Appendix A. Supplementary Material

Appendix A.1. Fault Impact Calculations on Sensors with Training Data Set

Results given in this section include the basis used to derive the results in Section 5.3. The results of fault impact on sensors for selective faults (which includes meaningful details for understanding the fault simulations with EnergyPlus) are illustrated with parallel coordinate plots showing the NMBE for each sensor and for each fault. An additional metric of normalized NMBE (NMBE*) is also used, where the NMBE is normalized again on the maximum NMBE of each sensor. The NMBE* provides an indication of how the sensor is affected by each fault, regardless of the relative magnitude of NMBEs between different sensors. The results are also differentiated between heating (January–February), cooling (July–August), and shoulder (April–May) seasons, to provide differences in affected sensors in different seasons.

Appendix A.1.1. HVAC Setback Error

HVAC setback errors cause HVAC systems to operate outside of occupied hours, resulting in additional energy usage. As can be expected, the entire space-conditioning equipment uses more energy when the setback schedule is not initiated properly. All sensors besides the lighting submeter (submeter: lighting) are affected in the heating season, as shown by the NMBE* result in Figure A1. Compared to the heating season, RTU heating coil related sensors (submeter: heating [gas], RTU heating coil runtime, and RTU heating coil capacity) are not affected by the fault in the cooling season, because preheating is not necessary under the hotter ambient condition. Although the HVAC setback errors increase cooling energy consumption in the cooling season, because of extended operating hours, the call for space reheat with VAV reheat coil (submeter: heating [elec] and VAV heating coil power) is relatively more significant in terms of NMBE, as shown in Figure A2. The shoulder season plot is not included because it only represents the linear transition between heating and cooling seasons.

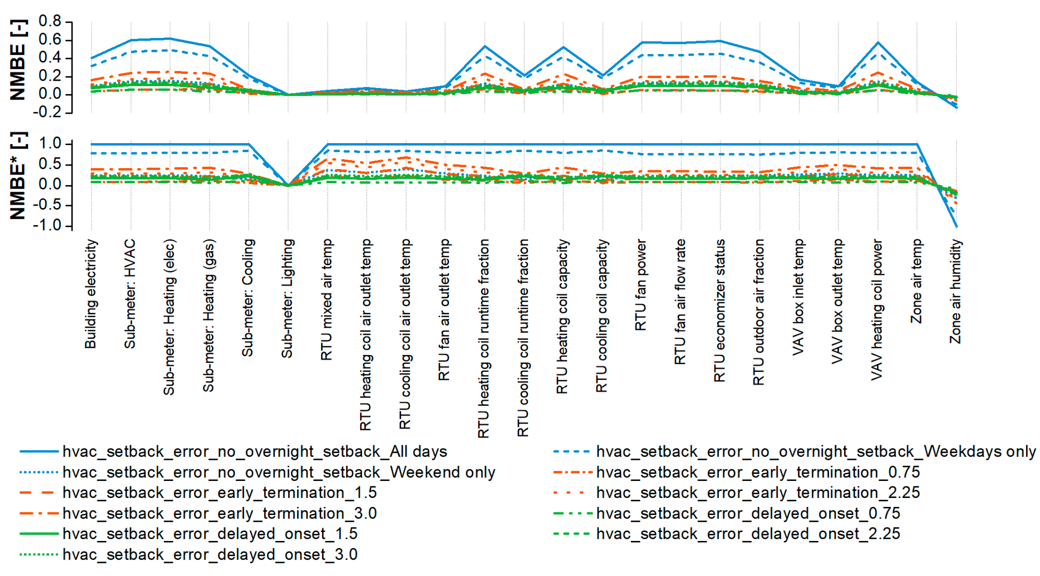

Figure A1. Normalized mean bias error (NMBE) and NMBE* of each sensor affected by heating, ventilation and air-conditioning (HVAC) setback error: heating season.

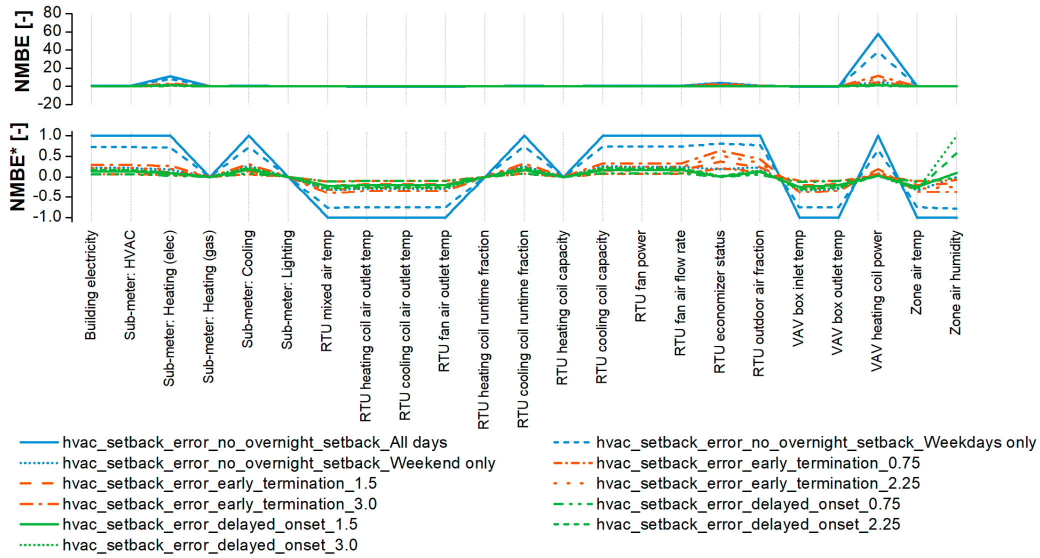

Figure A2. NMBE and NMBE* of each sensor affected by HVAC setback error: cooling season.

