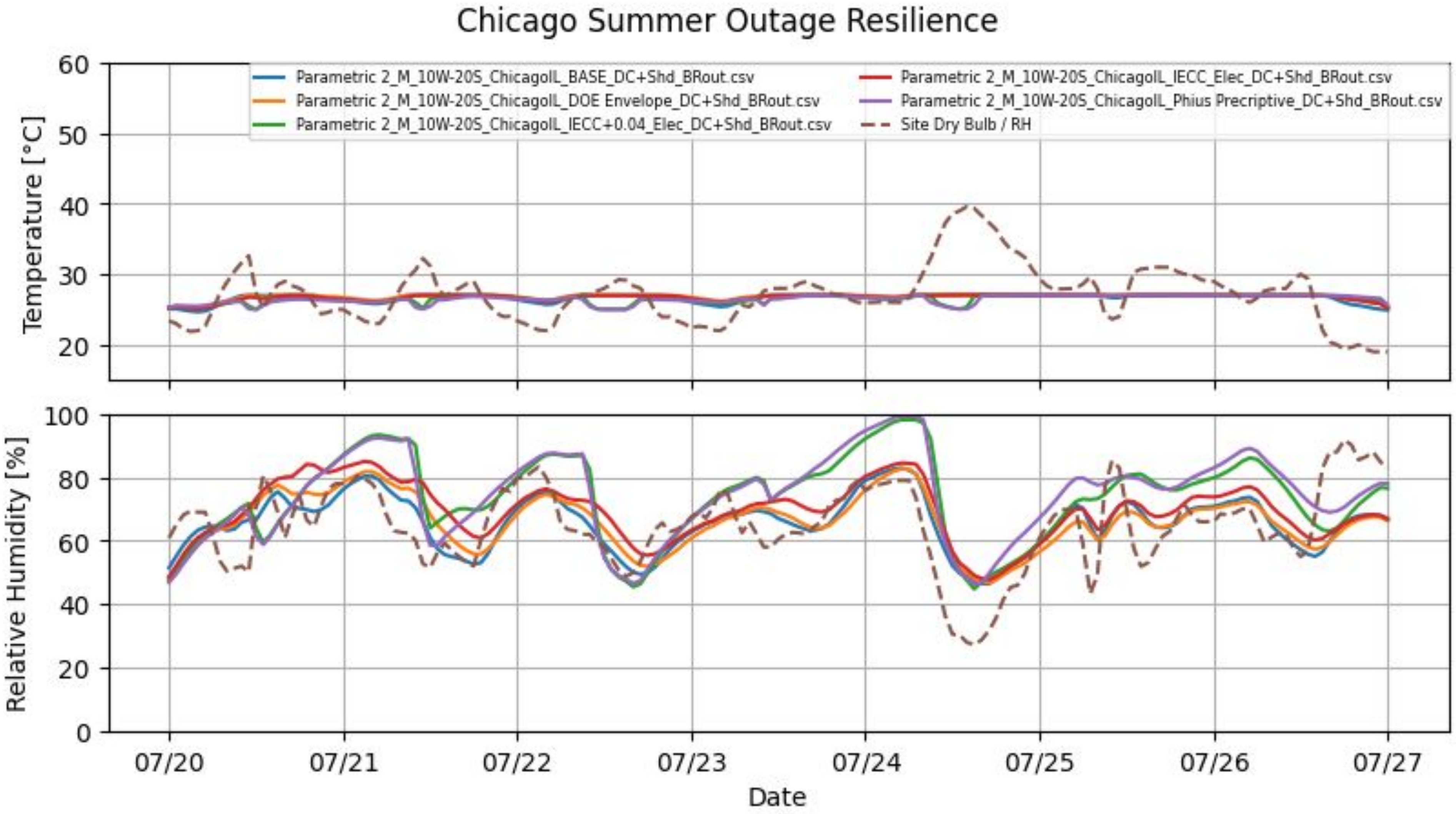
Parametric 2_M_10W-20S_ChicagoIL_DOE Envelope_DC_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC+0.04_Elec_DC_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC_Elec_DC_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_Phius Precriptive_DC_BRout.csv
Site Dry Bulb / RH
Temperature [°C]
60
50
40
30
20
Relative Humidity [%]
100
80
60
40
20
0
07/20
07/21
07/22
07/23
07/24
07/25
07/26
07/27
Date


Chicago Summer Outage Resilience
Temperature [°C]
60
50
40
30
20
Parametric 2_M_10W-20S_ChicagoIL_BASE_DC+Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_DOE Envelope_DC+Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC+0.04_Elec_DC+Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC_Elec_DC+Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_Phius Precriptive_DC+Shd_BRout.csv
Site Dry Bulb / RH
Relative Humidity [%]
100
80
60
40
20
0
07/20
07/21
07/22
07/23
07/24
07/25
07/26
07/27
Date

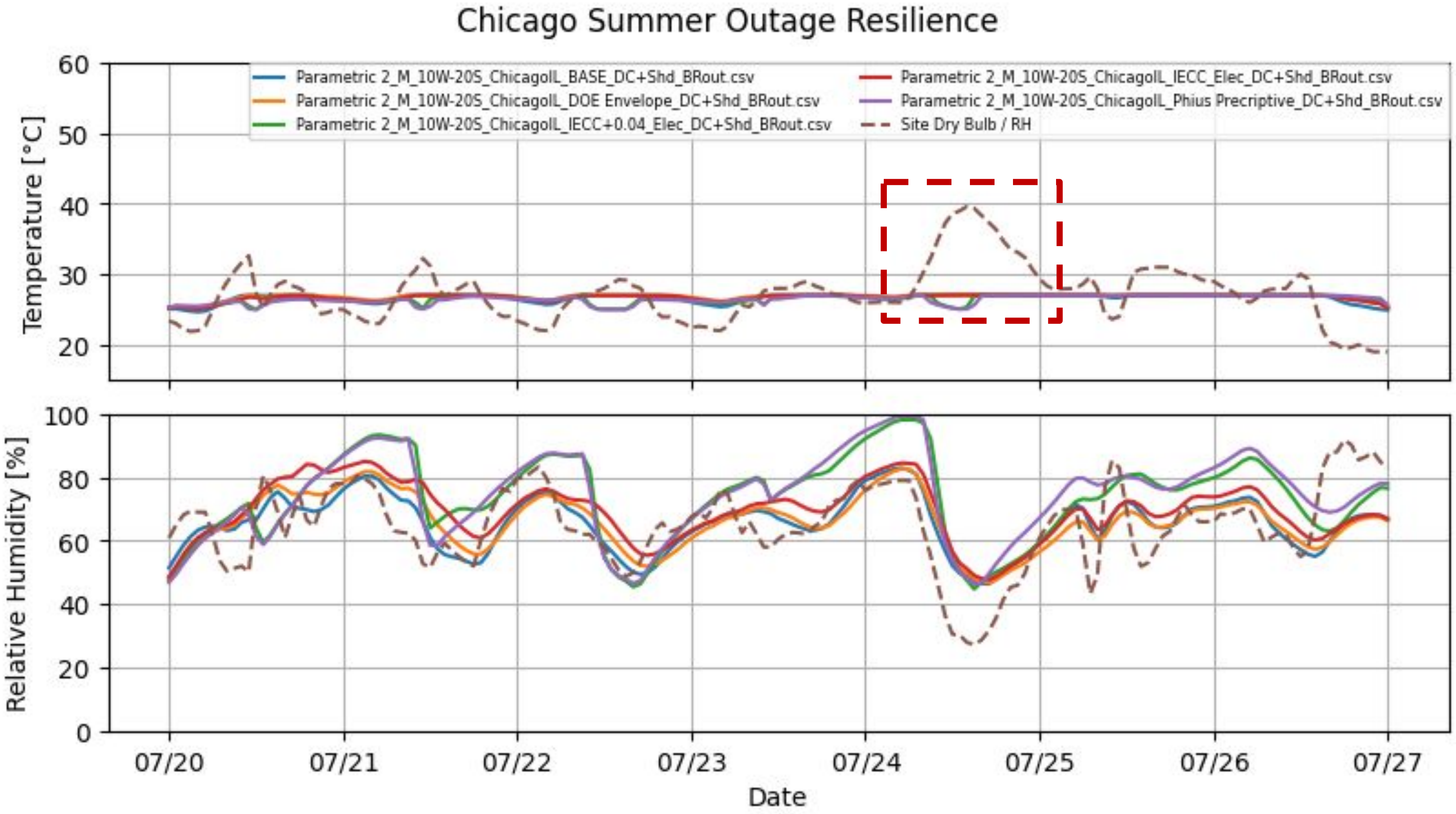

Chicago Summer Outage Resilience
Temperature [°C]
60
50
40
30
20
Parametric 2_M_10W-20S_ChicagoIL_BASE_DC+Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_DOE Envelope_DC+Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC+0.04_Elec_DC+Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_IECC_Elec_DC+Shd_BRout.csv
Parametric 2_M_10W-20S_ChicagoIL_Phius Precriptive_DC+Shd_BRout.csv
Site Dry Bulb / RH
Relative Humidity [%]
100
80
60
40
20
0
07/20
07/21
07/22
07/23
07/24
07/25
07/26
07/27
Date

Table 3: This table details the single point metrics for the 8 climates run in the parametric study. Failing metrics highlighted in blue for winter outage and red for summer outage.

Run Name	SET Hours <12.2°C	Hours <2°C [hr]	Total Deadly Days	Caution (>26.7, <32.2°C) [hr]	Extreme Caution (>32.2, <39.4°C) [hr]	Danger (>39.4, <51.7°C) [hr]	Extreme Danger (>51.7°C) [hr]	EUI [kWh/m2 yr]
Tampa, Florida								
BASE_NV	0.0	0.0	7.0	52.8	80.8	11.8	0.0	61.4
DOE Envelope_NV	0.0	0.0	5.0	61.0	83.0	0.0	0.0	46.4
IECC_NV	0.0	0.0	6.0	57.3	84.5	2.5	0.0	48.9
IECC+0.4_NV	0.0	0.0	6.0	55.8	64.0	24.8	0.0	46.3
Phius Prescriptive_NV	0.0	0.0	5.0	57.5	83.0	3.3	0.0	43.3
Chicago, Illinois								
BASE_NV	998.0	118.1	2.0	66.5	57.0	0.0	0.0	162.7
DOE Envelope_NV	540.3	48.6	2.0	67.0	56.5	0.0	0.0	88.6
IECC_NV	370.8	21.0	2.0	71.8	50.3	0.0	0.0	80.5
IECC+0.4_NV	2.7	0.0	3.0	54.0	59.8	7.0	0.0	54.6
Phius Prescriptive_NV	0.0	0.0	3.0	59.3	61.0	0.0	0.0	44.5
International Falls, Minnesota								
BASE_NV	1619.0	159.3	0.0	39.0	0.0	0.0	0.0	291.5
DOE Envelope_NV	1041.3	122.8	0.0	36.0	0.0	0.0	0.0	157.7
IECC_NV	777.5	103.3	0.0	33.0	0.0	0.0	0.0	141.7
IECC+0.4_NV	60.0	0.0	0.0	34.3	0.0	0.0	0.0	81.2
Phius Prescriptive_NV	0.0	0.0	0.0	34.0	0.0	0.0	0.0	54.6

Great Falls, Montana								
BASE_NV	1297.9	122.5	0.0	21.5	0.0	0.0	0.0	199.7
DOE Envelope_NV	790.9	97.3	0.0	18.3	0.0	0.0	0.0	103.4
IECC_NV	584.9	73.3	0.0	15.0	0.0	0.0	0.0	92.8
IECC+0.4_NV	48.7	0.0	0.0	21.3	0.0	0.0	0.0	57.6
Phius Prescriptive_NV	0.0	0.0	0.0	15.3	0.0	0.0	0.0	41.3
Albuquerque, New Mexico								
BASE_NV	0.0	0.0	0.0	90.3	0.0	0.0	0.0	98.7
DOE Envelope_NV	0.0	0.0	0.0	86.0	0.0	0.0	0.0	57.1
IECC_NV	0.0	0.0	0.0	68.8	0.0	0.0	0.0	53.4
IECC+0.4_NV	0.0	0.0	0.0	70.8	0.0	0.0	0.0	41.9
Phius Prescriptive_NV	0.0	0.0	0.0	57.0	0.0	0.0	0.0	37.0
Nashville, Tennessee								
BASE_NV	50.0	0.0	3.0	56.5	70.3	0.0	0.0	108.3
DOE Envelope_NV	0.0	0.0	3.0	60.8	68.8	0.0	0.0	64.8
IECC_NV	0.0	0.0	0.0	71.0	49.0	0.0	0.0	59.1
IECC+0.4_NV	0.0	0.0	1.0	57.5	59.0	0.0	0.0	46.0
Phius Prescriptive_NV	0.0	0.0	1.0	62.8	53.5	0.0	0.0	41.1
El Paso, Texas								
BASE_NV	0.0	0.0	0.0	73.0	9.3	0.0	0.0	72.5
DOE Envelope_NV	0.0	0.0	0.0	78.0	3.0	0.0	0.0	49.3
IECC_NV	0.0	0.0	0.0	72.5	1.0	0.0	0.0	50.0
IECC+0.4_NV	0.0	0.0	0.0	68.0	3.8	0.0	0.0	44.3
Phius Prescriptive_NV	0.0	0.0	0.0	62.0	0.0	0.0	0.0	38.0
Vancouver British Columbia								
BASE_NV	8.4	0.0	0.0	0.0	0.0	0.0	0.0	150.4
DOE Envelope_NV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.8
IECC_NV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	58.85
IECC+0.4_NV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	45.5
Phius Prescriptive_NV	0.0	0.0	0.0	0.0	0.0	0.0	0.0	38.5

Conclusions

Why This Metric

- Good measure of how passive a building is
- Less investment (capital and embodied CO2) than new construction passive buildings
- Buildings in values to the owner
  - Occupant health and safety
  - Load reduction
  - Operational energy savings
- Tunable to each specific building

Key Takeaways

- Thermal resilience is measurable and achievable
- Existing modeling tools can be used to simulate the outage period
- Passive measures work well for winter thermal resilience
- Summer reponses:
    - Passive strategies can work well in dry summers
    - Humid summers need some dehumidifcation

Future Work

- Run more studies to validate strategies
- Optimize mixed mode strategies for summer outages
- Real life study to validate modeling
- Work on multizonal model
- Future weather data
- Extreme weather data
- Non-residential buildings?

Questions?

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Technical Staff, Phius
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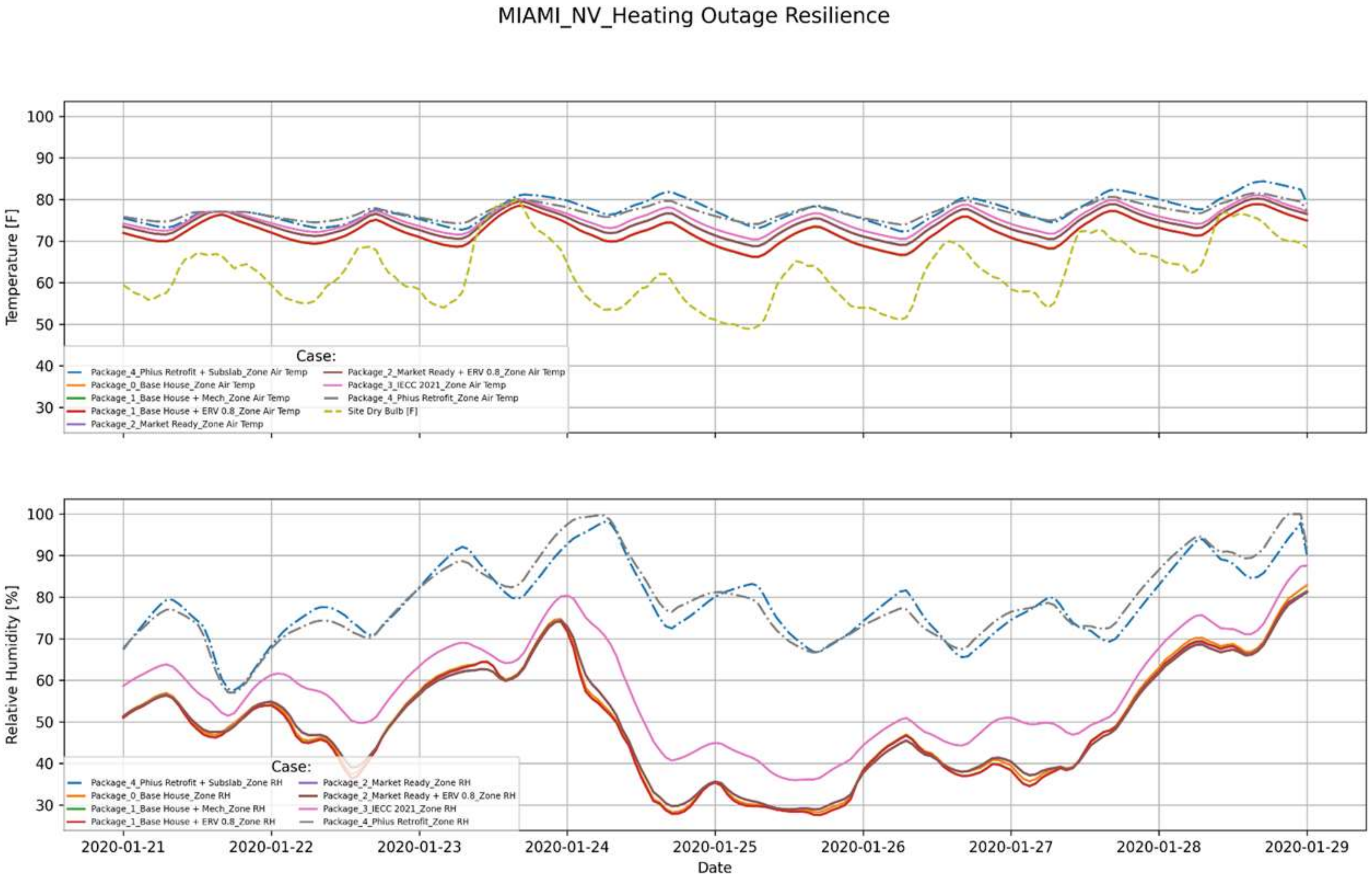
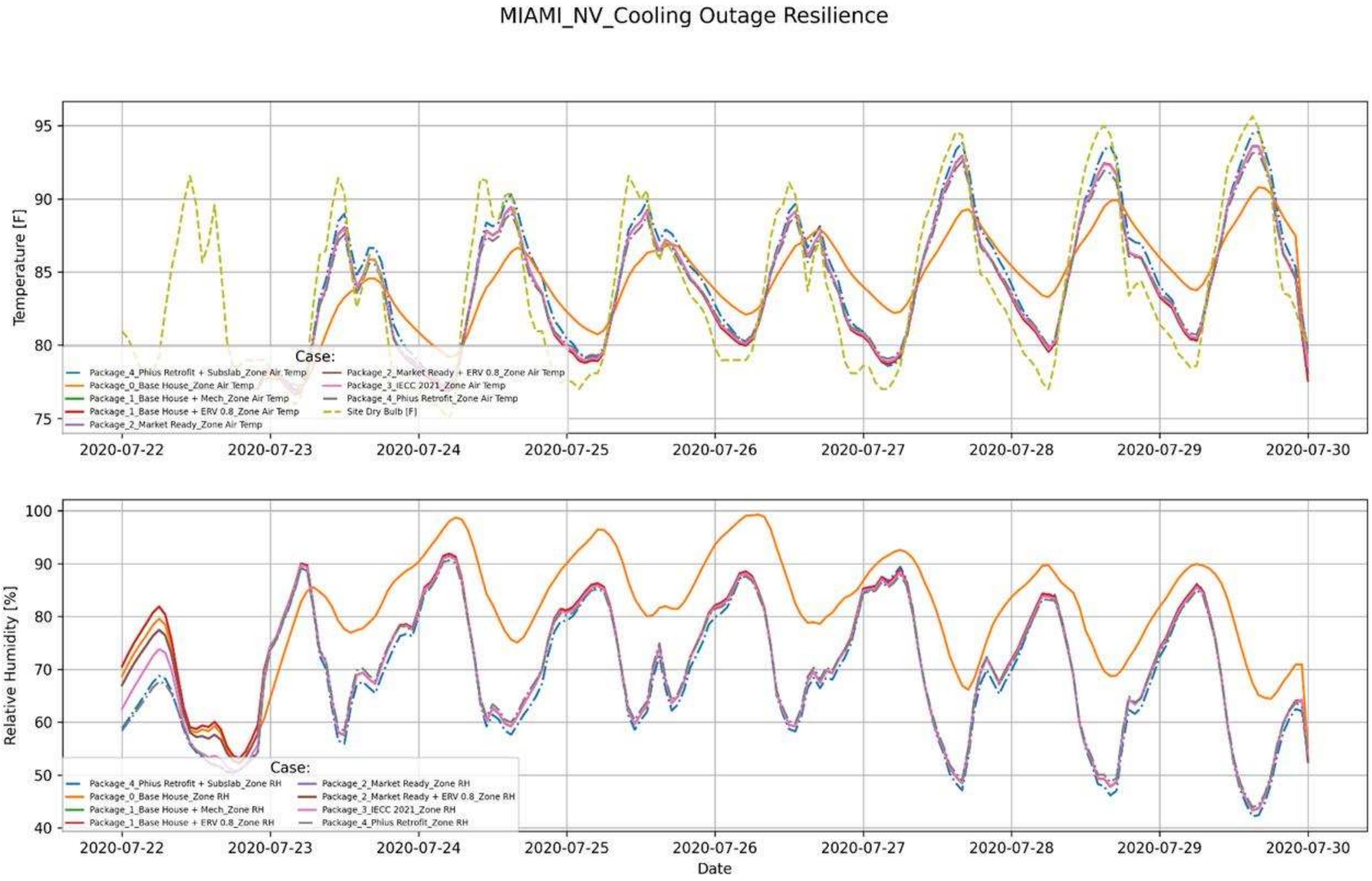
Appendix