Appendix A.1.2. Economizer Opening Stuck

The outdoor air damper being stuck in a certain position can introduce unnecessary outdoor air, which needs additional energy for air conditioning. Unfavorable outdoor air calls for additional preheating (submeter: heating [gas], RTU heating coil runtime, and RTU heating coil capacity) during the heating season (shown in Figure A3), and additional cooling (submeter: cooling and RTU cooling coil capacity) during the cooling season (shown in Figure A4). The outdoor air fraction (RTU outdoor air fraction) that can be derived from the outdoor and supply airflow, if measurements are available, can be the simplest indicator in both heating and cooling season. However, in the shoulder season (shown in Figure A5) where the economizing is activated more often (outdoor air damper frequently opens up), the relative impact on the outdoor air fraction becomes smaller, and the preheating-related sensors have the highest impact for the considered weather condition.

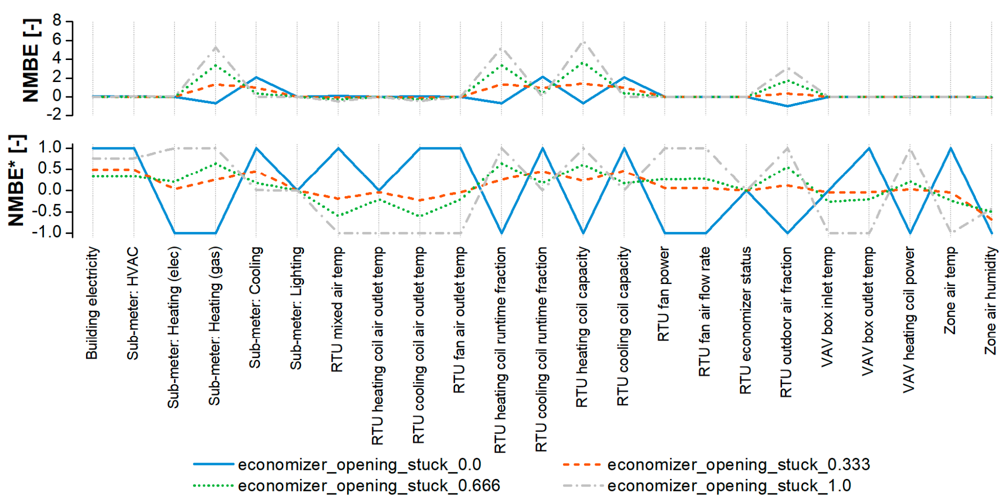

Figure A3. NMBE and NMBE* of each sensor affected by economizer opening stuck: heating season.

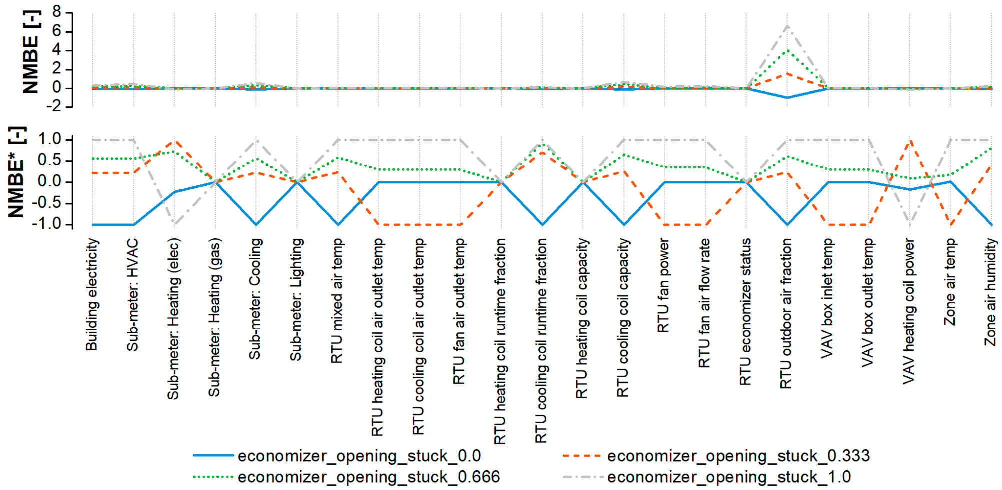

Figure A4. NMBE and NMBE* of each sensor affected by economizer opening stuck: cooling season

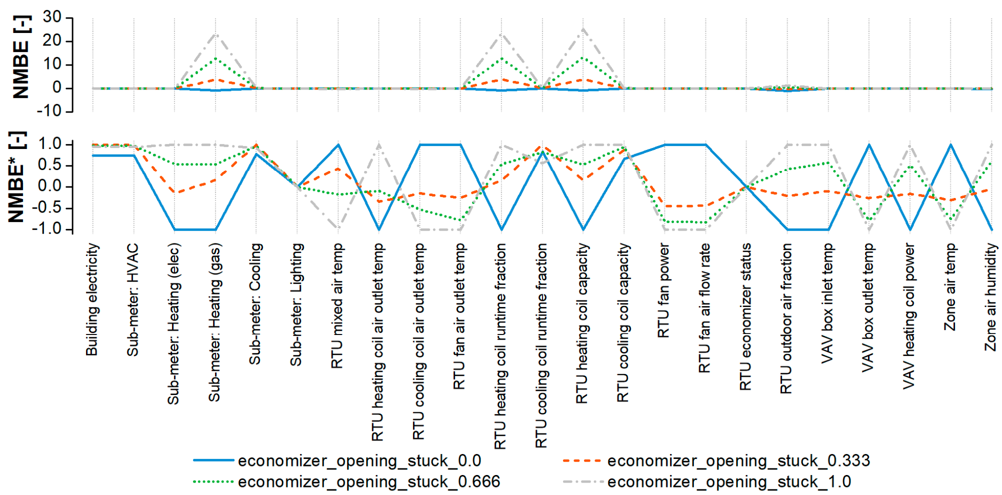

Figure A5. NMBE and NMBE* of each sensor affected by economizer opening stuck: shoulder season

Appendix A.1.3. Thermostat Measurement Bias

Thermostat measurement bias can affect the system in both ways, favorably and unfavorably, depending on the weather (heating or cooling season) and sensor biased direction (positive or negative). This is also reflected in the figures below, where NMBE varies between positive and negative (unfavorable and favorable, respectively, in terms of energy consumption) values in different scenarios. In general, the call for VAV reheat (VAV heating coil power) is affected significantly, regardless of the season, compared to other sensors. Sensors related to preheating (submeter: heating [gas], RTU heating coil runtime, and RTU heating coil capacity in Figure A6) also have an impact because of the fault in the heating season, while the relative variation in the cooling system in the cooling season is less significant compared to its impact on the VAV reheat (submeter: heating [elec] and VAV heating coil power in Figure A7). The shoulder season plot is not included because it only represents the linear transition between heating and cooling seasons.

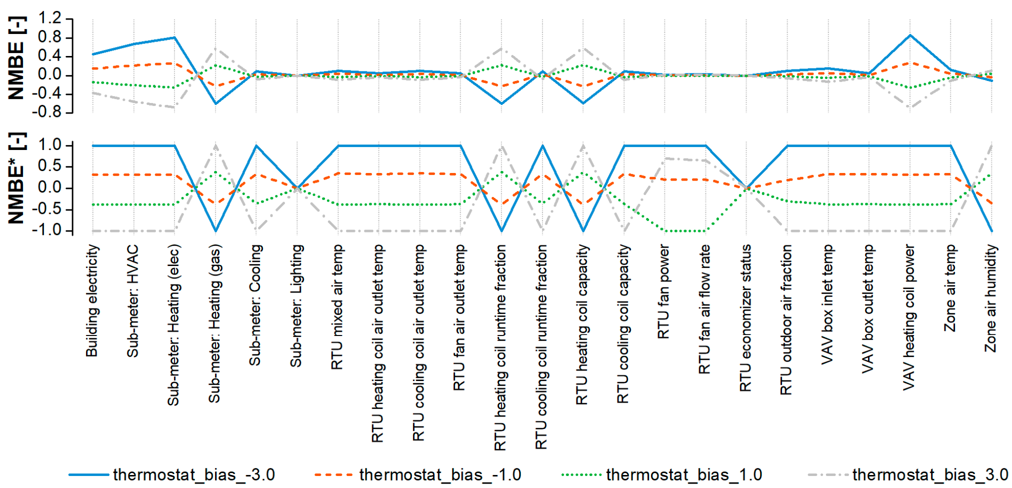

Figure A6. NMBE and NMBE* of each sensor affected by thermostat bias: heating season

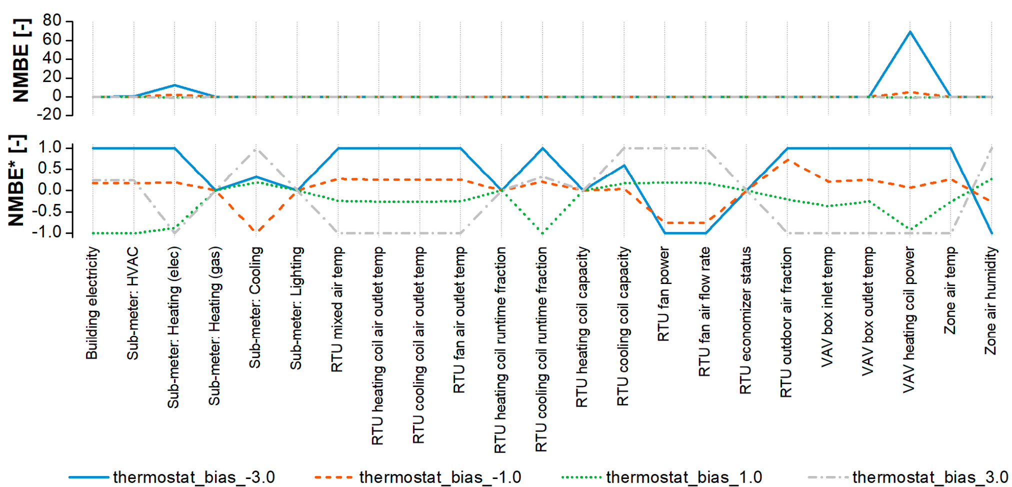

Figure A7. NMBE and NMBE* of each sensor affected by thermostat bias: cooling season

Appendix A.1.4. Faults in Vapor Compression System

Condenser fan degradation fault mostly affects the power consumption of the condenser fan, without causing significant harm to the heat exchange in the condenser, because the airflow can remain at a similar level. For this reason, sensors that are related to the cooling energy consumption (submeter: cooling, submeter: HVAC, and building electricity in Figure A8) are affected by the fault, while sensors that can be affected by the change in the cooling capacity (RTU cooling coil runtime, RTU cooling coil capacity, and VAV heating coil power in Figure A8) are not affected in terms of NMBE* for the condenser fan degradation fault.