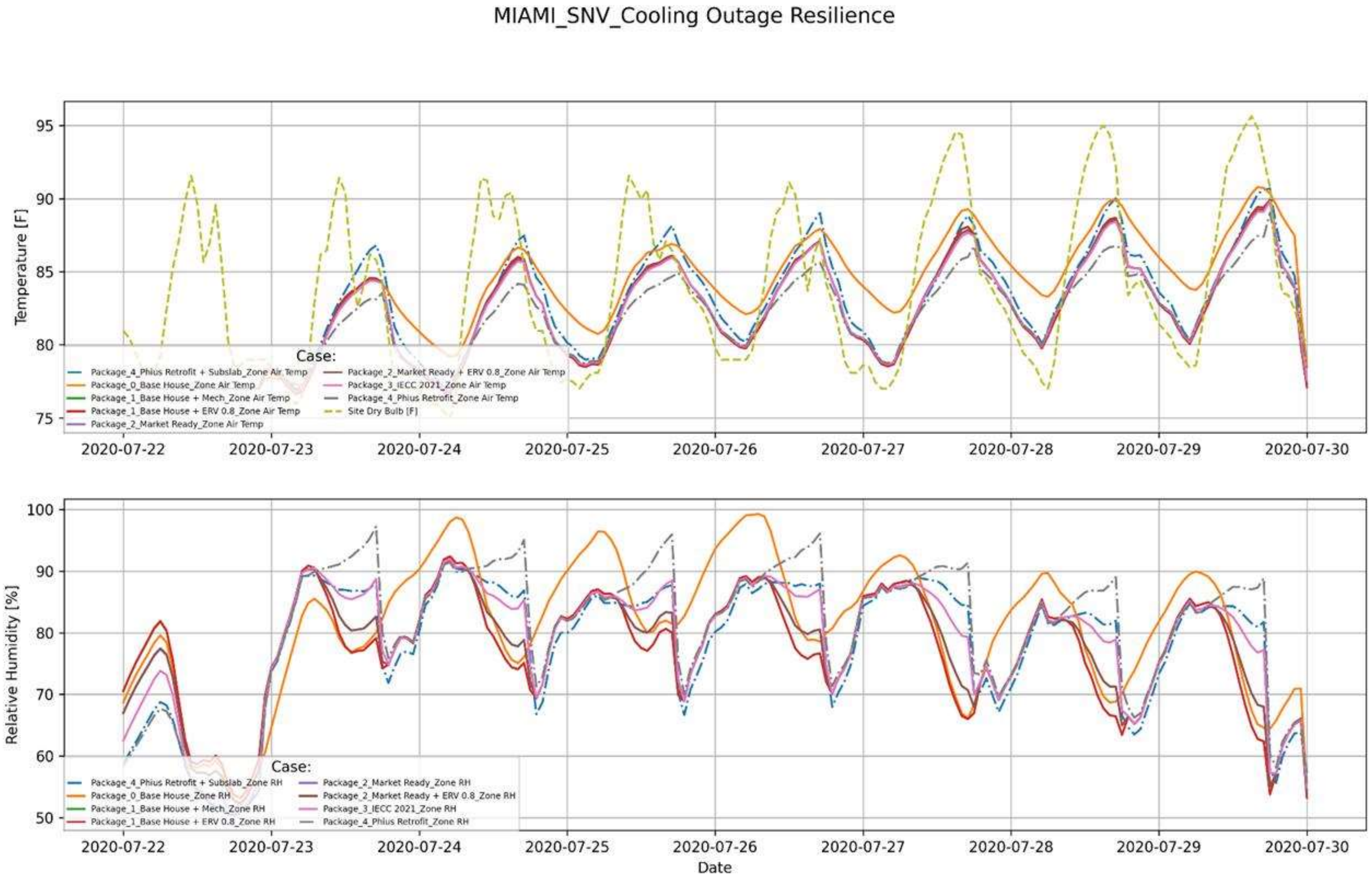
Full graph results for:

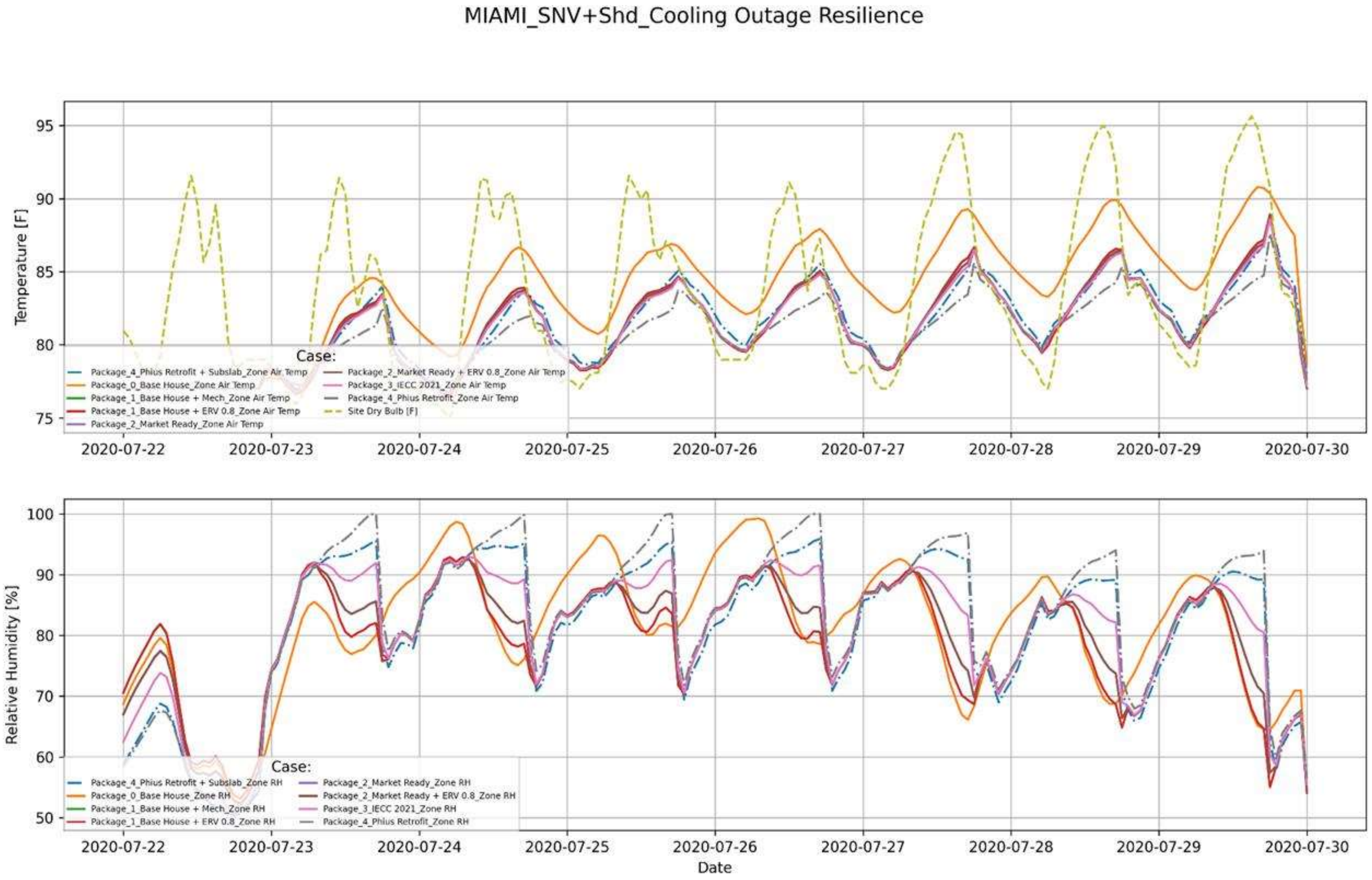
- Miami, FL
- El Paso, TX
- Seattle, WA
- Denver, CO
- International Falls, MN

Miami, FL

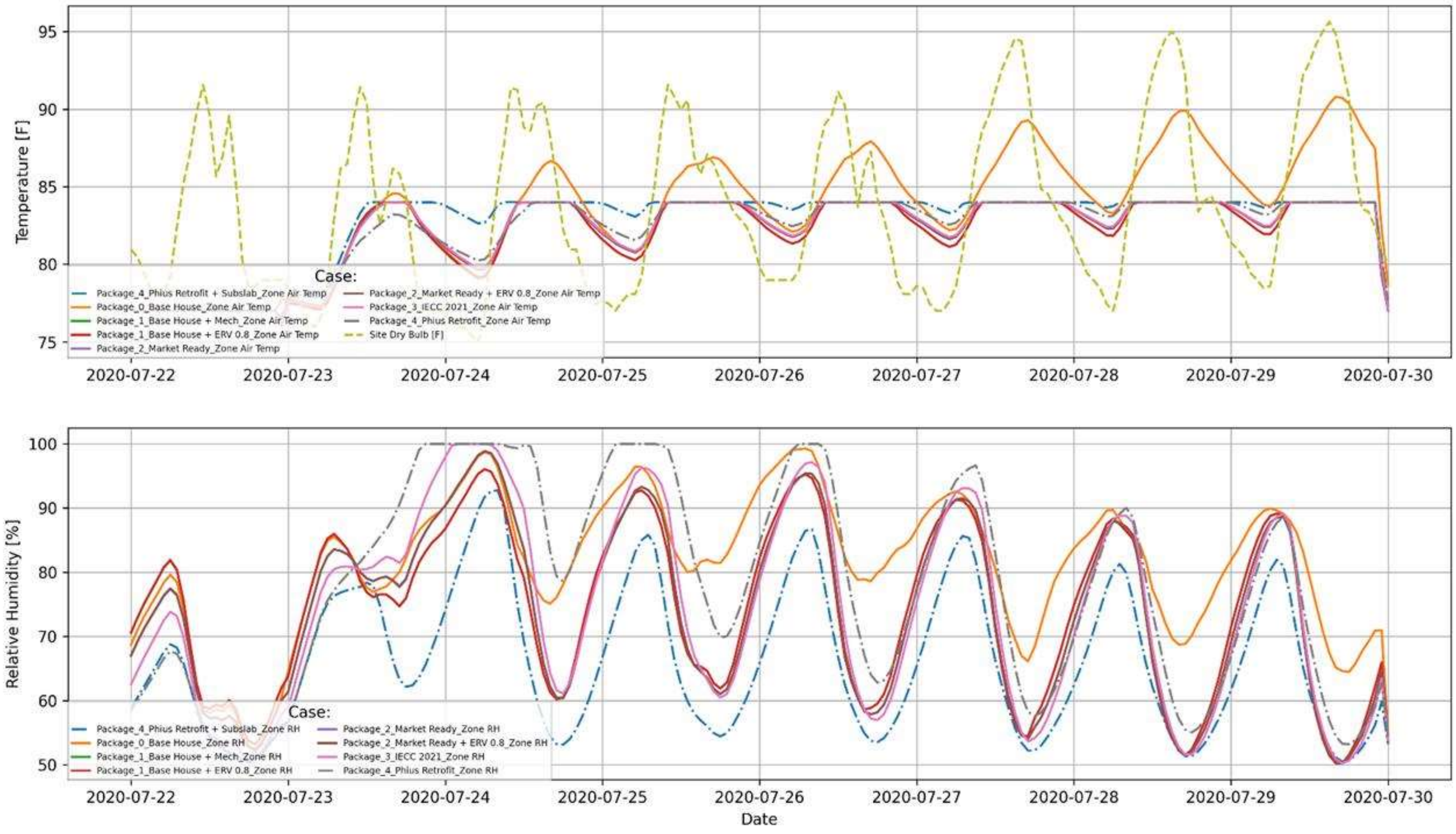

MIAMI_NV_Heating Outage Resilience
Temperature [F]
100
90
80
70
60
50
40
30
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
Relative Humidity [%]
100
90
80
70
60
50
40
30
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-01-21
2020-01-22
2020-01-23
2020-01-24
2020-01-25
2020-01-26
2020-01-27
2020-01-28
2020-01-29
Date

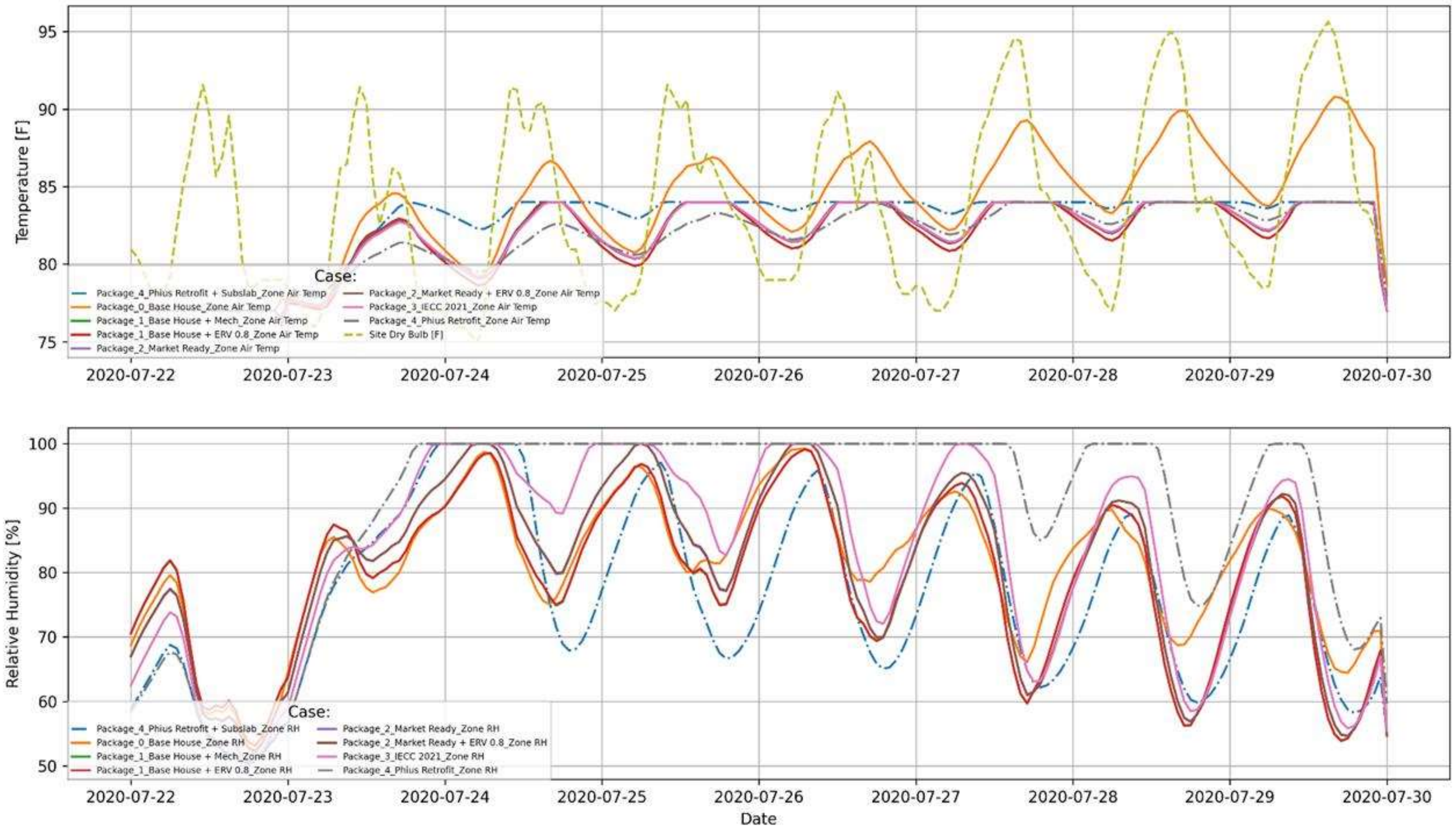


MIAMI_SNV_Cooling Outage Resilience
Temperature [F]
95
90
85
80
75
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
2020-07-22
2020-07-23
2020-07-24
2020-07-25
2020-07-26
2020-07-27
2020-07-28
2020-07-29
2020-07-30
Relative Humidity [%]
100
90
80
70
60
50
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-07-22
2020-07-23
2020-07-24
2020-07-25
2020-07-26
2020-07-27
2020-07-28
2020-07-29
2020-07-30
Date