The other four faults (condenser fouling, liquid–line restriction, presence of noncondensable gas in the refrigerant, and nonstandard refrigerant charging) also affect the total cooling capacity at the evaporator, as well as the compressor power consumption. Meters of cooling energy consumption, as well as sensors affected by the change in the cooling capacity (RTU cooling coil runtime, RTU cooling coil capacity, VAV heating coil power, and zone air humidity), are indicated in terms of NMBE in Figures A8–10.

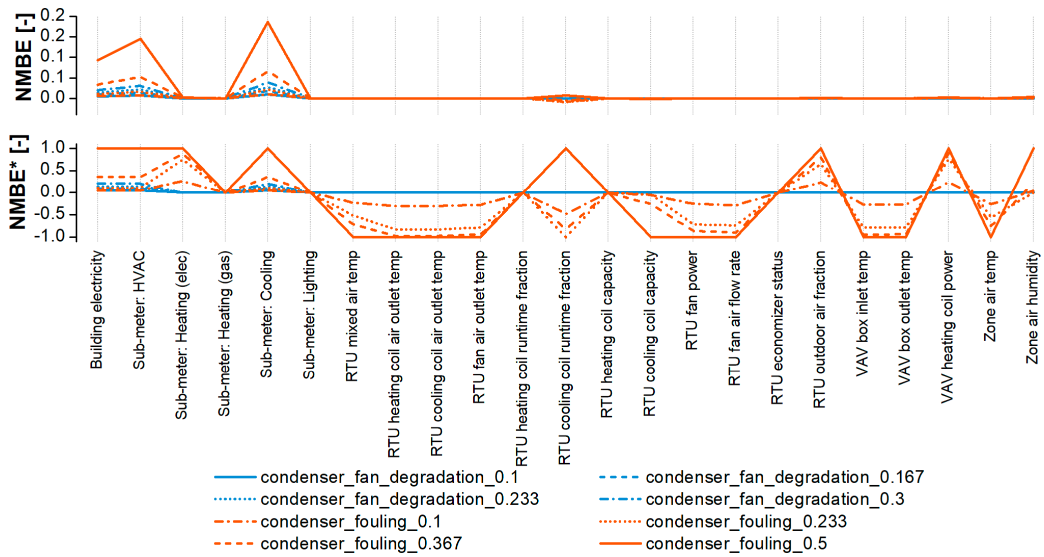

Figure A8. NMBE and NMBE* of each sensor affected by condenser fan degradation and condenser fouling: cooling season

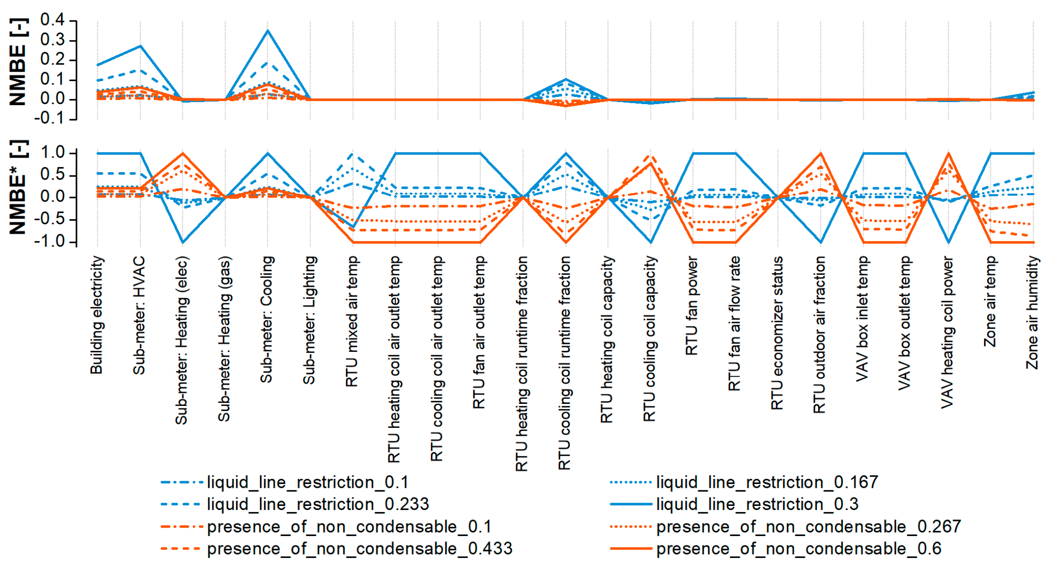

Figure A9. NMBE and NMBE* of each sensor affected by liquid-line restriction and presence of noncondensable gas: cooling season