MIAMI_SNV+Shd_Cooling Outage Resilience
Temperature [F]
95
90
85
80
75
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
2020-07-22
2020-07-23
2020-07-24
2020-07-25
2020-07-26
2020-07-27
2020-07-28
2020-07-29
2020-07-30
Relative Humidity [%]
100
90
80
70
60
50
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-07-22
2020-07-23
2020-07-24
2020-07-25
2020-07-26
2020-07-27
2020-07-28
2020-07-29
2020-07-30
Date

MIAMI_HP_Cooling Outage Resilience

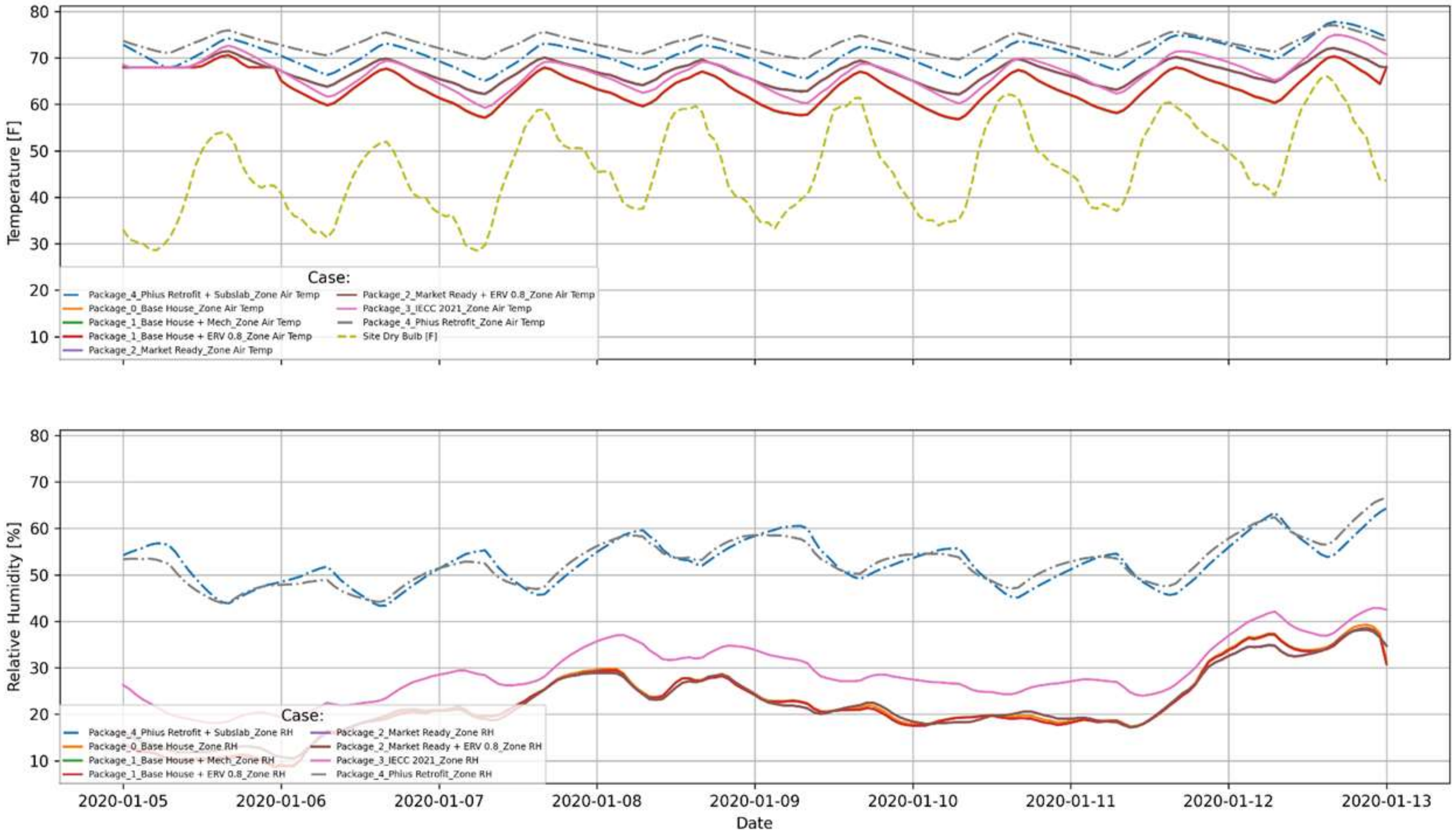


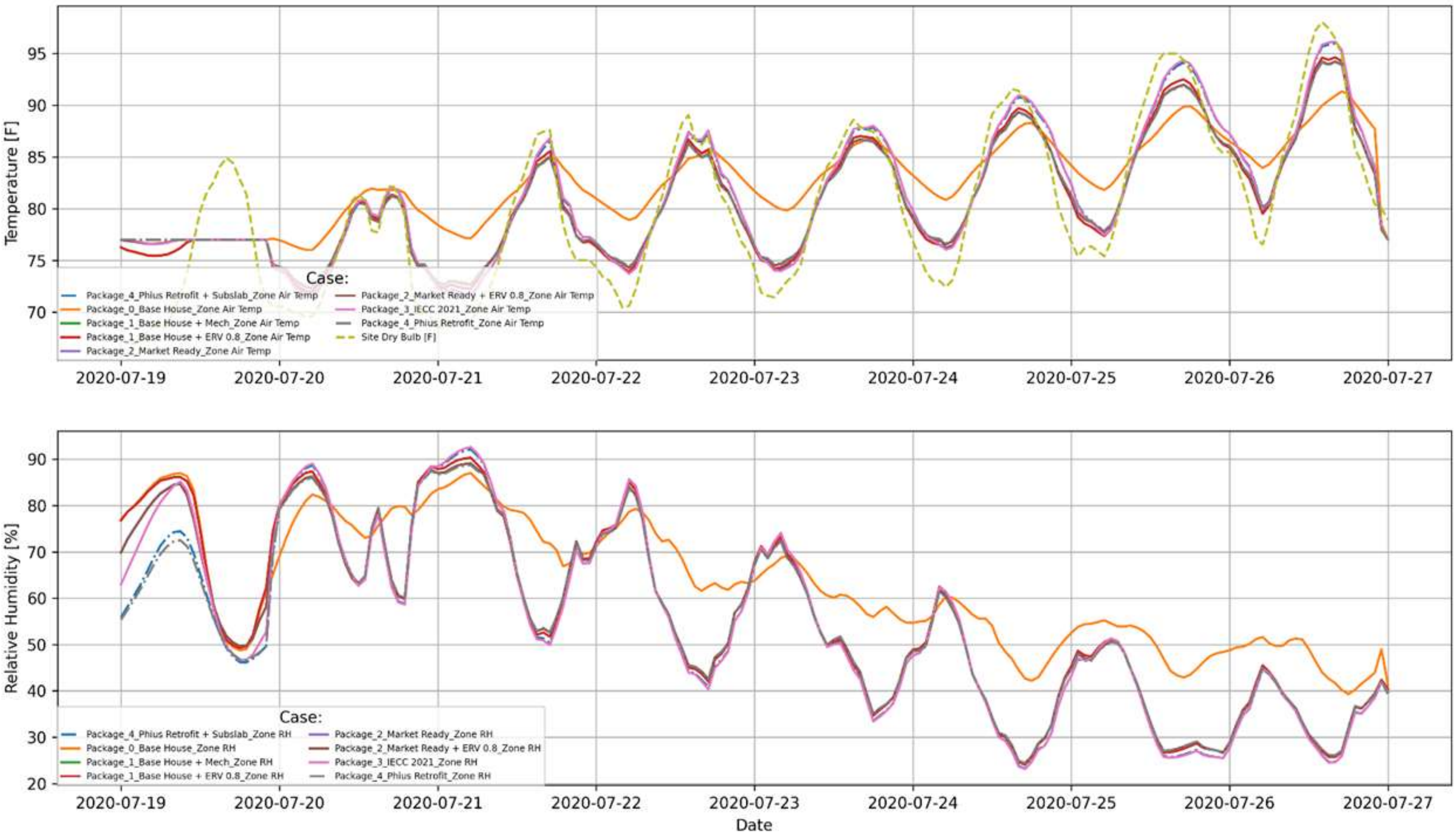


MIAMI_HP+Shd_Cooling Outage Resilience

El Paso, TX

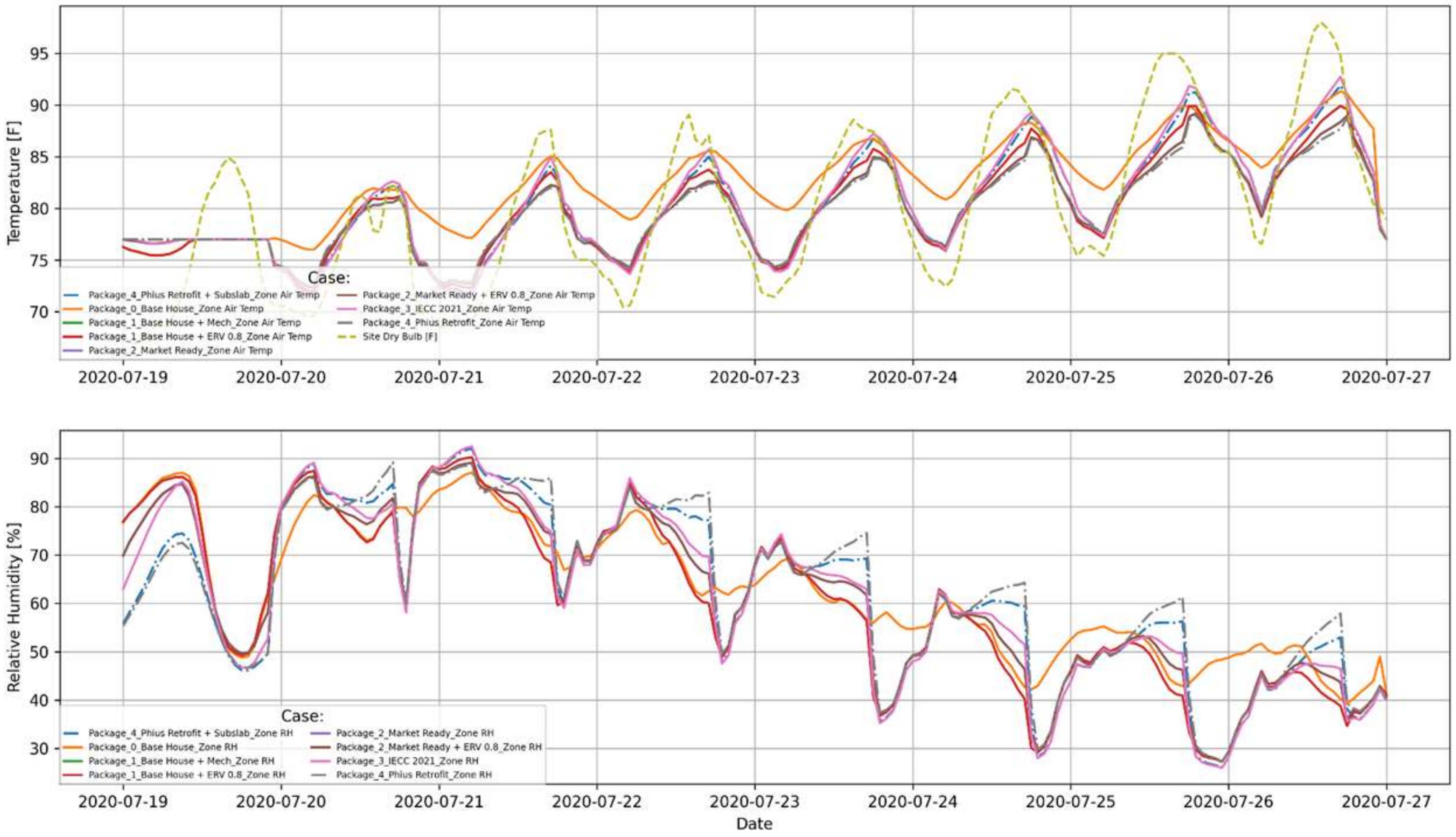
EL-PASO_NV_Heating Outage Resilience

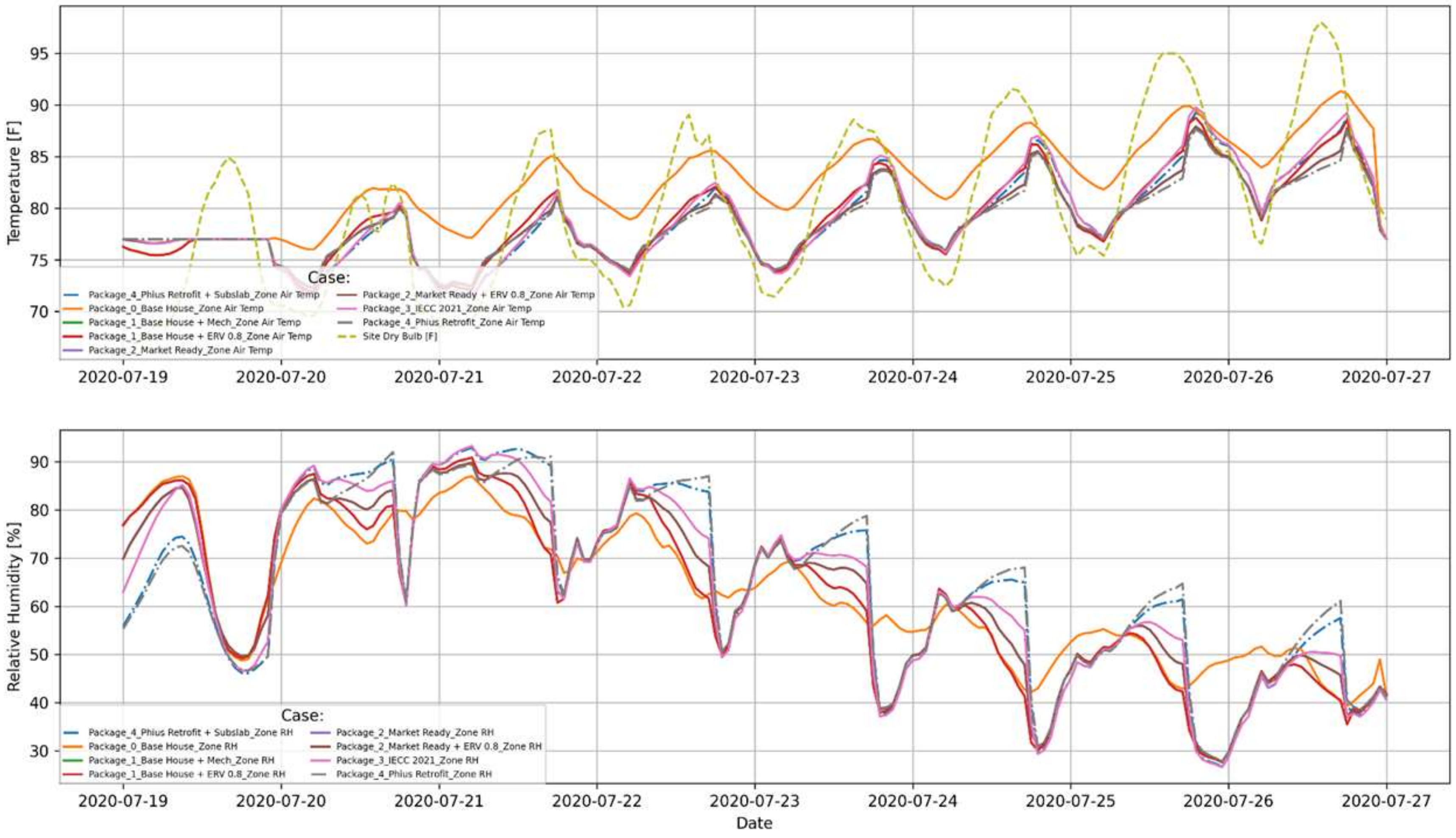


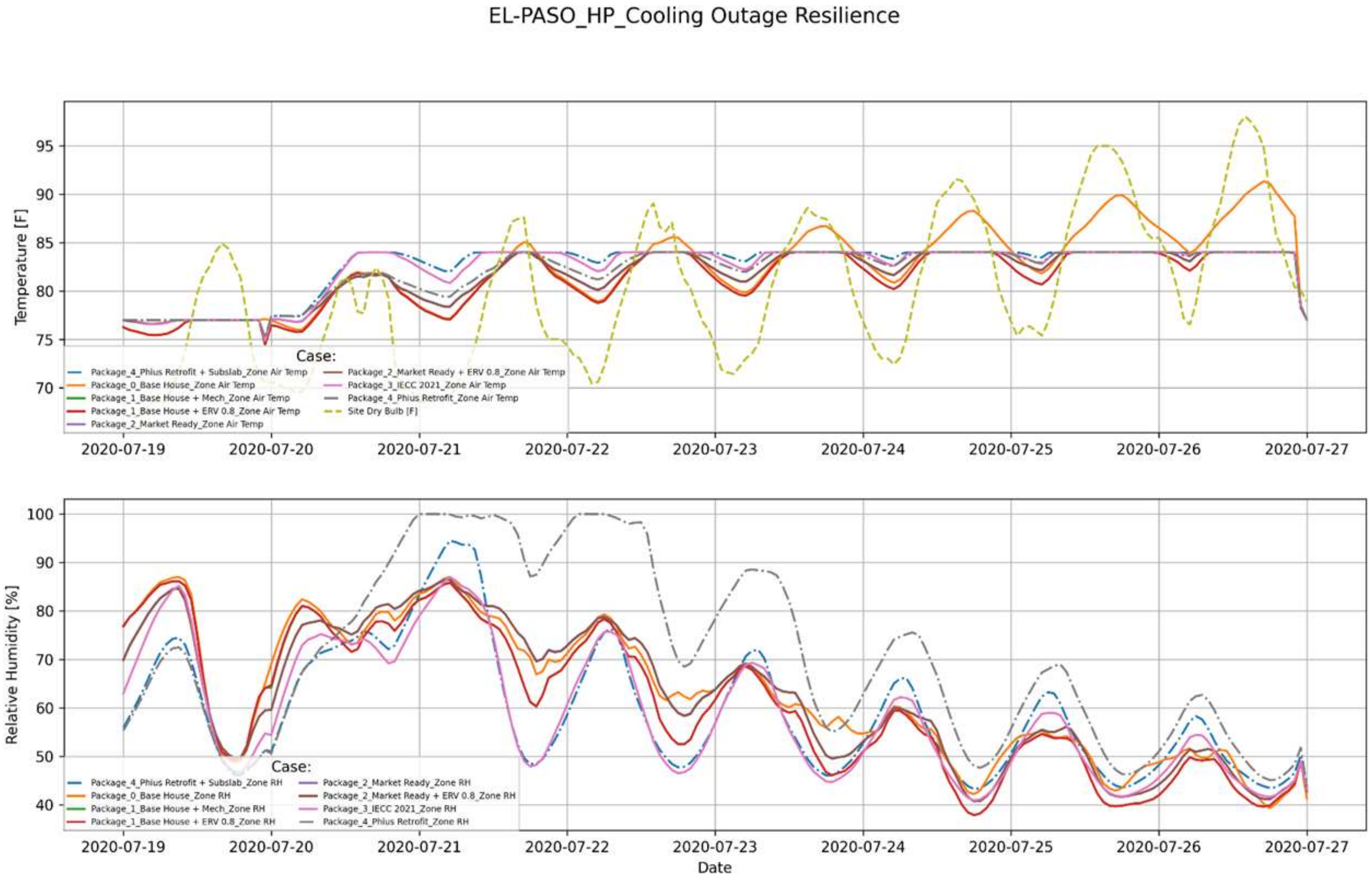


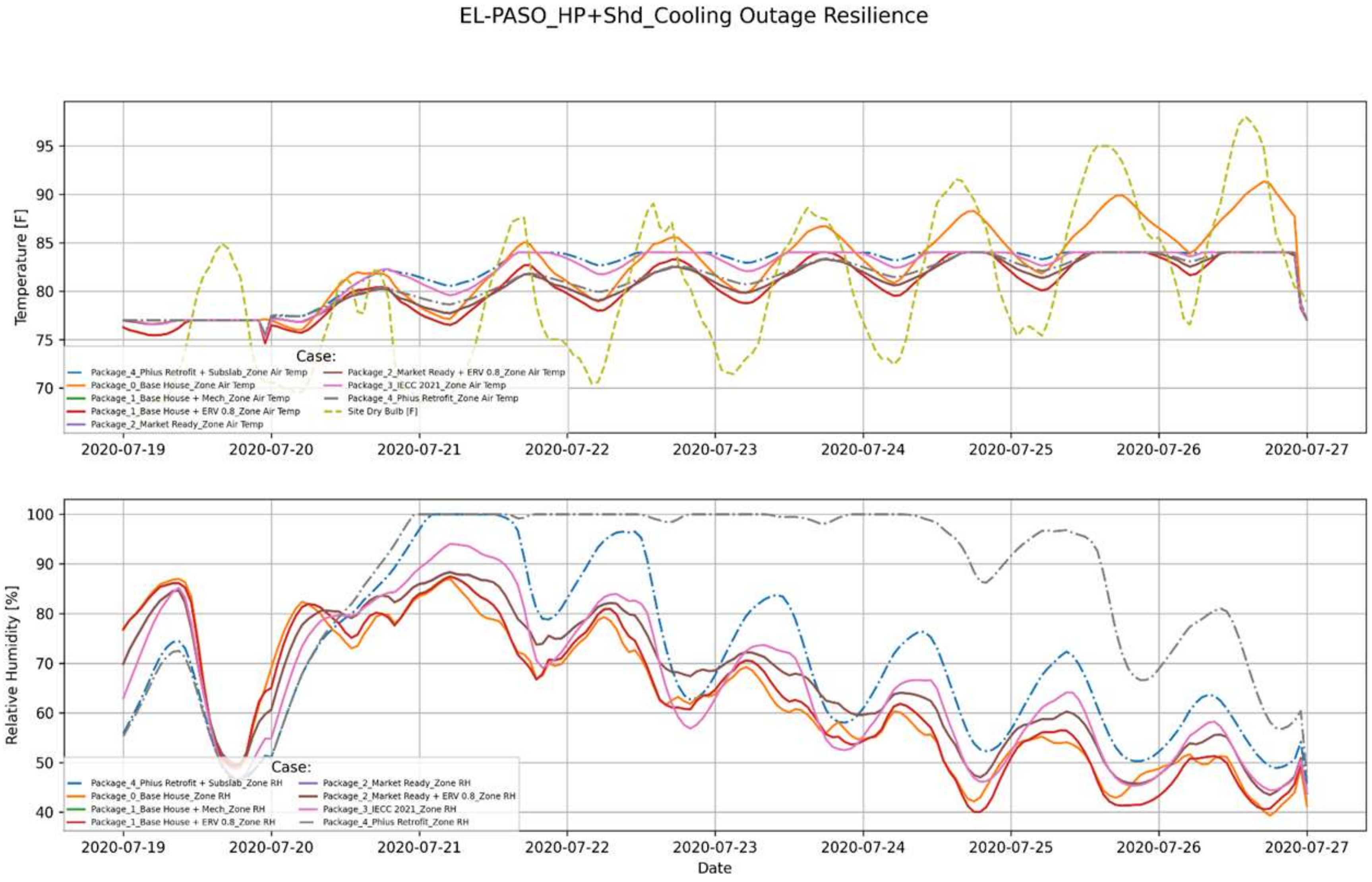
EL-PASO_NV_Cooling Outage Resilience

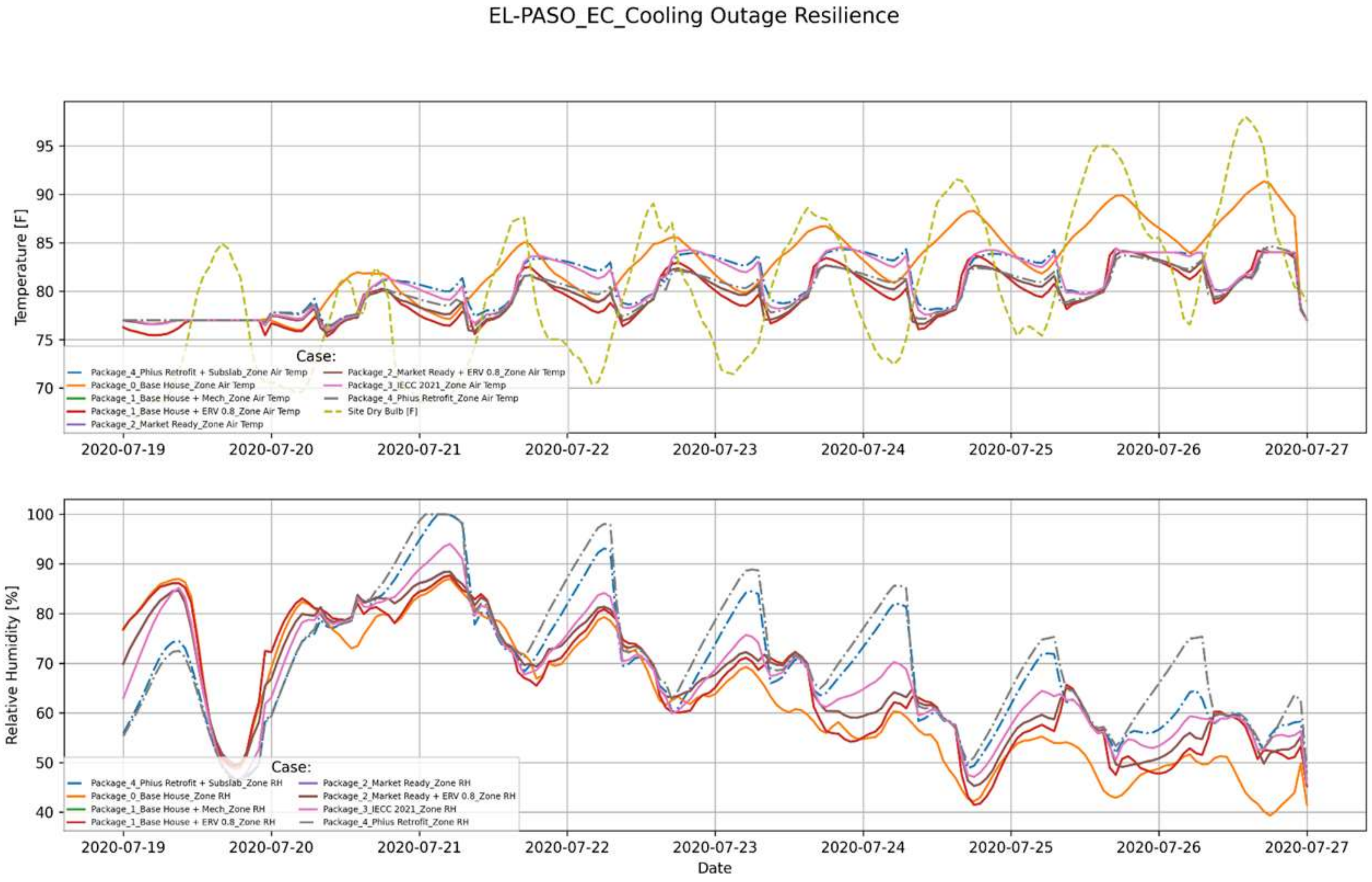
EL-PASO_SNV_Cooling Outage Resilience

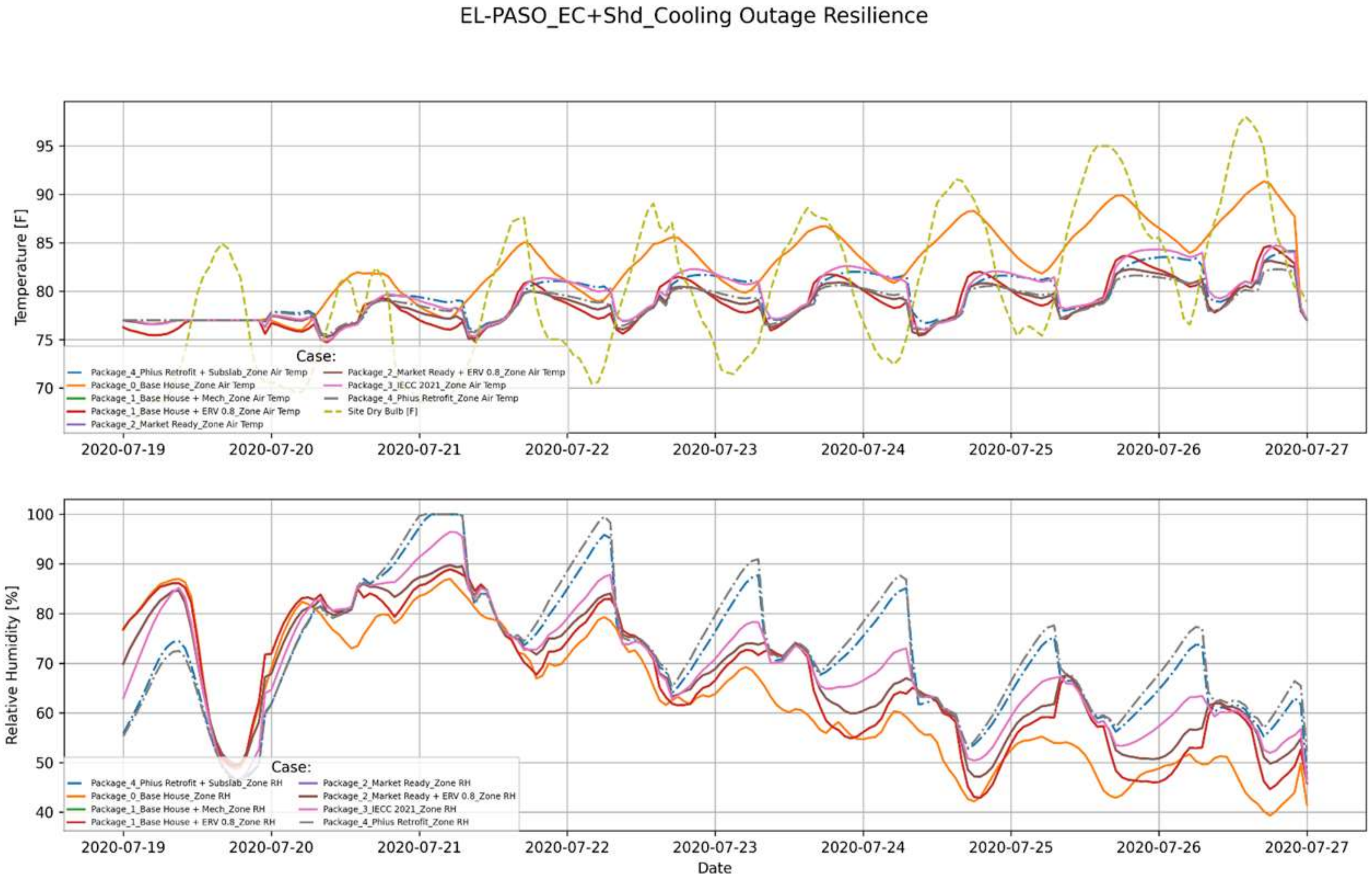



EL-PASO_SNV+Shd_Cooling Outage Resilience


EL-PASO_HP_Cooling Outage Resilience
Temperature [F]
95
90
85
80
75
70
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
2020-07-19
2020-07-20
2020-07-21
2020-07-22
2020-07-23
2020-07-24
2020-07-25
2020-07-26
2020-07-27
Relative Humidity [%]
100
90
80
70
60
50
40
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-07-19
2020-07-20
2020-07-21
2020-07-22
2020-07-23
2020-07-24
2020-07-25
2020-07-26
2020-07-27
Date

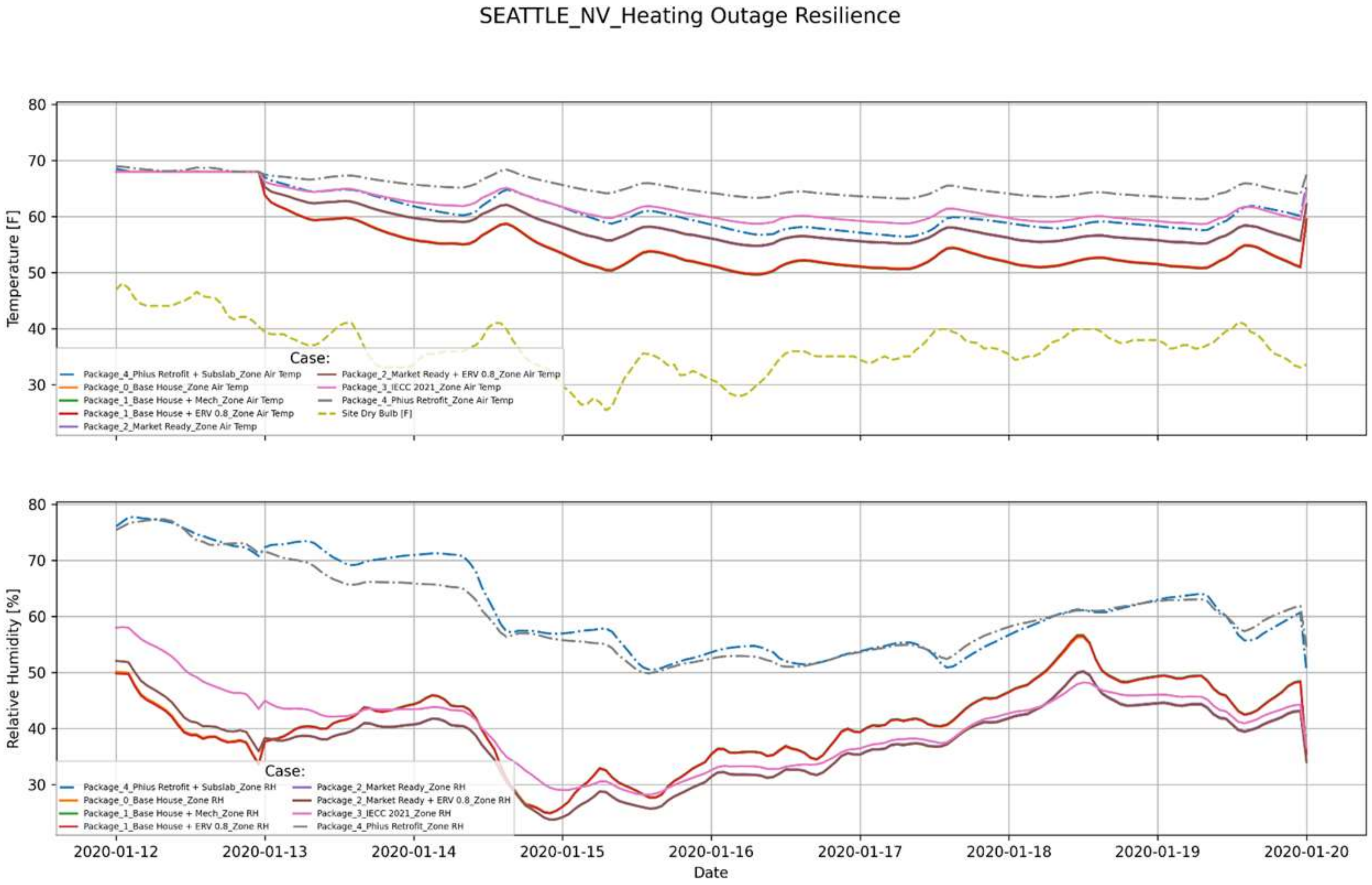
EL-PASO_HP+Shd_Cooling Outage Resilience
Temperature [F]
95
90
85
80
75
70
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
2020-07-19
2020-07-20
2020-07-21
2020-07-22
2020-07-23
2020-07-24
2020-07-25
2020-07-26
2020-07-27
Relative Humidity [%]
100
90
80
70
60
50
40
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-07-19
2020-07-20
2020-07-21
2020-07-22
2020-07-23
2020-07-24
2020-07-25
2020-07-26
2020-07-27
Date