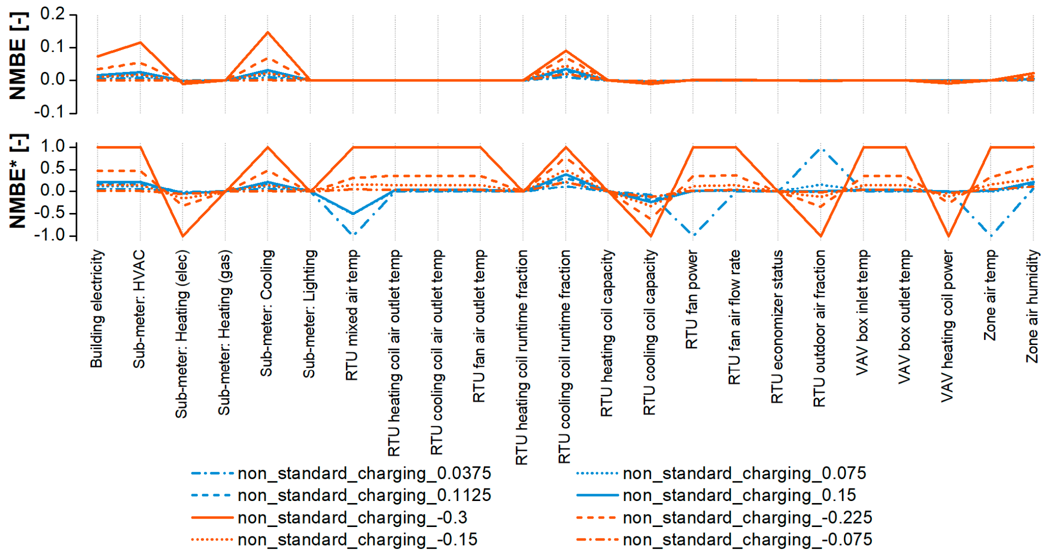

Figure A10. NMBE and NMBE* of each sensor affected by nonstandard refrigerant charging: cooling season

Appendix A.1.5. AHU Fan Motor Degradation/Duct Fouling

Supply fan motor degradation and duct fouling are similarly modeled by degrading the performance of the fan because of either efficiency degradation or fouling in the duct system. As expected, the fan power has the highest relative impact in terms of NMBE, as shown in Figure A11. Additionally, an increased heat gain because of inefficient operation of the fan increases the temperature coming out from the supply fan. The increased supply air temperature decreases the load on the preheating coil (submeter: heating [gas], RTU heating coil runtime, and RTU heating coil capacity in Figure A11) in the heating season, because the capacities of the coil are controlled by referencing the supply air temperature sensor located after the supply fan against the setpoint.

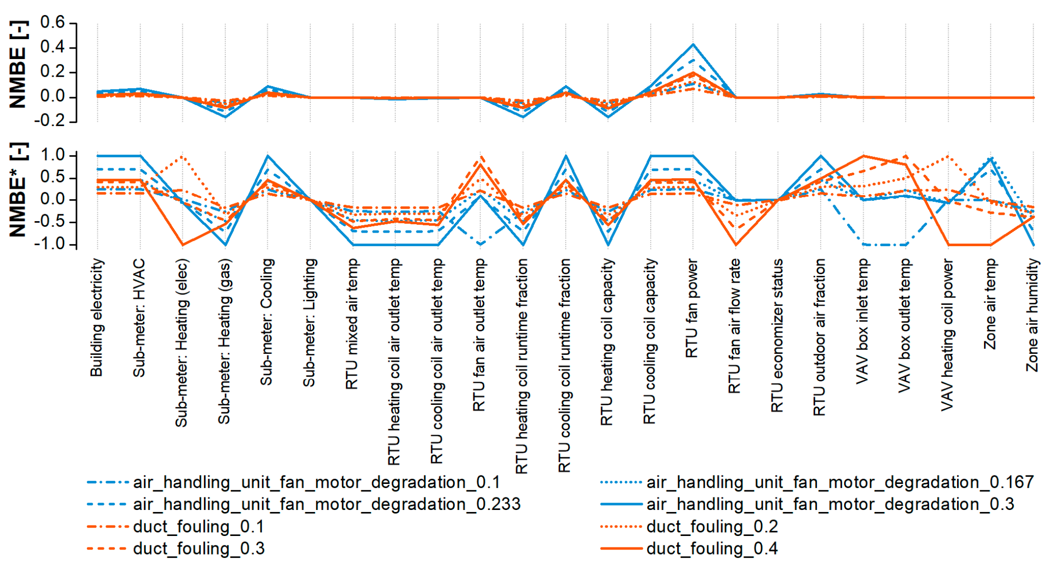

Figure A11. NMBE and NMBE* of each sensor affected by AHU fan motor degradation and duct fouling: heating season

Appendix A.1.6. Faults in the Lighting System

Faults that affect control of the lighting schedule (improper time delay setting in occupancy sensor and lighting setback error faults) directly increase lighting power consumption (submeter: lighting in Figure A12). Additionally, heat gain from increased operation of the lighting slightly affects the heating and cooling load between seasons (indicated with submeter: HVAC, submeter: heating [elec], and submeter: heating [gas] in Figure A12). However, the relative effect on the lighting end use, shown with NMBE, is much larger than the effect on the heating and cooling load.

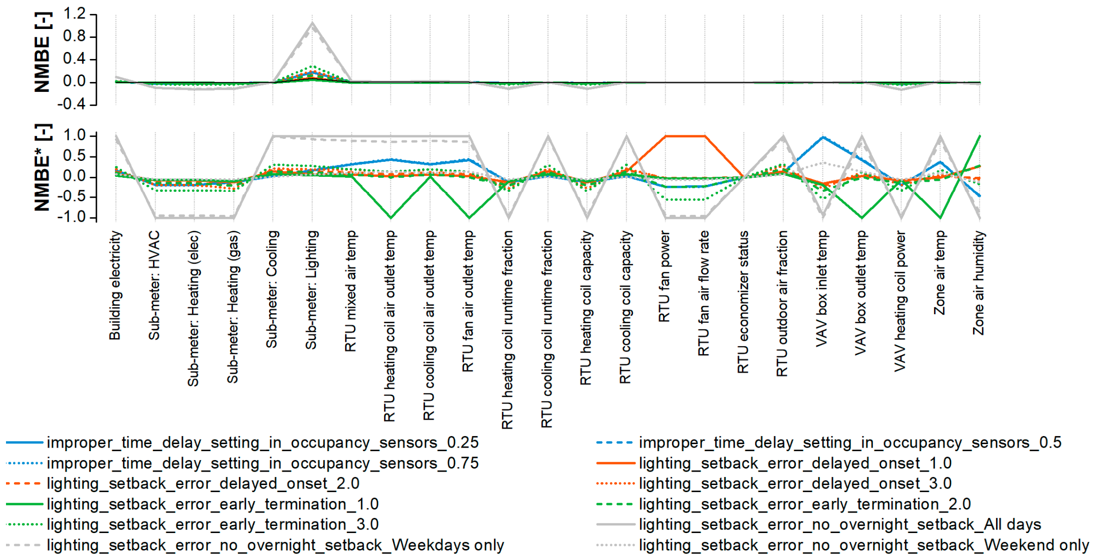

Figure A12. NMBE and NMBE* of each sensor affected by faults in lighting system: heating season

Appendix A.1.7. Biased Economizer Sensor: Mixed Air Temperature

The supply air temperature reset (13–20 °C) is applied in the simulation scenario based on the outdoor air temperature range (8–14 °C), and the fixed dry-bulb control strategy is used for the economizer control in this training data set. During the cooling season, when the outdoor air temperature is higher than the economizer high-limit cut-off temperature (18 °C), the outdoor air damper in the economizer remains in the minimum position, providing the minimum ventilation requirement to thermal zones. Because there is no modulation of the damper, the biased sensor has no impact on the economizing. Early in the occupied hours, when the outdoor condition is favorable for the economizing, the outdoor air temperature is still higher than the mixed air temperature setpoint, where the outdoor air damper stays 100% open without the modulation. For the considered weather condition, the temperature difference between the outdoor air temperature and "biased" mixed air temperature setpoint (because of the biased sensor) is higher than the biased level of the sensor, thus, the effect of biased mixed air temperature sensor between −3 and 3 °C bias does not cause any difference in the economizer behavior, as shown in Figure A13.

During the shoulder and heating season, when the economizer is used to preheat the outdoor air by mixing with the return air, the positive bias (sensor reading higher than actual value) decreases the mixed air temperature compared to the baseline, resulting in an additional load on the preheating coil (submeter: heating [gas], RTU heating coil runtime, and RTU heating coil capacity in Figure A14).

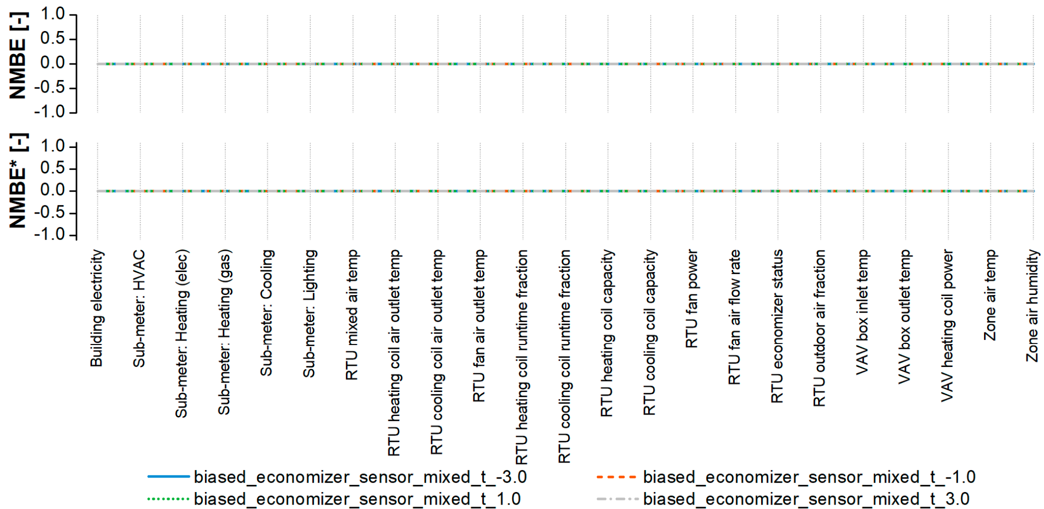

Figure A13. NMBE and NMBE* of each sensor affected by biased economizer sensor (mixed air temperature): cooling season