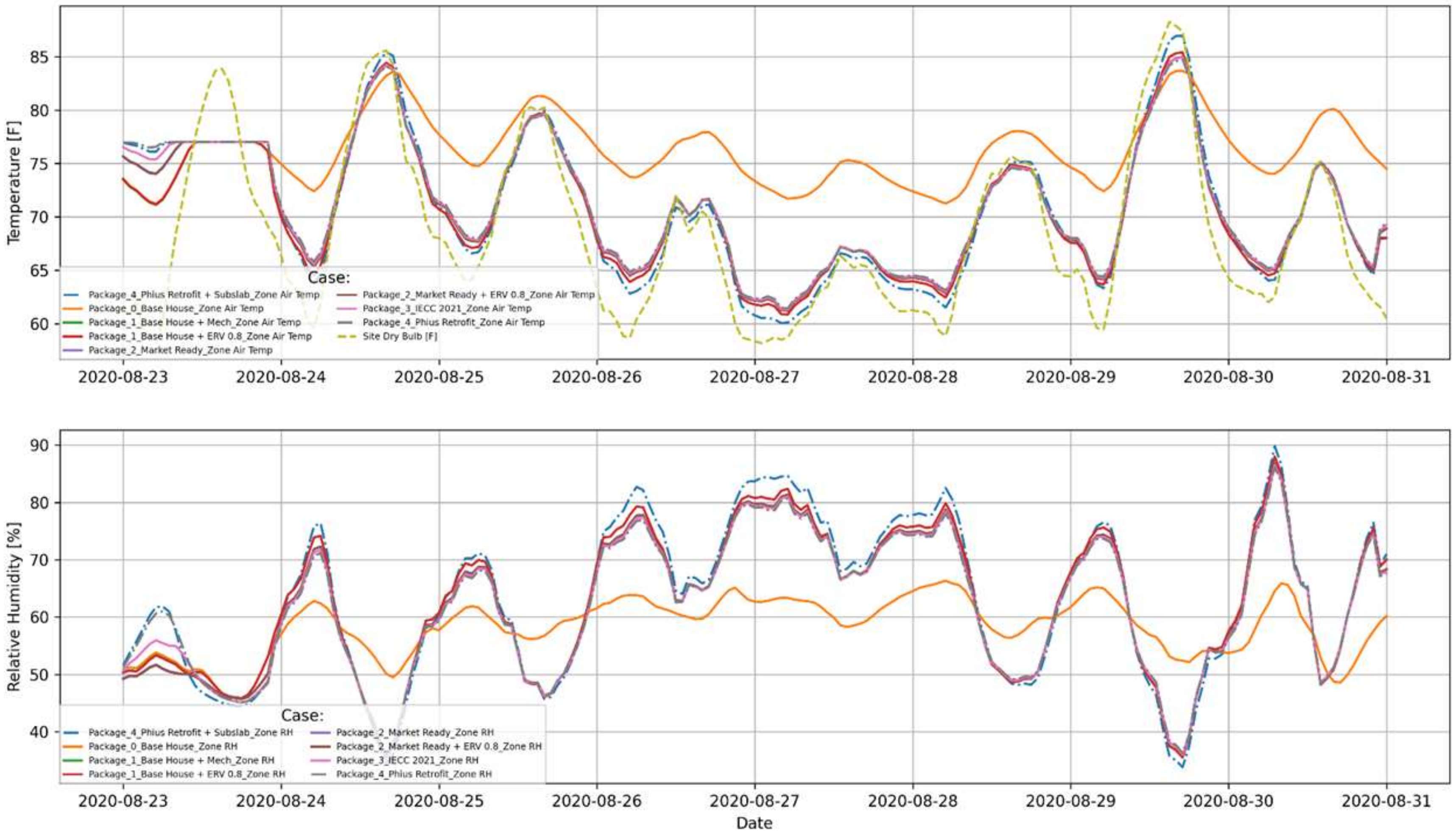

EL-PASO_EC_Cooling Outage Resilience
Temperature [F]
95
90
85
80
75
70
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
2020-07-19
2020-07-20
2020-07-21
2020-07-22
2020-07-23
2020-07-24
2020-07-25
2020-07-26
2020-07-27
Relative Humidity [%]
100
90
80
70
60
50
40
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-07-19
2020-07-20
2020-07-21
2020-07-22
2020-07-23
2020-07-24
2020-07-25
2020-07-26
2020-07-27
Date



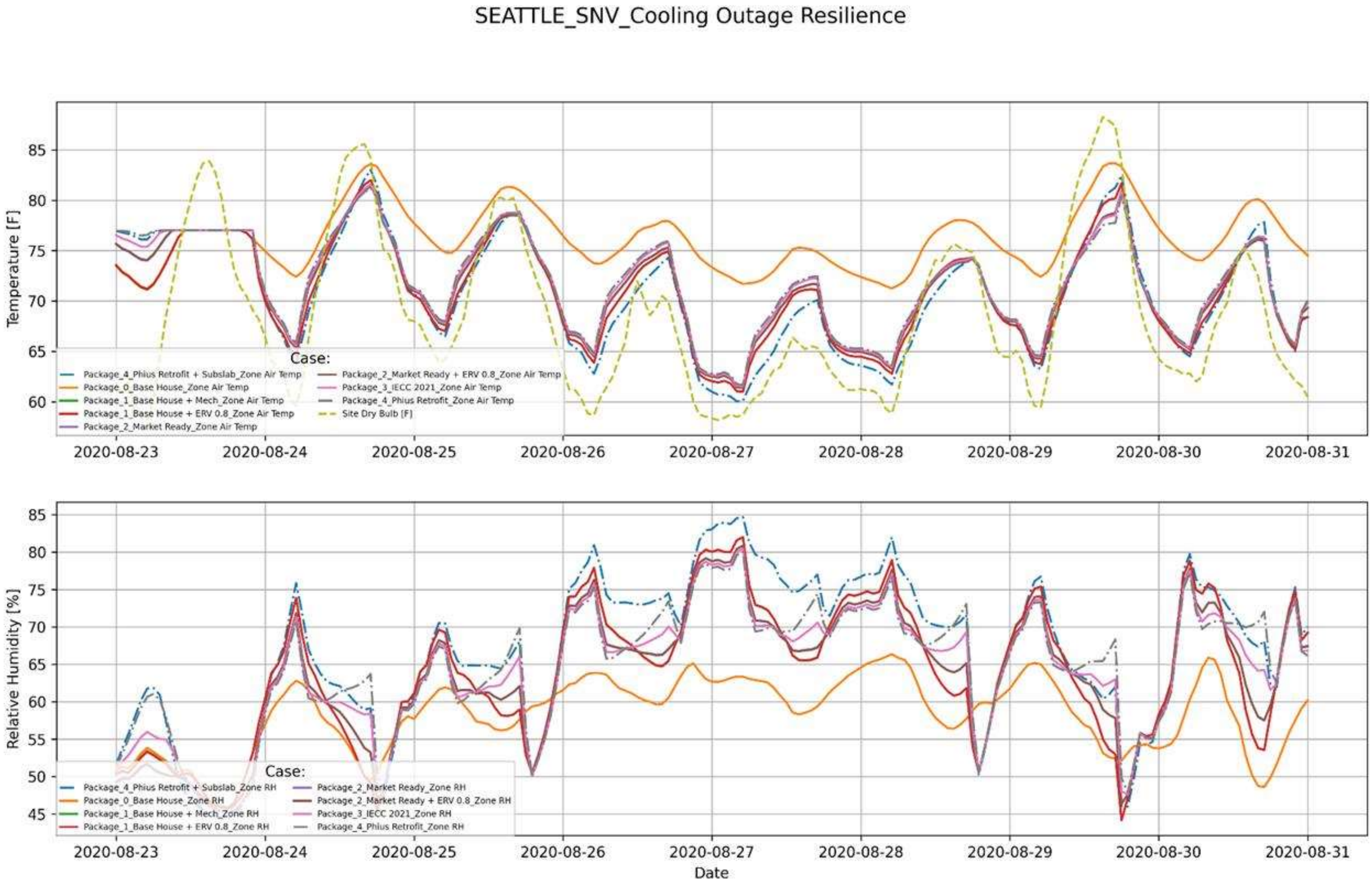
EL-PASO_EC+Shd_Cooling Outage Resilience

Seattle, WA

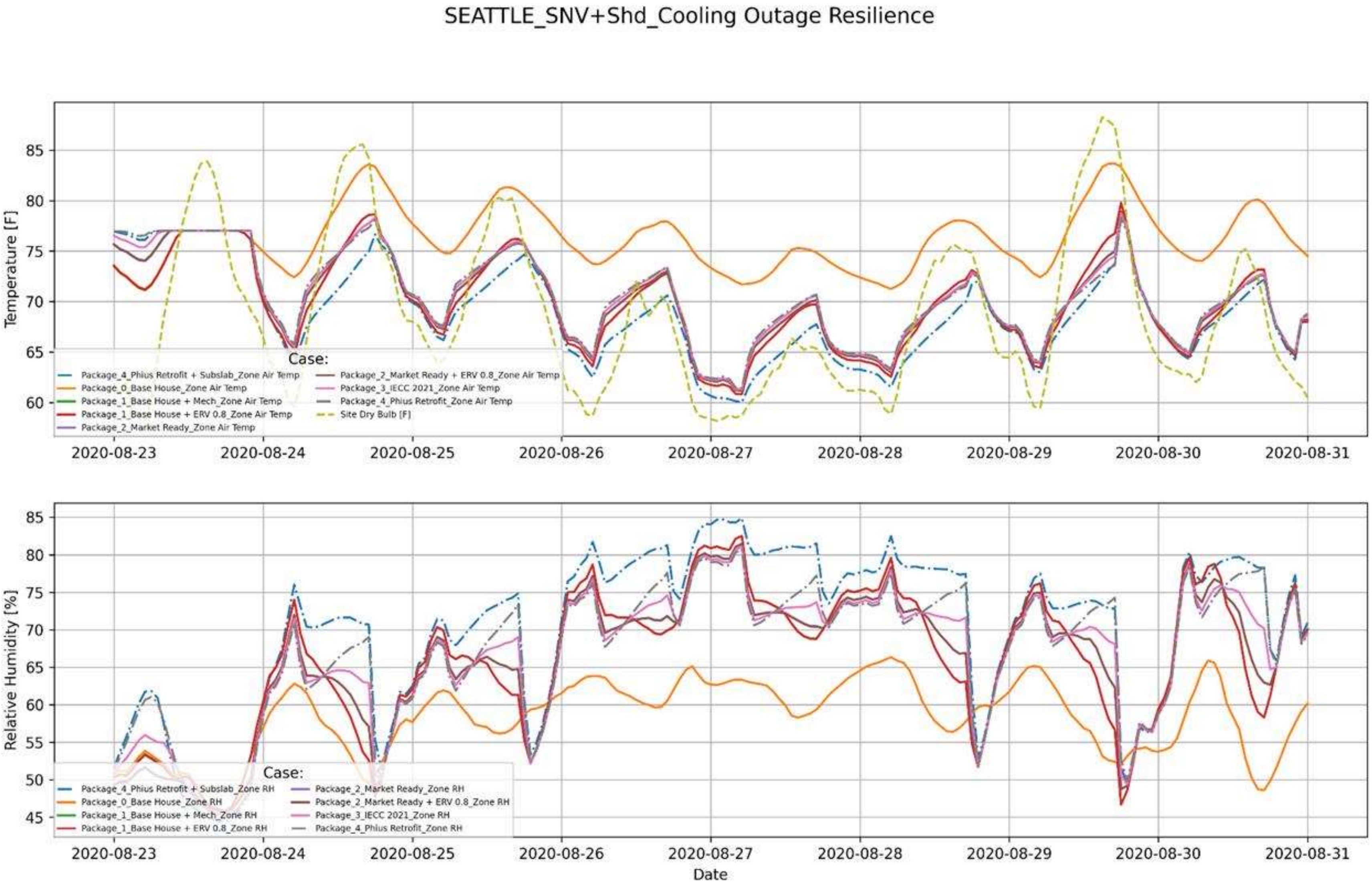

SEATTLE_NV_Heating Outage Resilience
Temperature [F]
80
70
60
50
40
30
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
Relative Humidity [%]
80
70
60
50
40
30
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-01-12
2020-01-13
2020-01-14
2020-01-15
2020-01-16
2020-01-17
2020-01-18
2020-01-19
2020-01-20
Date

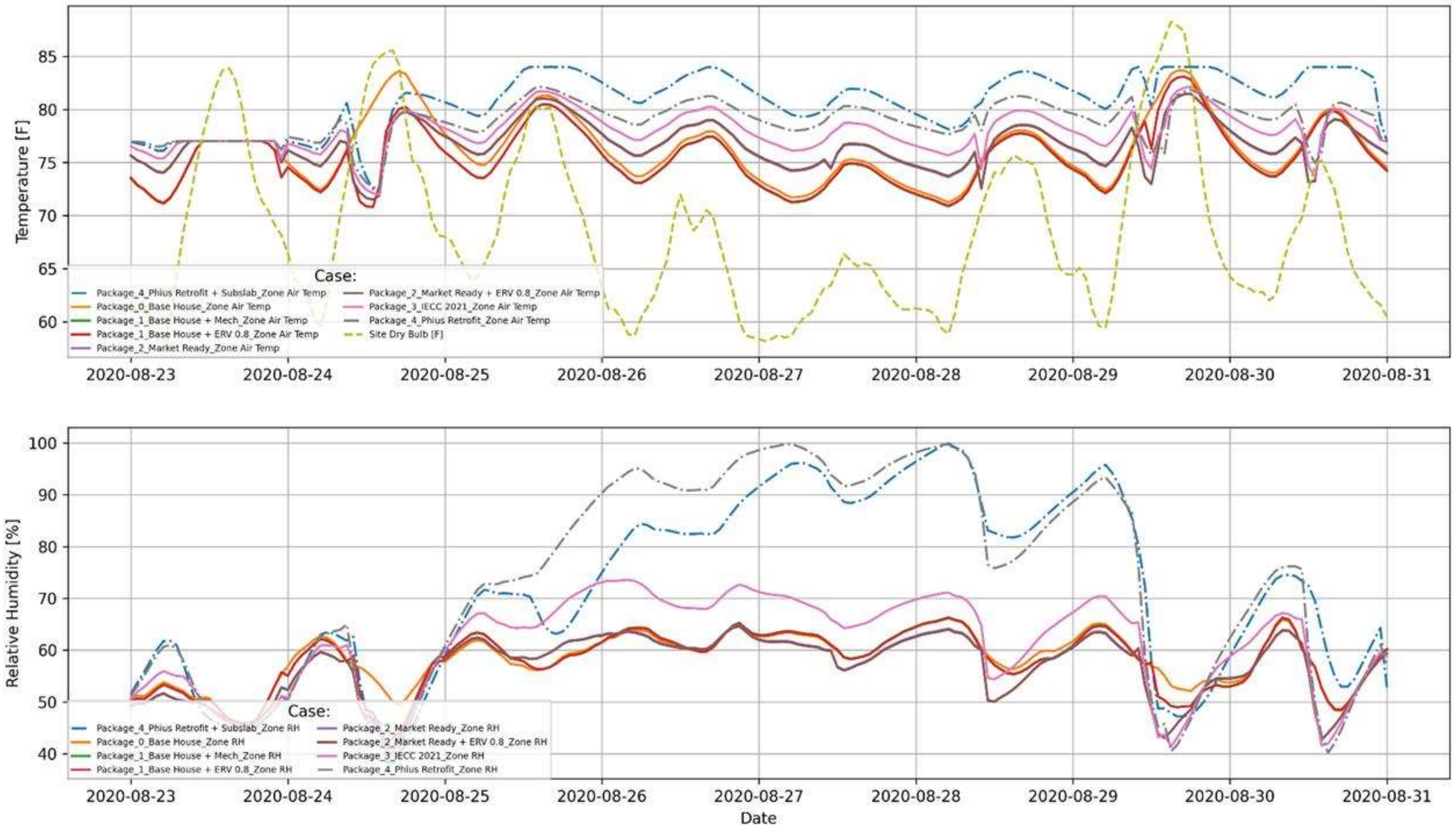


SEATTLE_NV_Cooling Outage Resilience

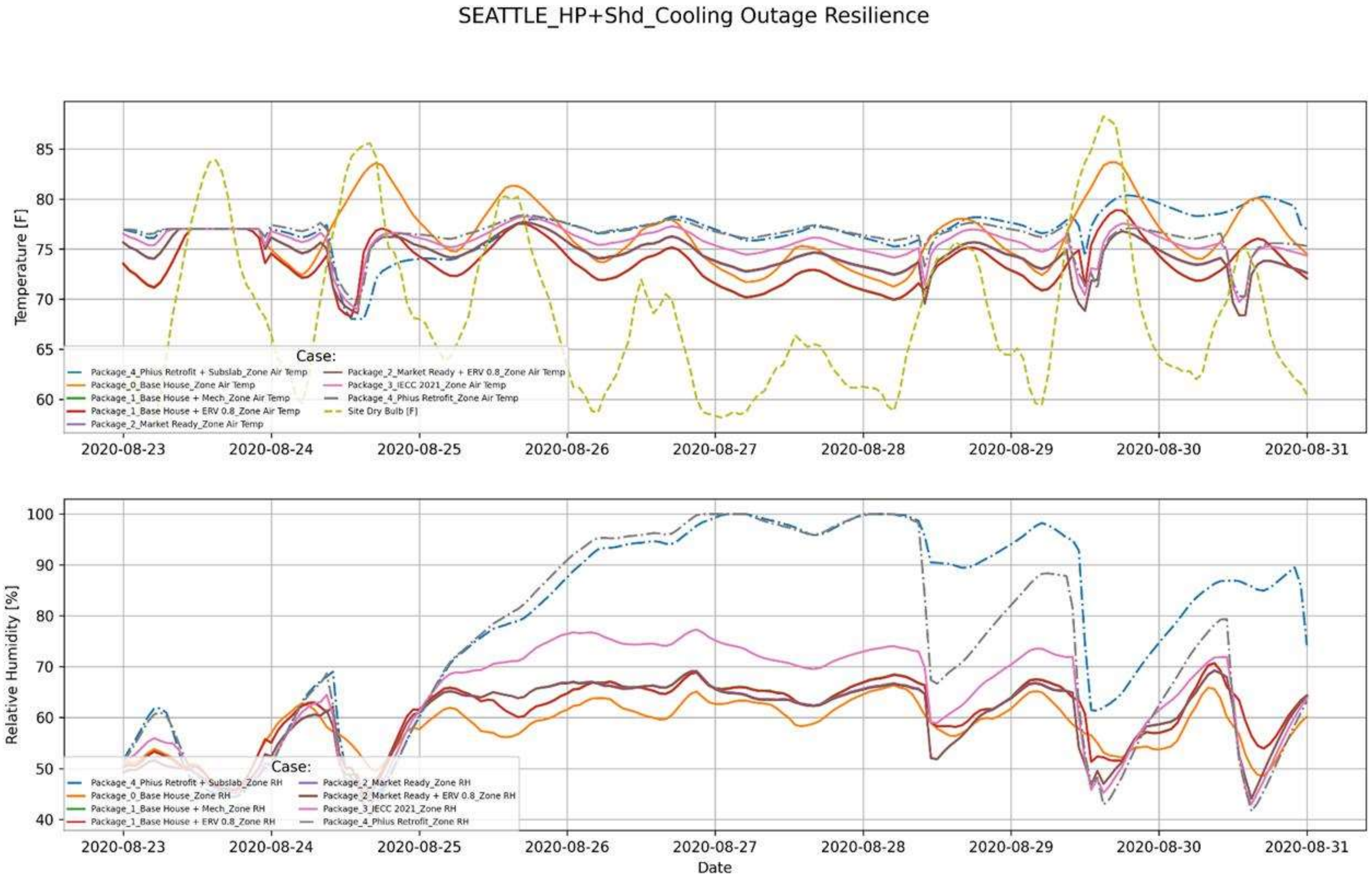


SEATTLE_SNV_Cooling Outage Resilience

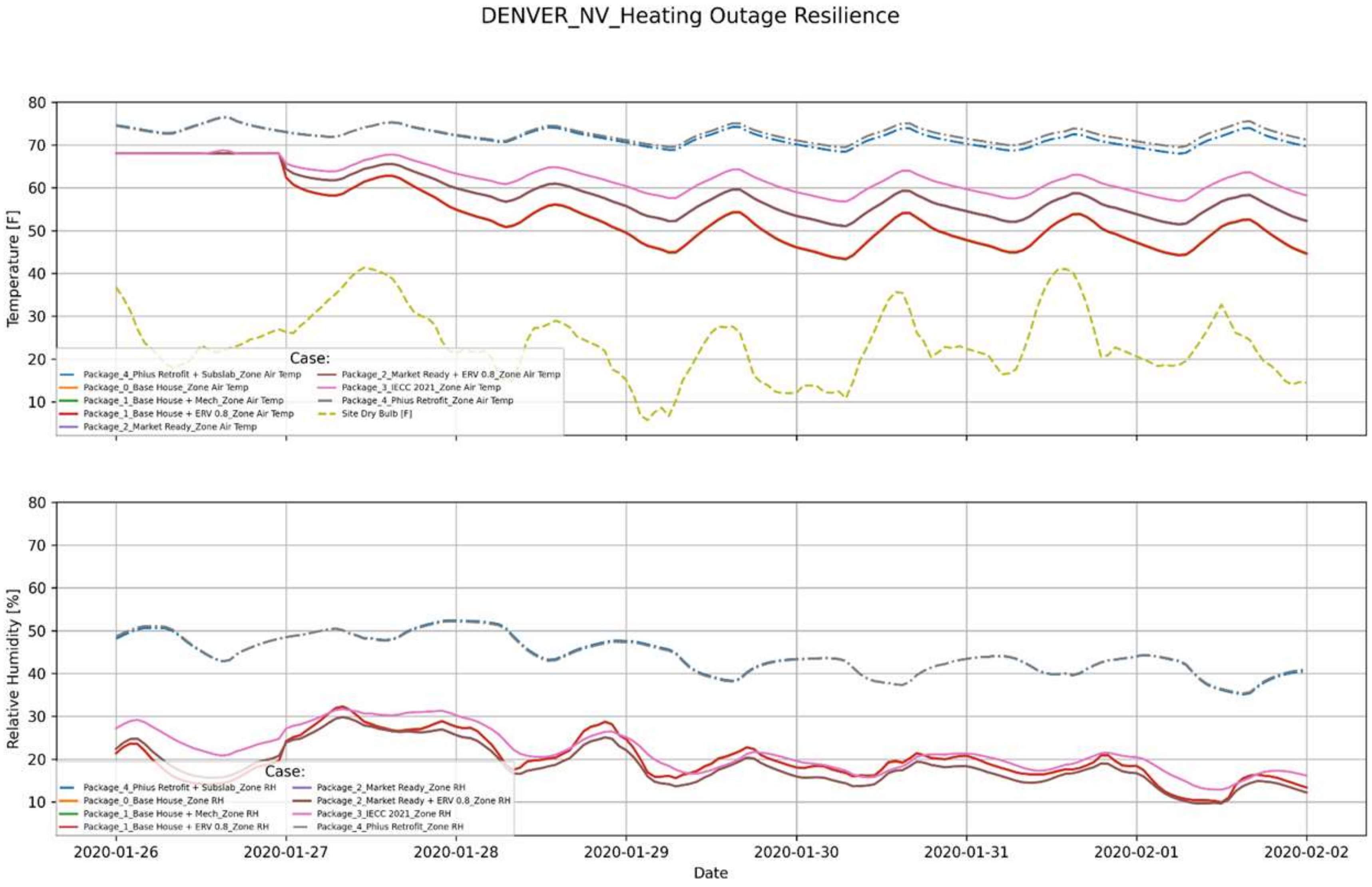

SEATTLE_SNV+Shd_Cooling Outage Resilience
Temperature [F]
85
80
75
70
65
60
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
2020-08-23
2020-08-24
2020-08-25
2020-08-26
2020-08-27
2020-08-28
2020-08-29
2020-08-30
2020-08-31
Relative Humidity [%]
85
80
75
70
65
60
55
50
45
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-08-23
2020-08-24
2020-08-25
2020-08-26
2020-08-27
2020-08-28
2020-08-29
2020-08-30
2020-08-31
Date



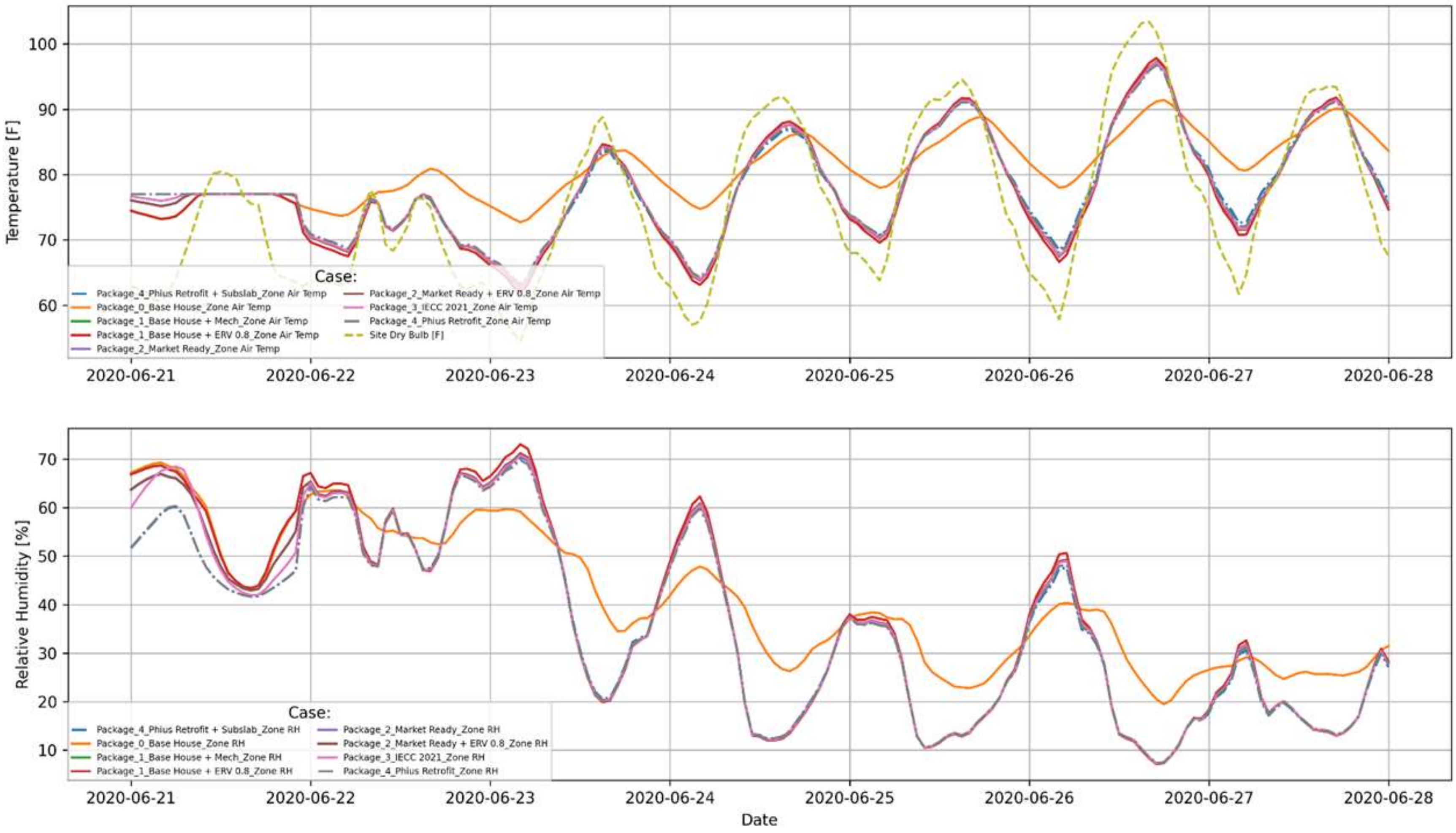
SEATTLE_HP_Cooling Outage Resilience

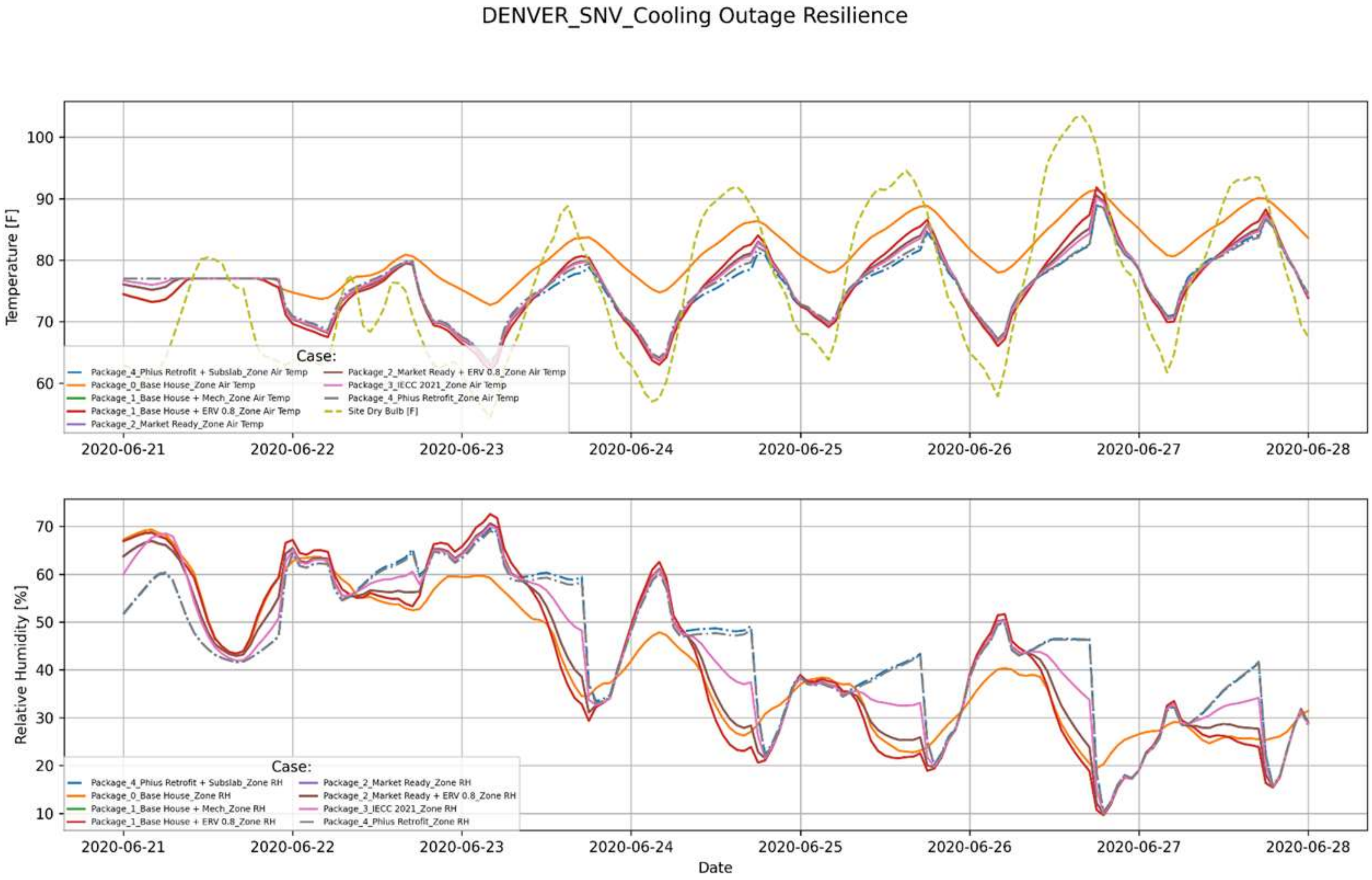

SEATTLE_HP+Shd_Cooling Outage Resilience
Temperature [F]
85
80
75
70
65
60
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
2020-08-23
2020-08-24
2020-08-25
2020-08-26
2020-08-27
2020-08-28
2020-08-29
2020-08-30
2020-08-31
Relative Humidity [%]
100
90
80
70
60
50
40
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-08-23
2020-08-24
2020-08-25
2020-08-26
2020-08-27
2020-08-28
2020-08-29
2020-08-30
2020-08-31
Date

Denver, CO

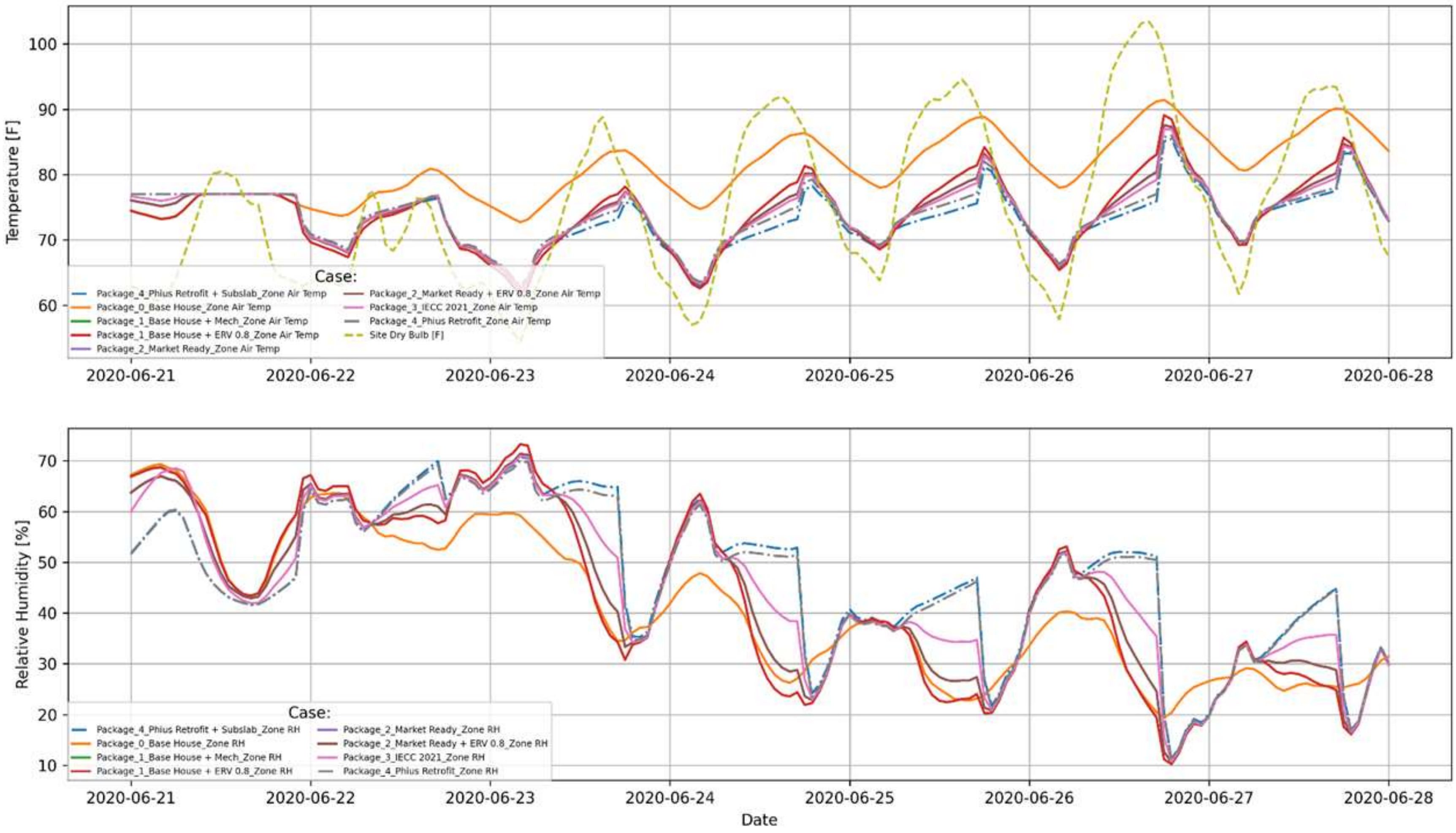

DENVER_NV_Heating Outage Resilience
Temperature [F]
80
70
60
50
40
30
20
10
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
Relative Humidity [%]
80
70
60
50
40
30
20
10
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-01-26
2020-01-27
2020-01-28
2020-01-29
2020-01-30
2020-01-31
2020-02-01
2020-02-02
Date