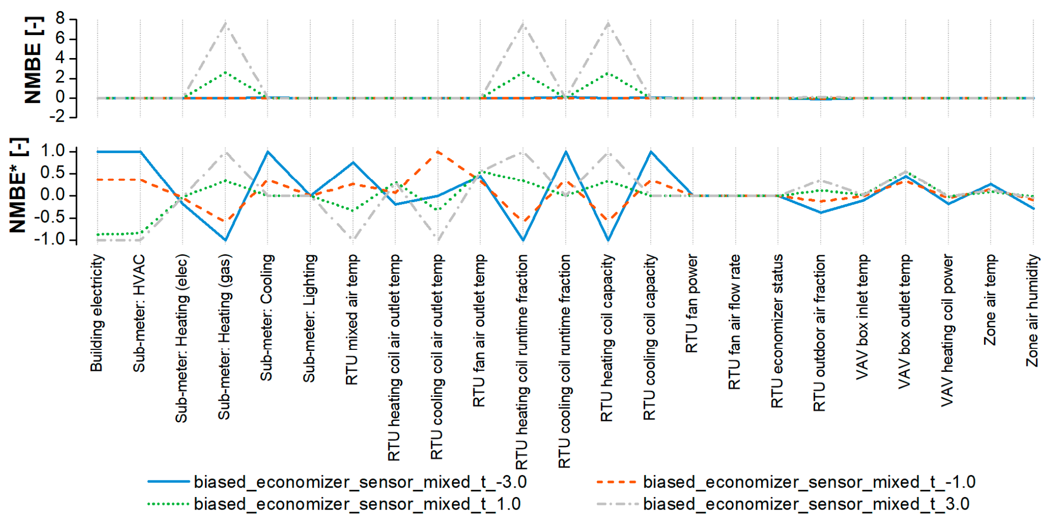

Figure A14. NMBE and NMBE* of each sensor affected by biased economizer sensor (mixed air temperature): shoulder season

Appendix A.1.8. Biased Economizer Sensor: Outdoor Air Temperature

A biased outdoor air temperature sensor in the economizer causes a timing shift in the switch-off point between economizing and noneconomizing modes. Although various sensors are affected by the fault, because the use of favorable or unfavorable outdoor air is directly connected to the energy consumption in the heating and cooling coils, the most significant impact in terms of NMBE is on the outdoor air fraction, as shown in Figures A15 and A16. Besides the outdoor air fraction, an additional load on the cooling coil (submeter: cooling, RTU cooling coil capacity, and RTU cooling coil runtime) is detected as the most significant impact in the cooling season and an additional load on the preheating coil (submeter: heating [gas], RTU heating coil capacity, RTU heating coil runtime) is detected as the most significant impact in the shoulder season.

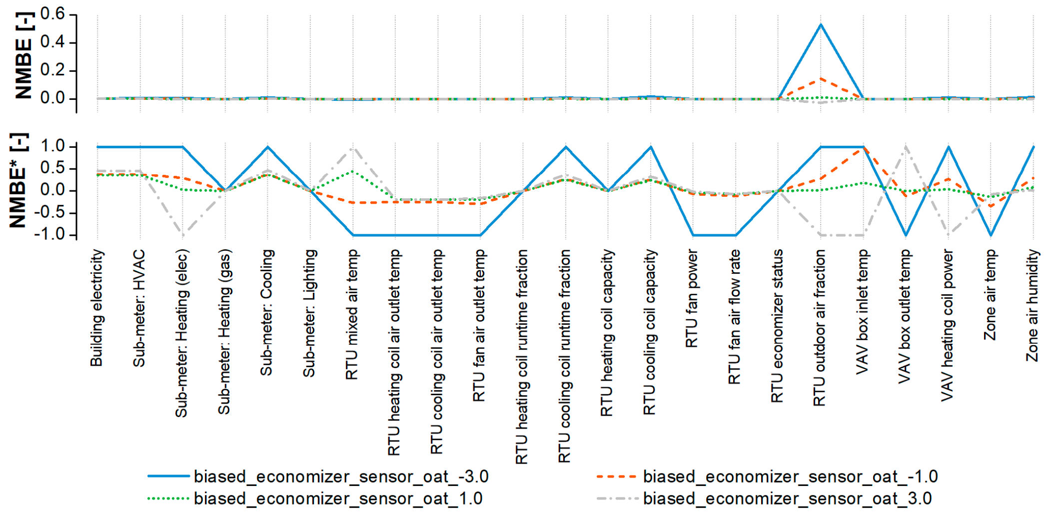

Figure A15. NMBE and NMBE* of each sensor affected by biased economizer sensor (outdoor air temperature): cooling season.

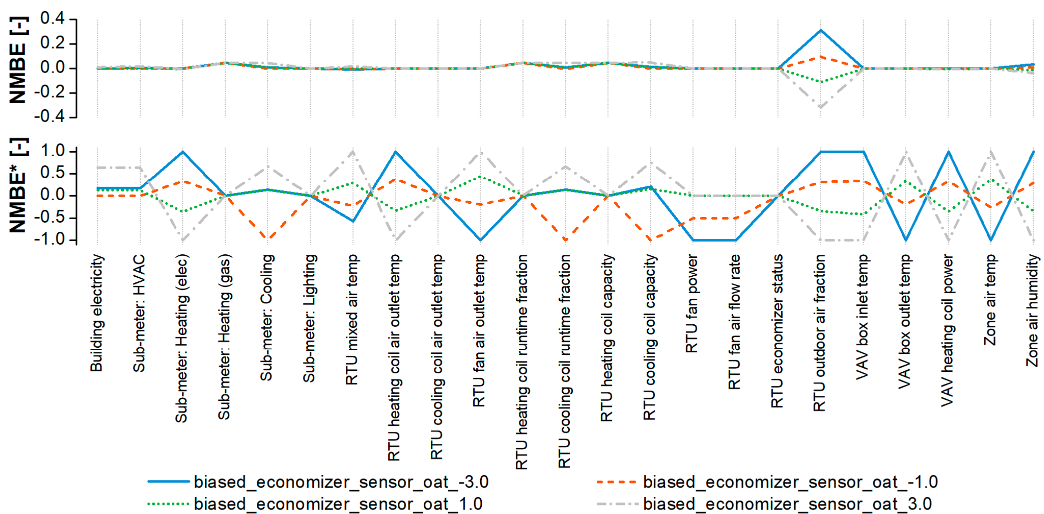

Figure A16. NMBE and NMBE* of each sensor affected by biased economizer sensor (outdoor air temperature): shoulder season

Tables A1–3 display the top five sensors prioritized based on NMBE that were calculated for each fault for the heating season (January–February), cooling season (July–August) and shoulder season (April–May), respectively, for Knoxville, Tennessee. Absolute values of NMBEs for different fault intensity scenarios (e.g., thermostat measurement bias of −3 K, −1 K, 1 K, and 3 K) for a single fault were averaged to derive a representative value for each fault in the prioritization process. These figures also include additional subdivisions depending on the sensor availability (basic, moderate, or rich sensor set) and sensor category (building level meter, building submeter, RTU sensor, and VAV box sensor), described in Table 3.