DENVER_NV_Cooling Outage Resilience

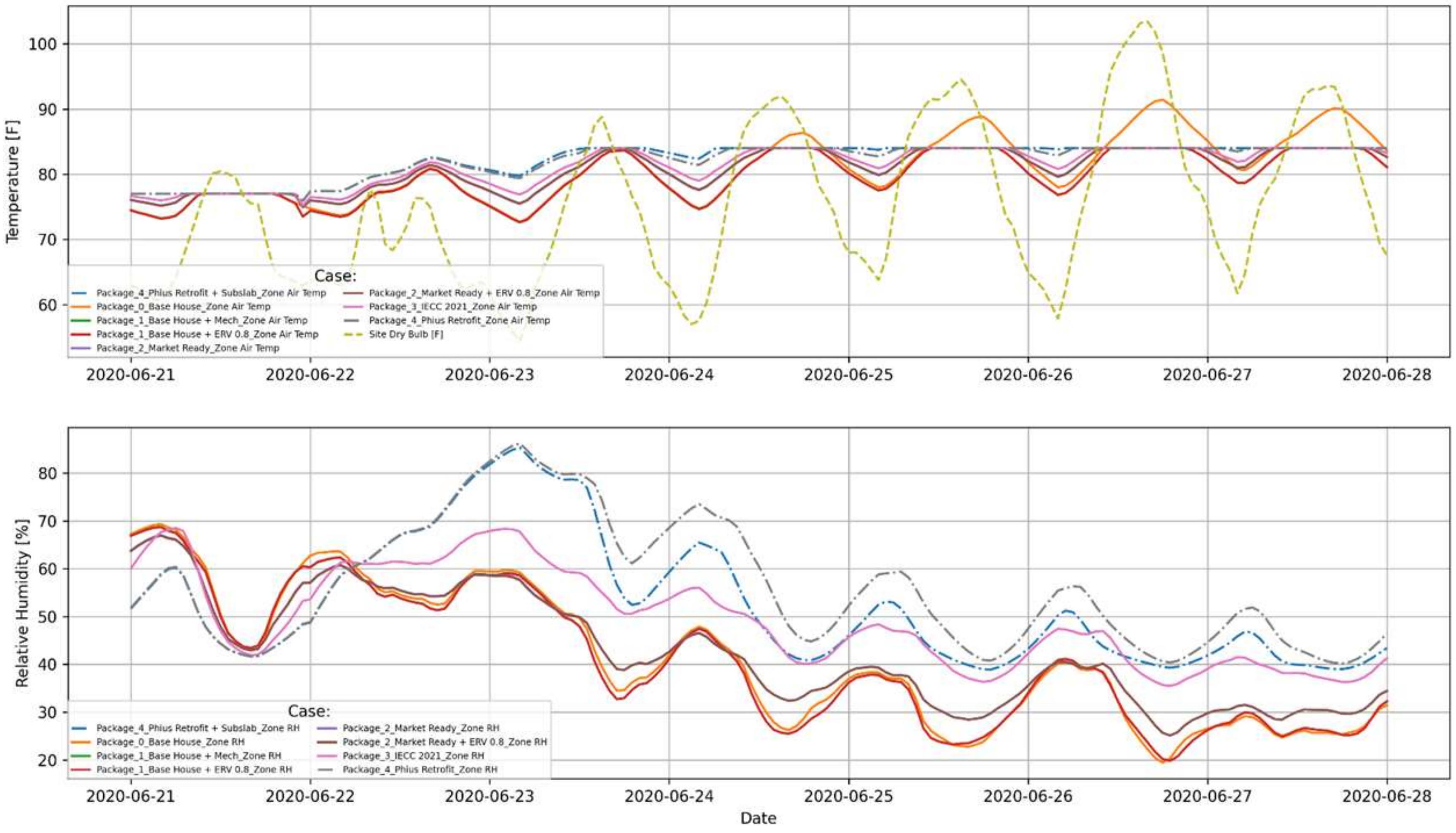


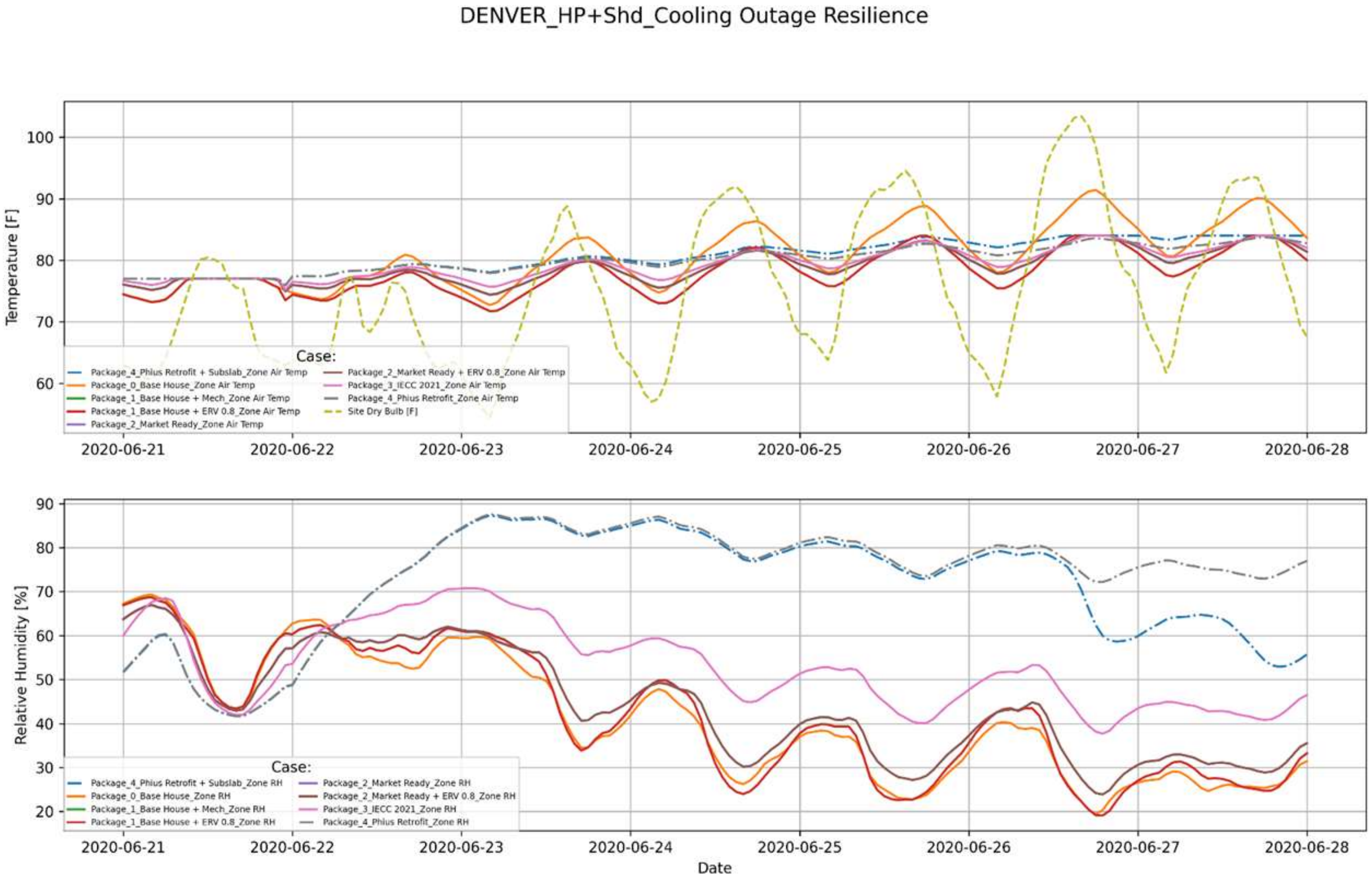

DENVER_SNV_Cooling Outage Resilience

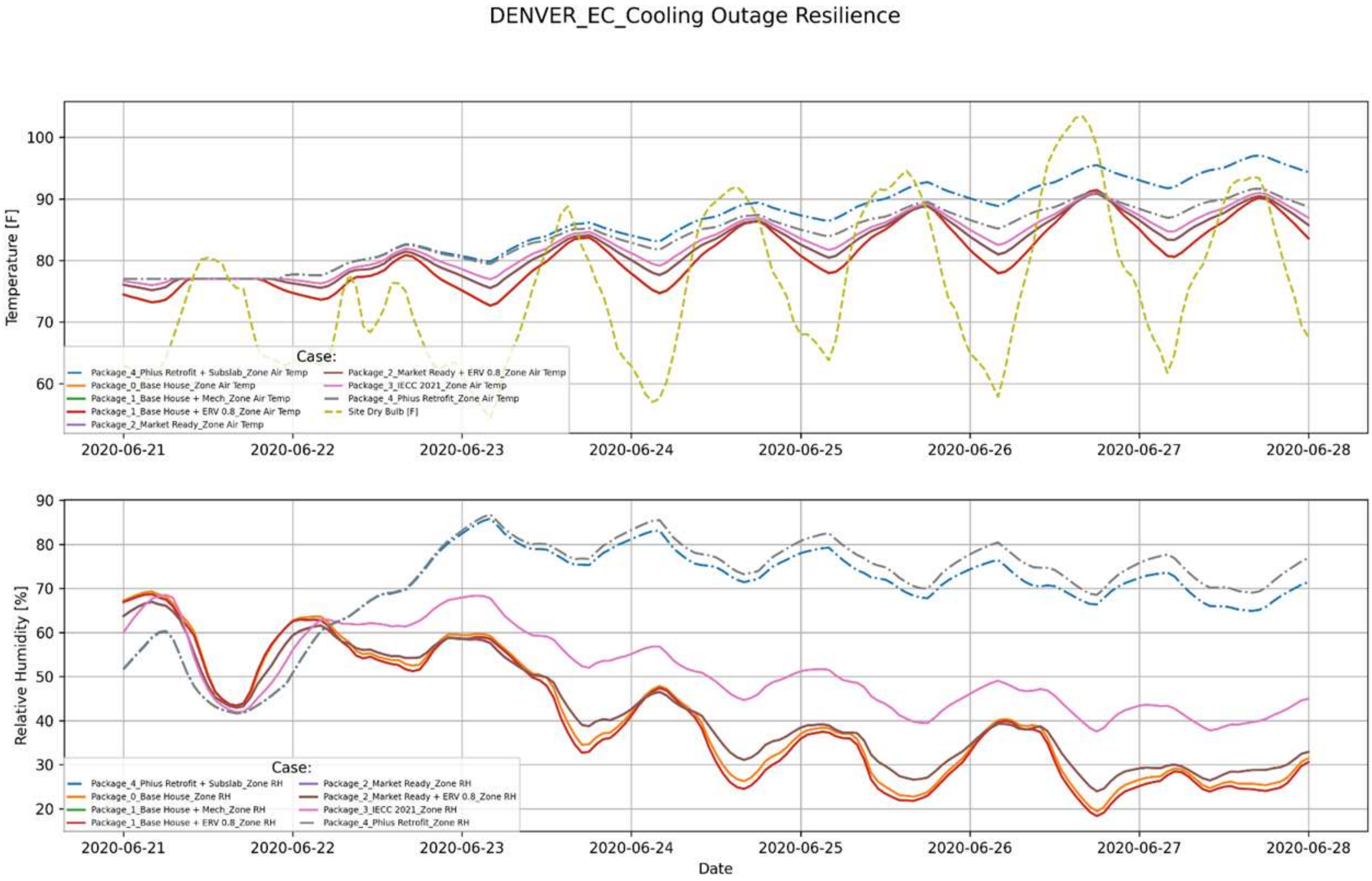
DENVER_SNV+Shd_Cooling Outage Resilience

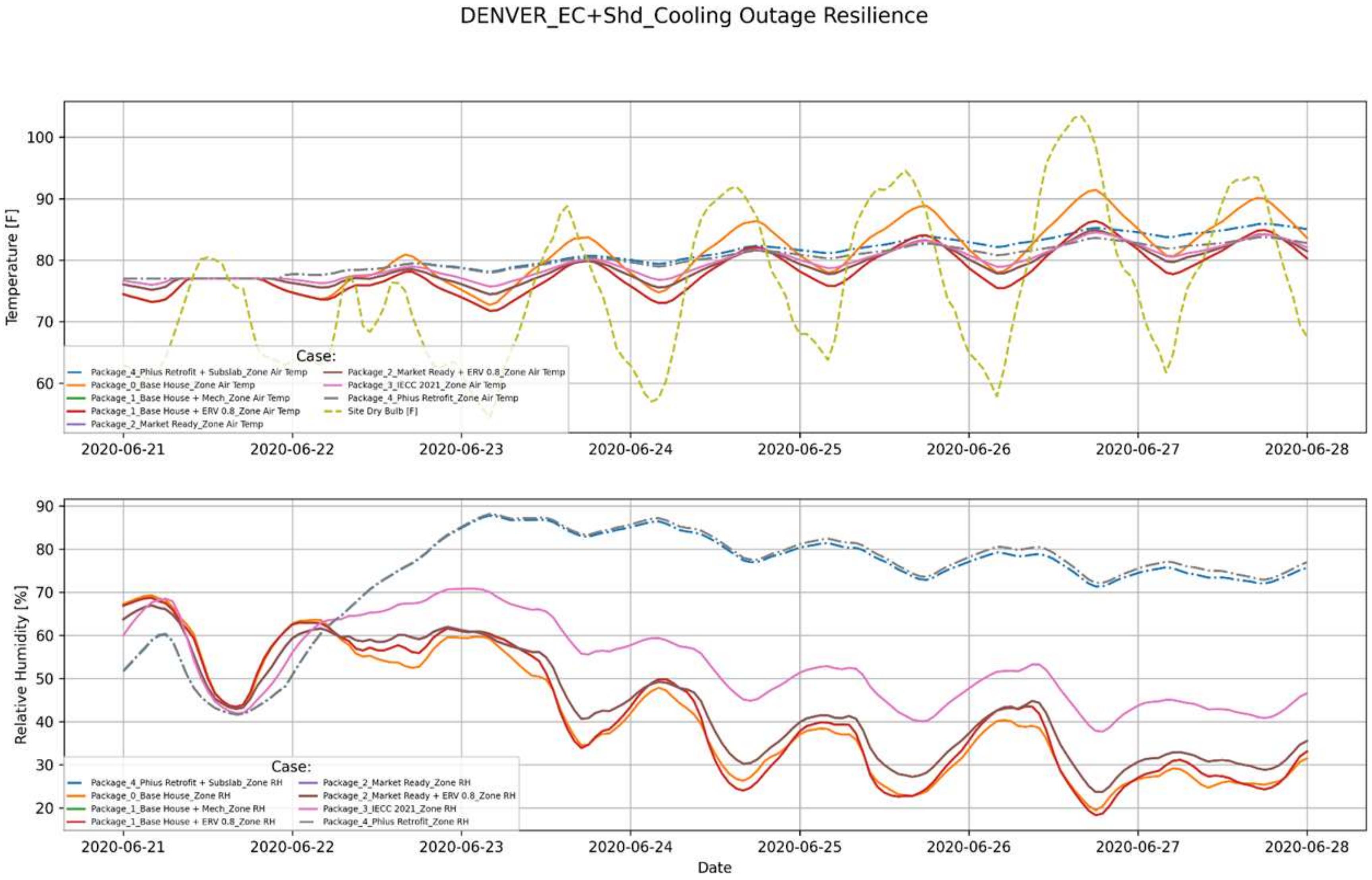


DENVER_HP_Cooling Outage Resilience



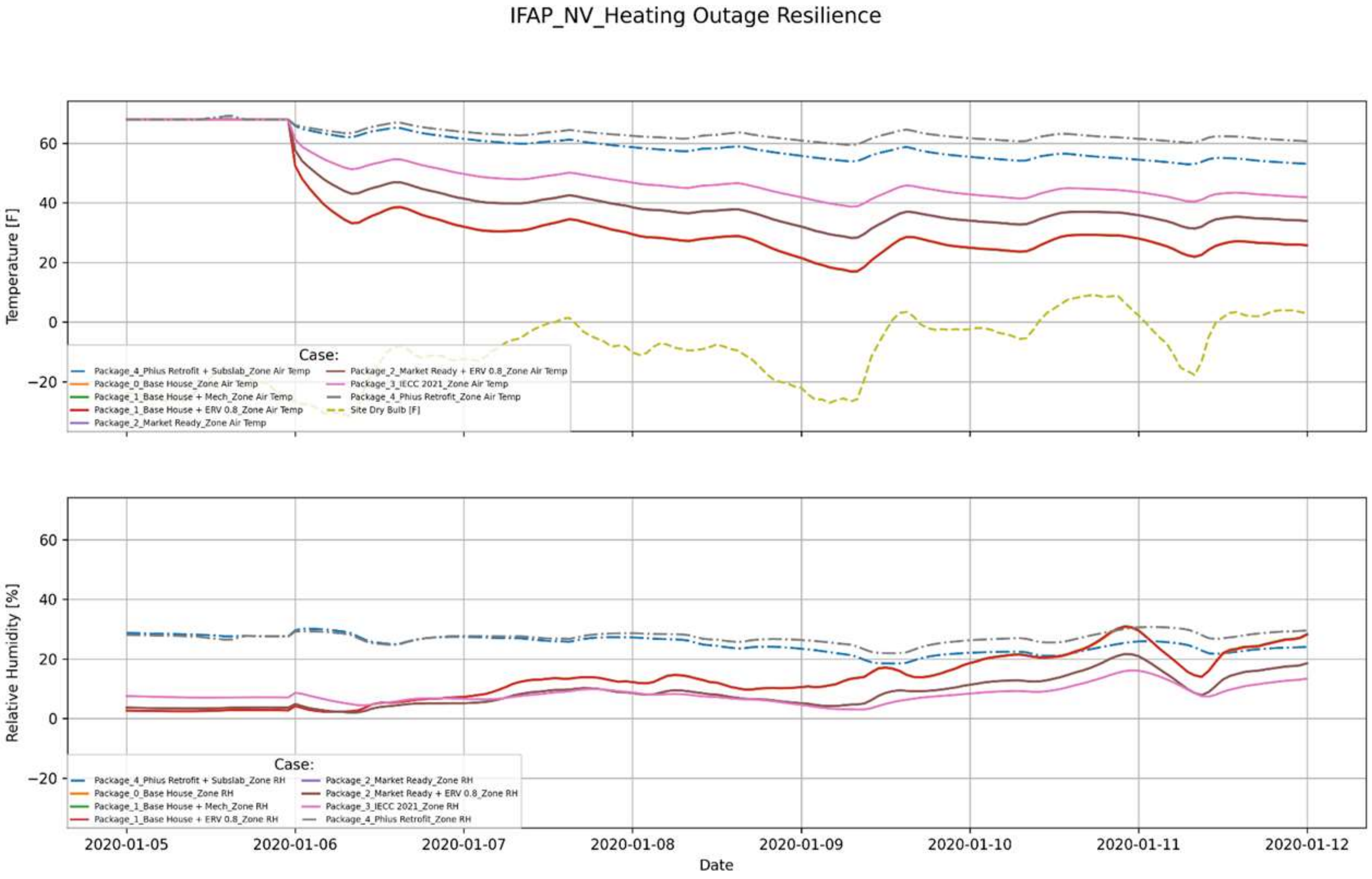

DENVER_HP+Shd_Cooling Outage Resilience
Temperature [F]
100
90
80
70
60
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
2020-06-21
2020-06-22
2020-06-23
2020-06-24
2020-06-25
2020-06-26
2020-06-27
2020-06-28
Relative Humidity [%]
90
80
70
60
50
40
30
20
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-06-21
2020-06-22
2020-06-23
2020-06-24
2020-06-25
2020-06-26
2020-06-27
2020-06-28
Date

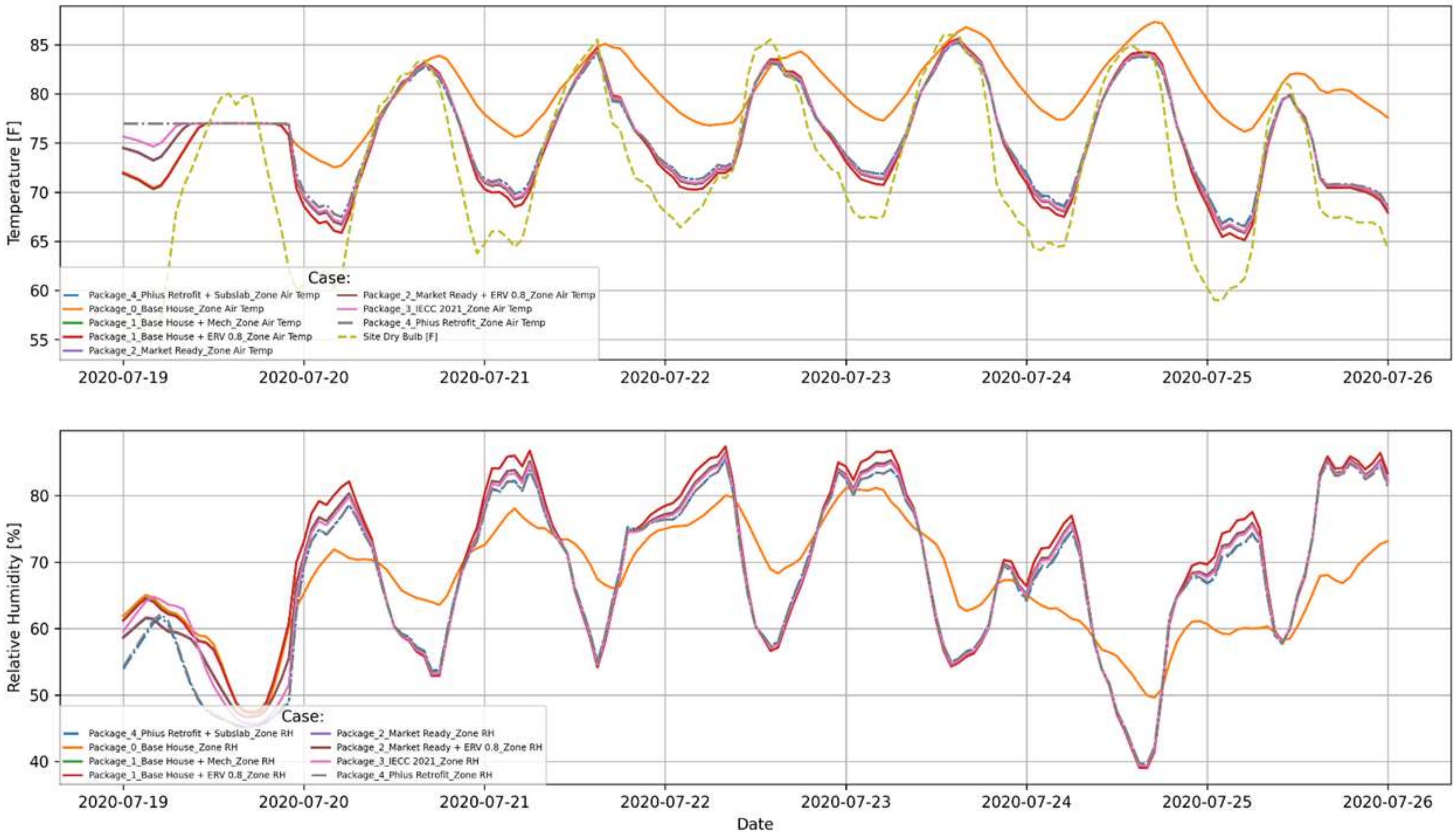

DENVER_EC_Cooling Outage Resilience
Temperature [F]
100
90
80
70
60
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
2020-06-21
2020-06-22
2020-06-23
2020-06-24
2020-06-25
2020-06-26
2020-06-27
2020-06-28
Relative Humidity [%]
90
80
70
60
50
40
30
20
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-06-21
2020-06-22
2020-06-23
2020-06-24
2020-06-25
2020-06-26
2020-06-27
2020-06-28
Date



DENVER_EC+Shd_Cooling Outage Resilience

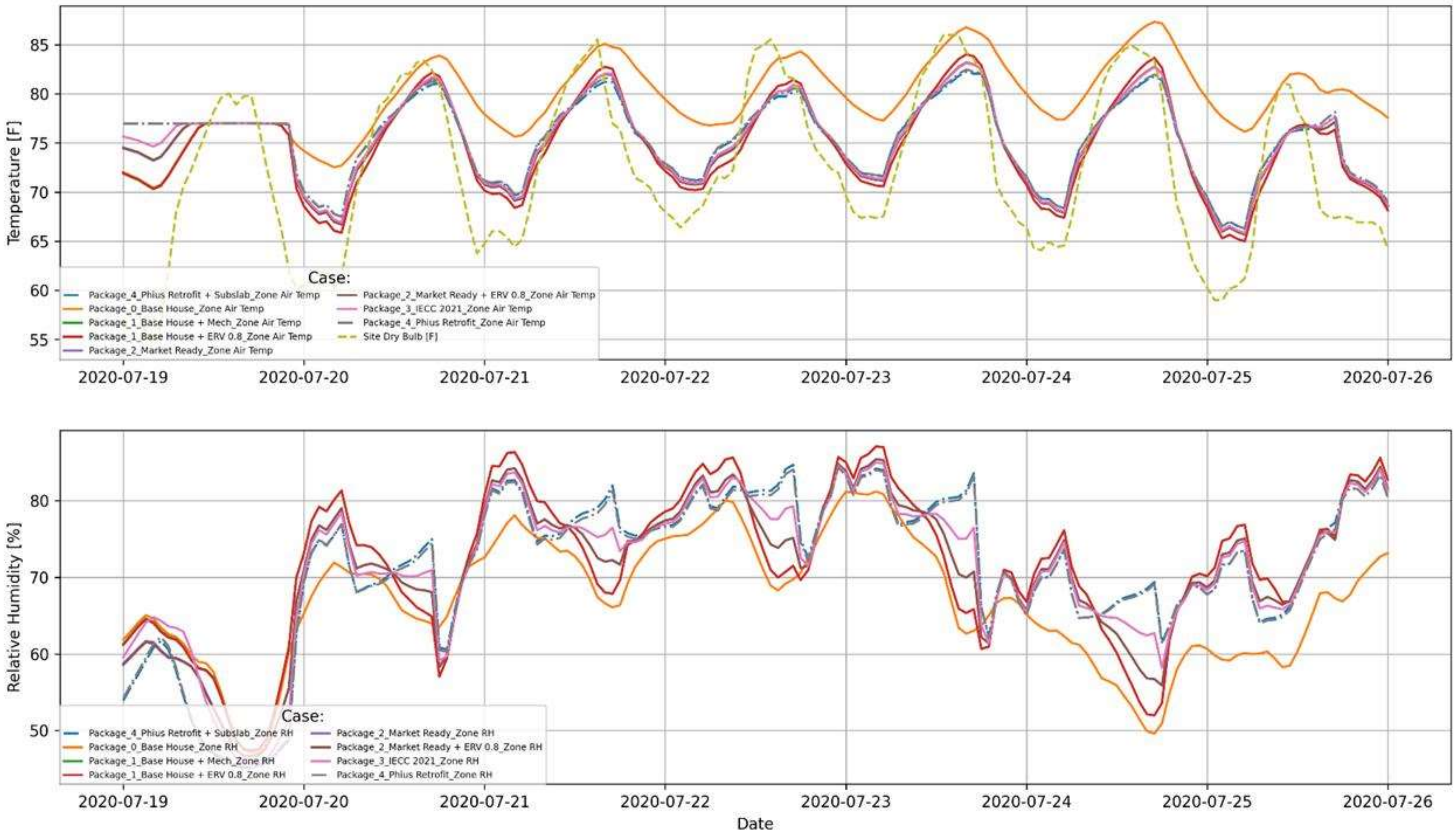
International Falls, MN


IFAP_NV_Heating Outage Resilience
Temperature [F]
60
40
20
0
−20
Case:
Package_4_Phius Retrofit + Subslab_Zone Air Temp
Package_0_Base House_Zone Air Temp
Package_1_Base House + Mech_Zone Air Temp
Package_1_Base House + ERV 0.8_Zone Air Temp
Package_2_Market Ready_Zone Air Temp
Package_2_Market Ready + ERV 0.8_Zone Air Temp
Package_3_IECC 2021_Zone Air Temp
Package_4_Phius Retrofit_Zone Air Temp
Site Dry Bulb [F]
Relative Humidity [%]
60
40
20
0
−20
Case:
Package_4_Phius Retrofit + Subslab_Zone RH
Package_0_Base House_Zone RH
Package_1_Base House + Mech_Zone RH
Package_1_Base House + ERV 0.8_Zone RH
Package_2_Market Ready_Zone RH
Package_2_Market Ready + ERV 0.8_Zone RH
Package_3_IECC 2021_Zone RH
Package_4_Phius Retrofit_Zone RH
2020-01-05
2020-01-06
2020-01-07
2020-01-08
2020-01-09
2020-01-10
2020-01-11
2020-01-12
Date

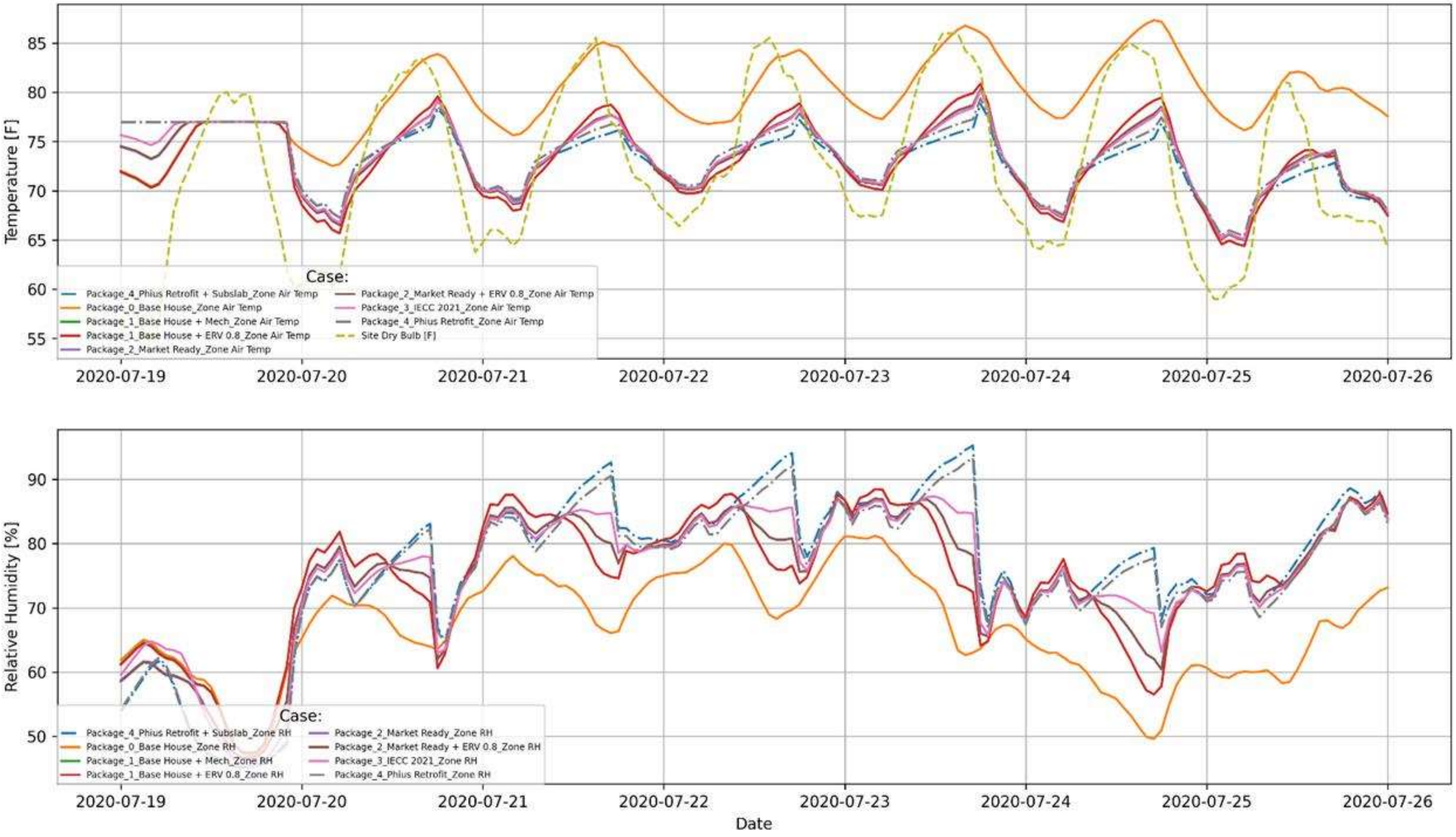


IFAP_NV_Cooling Outage Resilience

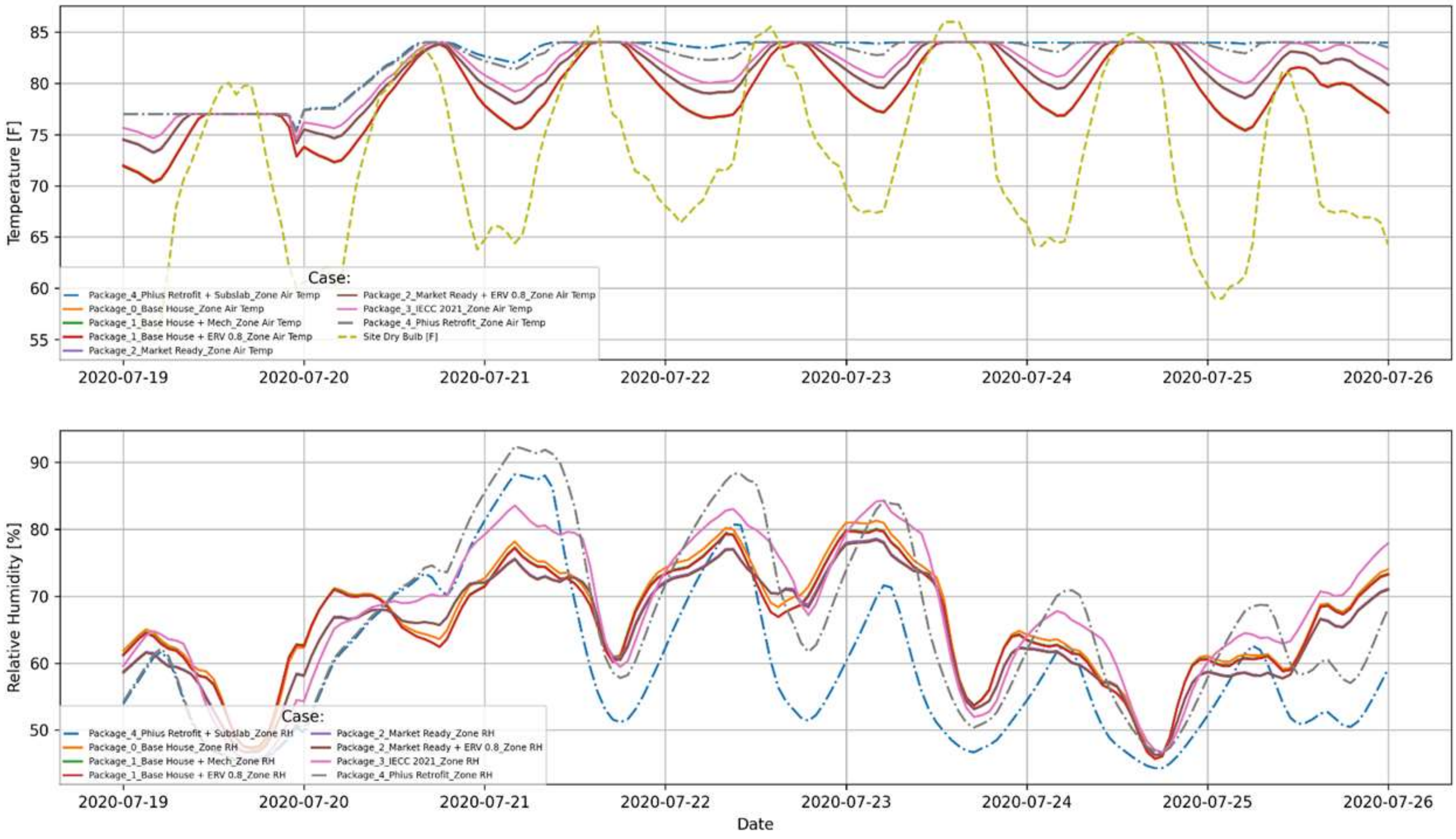
IFAP_SNV_Cooling Outage Resilience

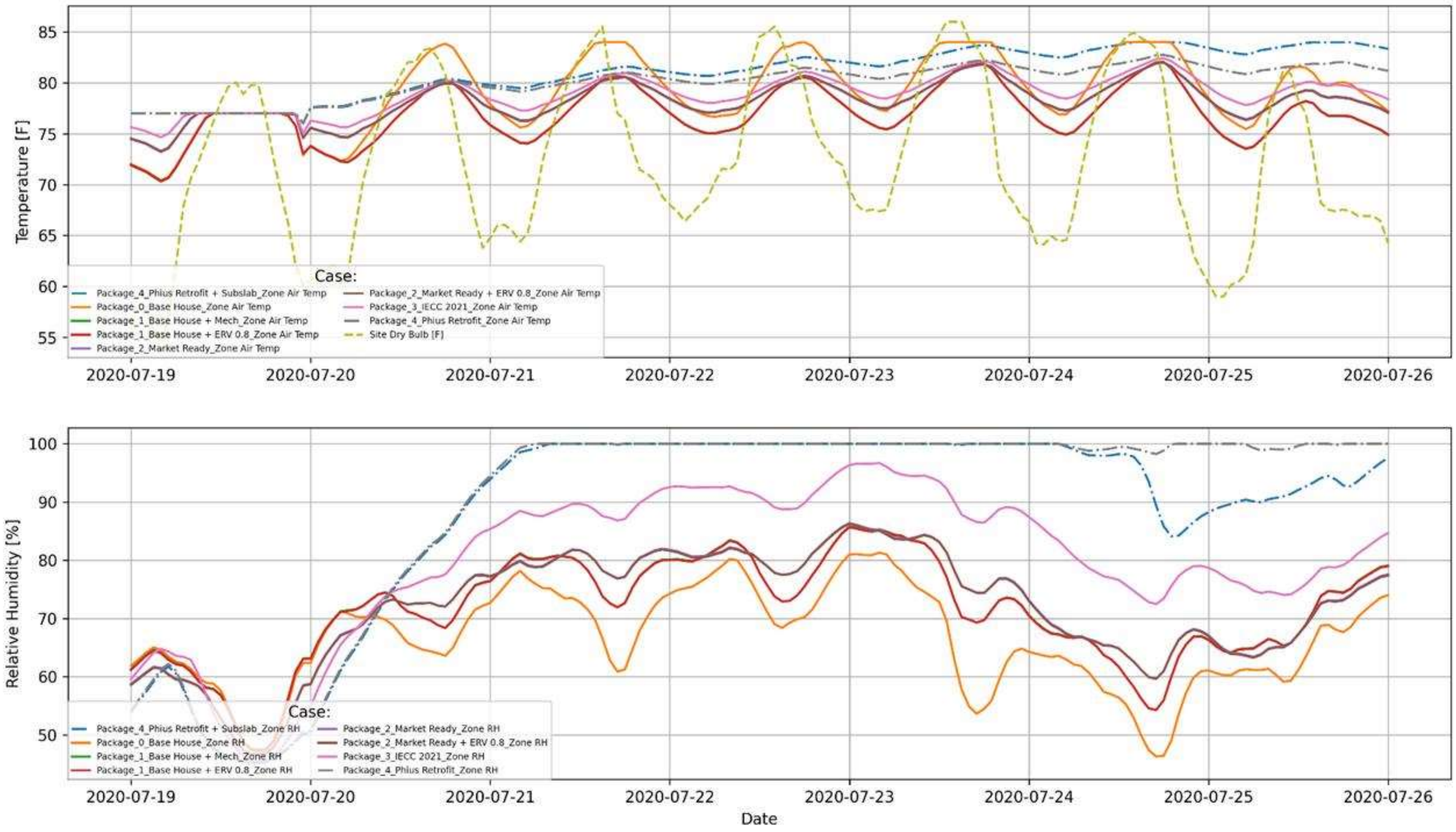


IFAP_SNV+Shd_Cooling Outage Resilience



IFAP_HP_Cooling Outage Resilience





IFAP_HP+Shd_Cooling Outage Resilience