Specifically for the condenser fan degradation fault, the impact of the fault is limited to the isolated component (i.e., condenser fan) and does not affect the cooling performance of the DX unit. Therefore, the fault effects are observable in only the three sensors that include the measurement of the condenser fan power consumption (building electricity, submeter: cooling, and submeter: HVAC). For the biased economizer mixed air sensor, the fault has no impact on the building system in the cooling season for the considered weather conditions, as shown in Table A2. This is a result of the outdoor air temperature being higher than the effective "biased" mixed air temperature setpoint (because of the biased sensor) during occupied hours. The outdoor air damper remains 100% open without modulation whenever it is in the economizing mode, and the final mixed air temperature is still higher than the biased mixed air temperature setpoint. The zone relative humidity sensor is included in the prioritized list for both cooling (Table A2) and shoulder (Table A3) seasons; it is also included for several faults where the cooling capacity is changed because of the fault (faults in the vapor compression system) or the humidity level in thermal zones changed directly because of the fault (excessive infiltration). The prioritized sensors list for some of the faults (e.g., HVAC setback error, thermostat bias, supply air duct leakages, and excessive infiltration) shown in Table A2 show an impact on VAV reheat (i.e., submeter: heating [elec]) that is relatively higher than the impact on the cooling side of the equipment in the cooling season.

As shown in Tables A1–3, a sensor in the rich sensor set is always selected as the first sensor for all faults and for all seasons. The submeter—HVAC sensor, which is categorized in the moderate sensor set—is included in the top five prioritized sensors for many faults, because most of these faults have impacts on the heating and cooling systems. This is also depicted in figures where the RTU sensors (blue lettering) are mostly included in the prioritized list. The building-level electricity measurement (i.e., building electricity sensor in figures) is included in the prioritized list, mostly for the faults in the vapor compression system (e.g., condenser fan degradation, condenser fouling, liquid–line restriction, presence of noncondensable gas, and nonstandard refrigerant charging). However, the zone air temperature, which is categorized in the basic sensor set, is not included in any of the prioritized sensors list. Although an in-depth look in the training data set showed changes in zone temperatures because of faults (e.g., supply air duct leakage, and so on) that caused differences in heating or cooling capacity, the relative impacts in terms of NMBE were smaller than the other sensors included in these figures.

Table A1. Prioritized Sensor List for Each Fault in Heating Season.

Fault	Prioritized Sensors for Heating Season				
	1st Sensor	2nd Sensor	3rd Sensor	4th Sensor	5th Sensor
HVAC setback error	Sub-meter: Heating (elec)	Sub-meter: HVAC	VAV reheat coil capacity	RTU economizer status	RTU fan power
Thermostat measurement bias	VAV reheat coil capacity	Sub-meter: Heating (elec)	Sub-meter: HVAC	RTU heating coil capacity	RTU heating coil runtime fraction
Economizer opening stuck	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU outdoor air fraction	RTU cooling coil runtime fraction
Supply air duct leakages	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	Sub-meter: Heating (elec)	VAV reheat coil capacity
Return air duct leakages	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU outdoor air fraction	RTU cooling coil air outlet temp
Excessive infiltration	VAV reheat coil capacity	Sub-meter: Heating (elec)	RTU heating coil capacity	Sub-meter: HVAC	RTU heating coil runtime fraction
Oversized equipment at design	RTU cooling coil runtime fraction	RTU heating coil runtime fraction	RTU cooling coil capacity	Sub-meter: Cooling	VAV reheat coil capacity
Biased economizer sensor: mixed air temperature	RTU cooling coil runtime fraction	Sub-meter: Cooling	RTU cooling coil capacity	RTU outdoor air fraction	RTU heating coil runtime fraction
Biased economizer sensor: outdoor air temperature	RTU outdoor air fraction	RTU cooling coil capacity	RTU cooling coil runtime fraction	Sub-meter: Cooling	RTU heating coil capacity
AHU fan motor degradation	RTU fan power	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU cooling coil capacity
Duct fouling	RTU fan power	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU cooling coil capacity
Condenser fan degradation	Sub-meter: Cooling	Sub-meter: HVAC	Building electricity	-	-
Condenser fouling	Sub-meter: Cooling	RTU cooling coil runtime fraction	RTU cooling coil capacity	Sub-meter: HVAC	Building electricity
Refrigerant liquid-line restriction	RTU cooling coil runtime fraction	Sub-meter: Cooling	RTU cooling coil capacity	Sub-meter: HVAC	Building electricity
Presence of noncondensable	Sub-meter: Cooling	RTU cooling coil runtime fraction	RTU cooling coil capacity	Sub-meter: HVAC	Building electricity
Nonstandard refrigerant charging	RTU cooling coil runtime fraction	Sub-meter: Cooling	RTU cooling coil capacity	Sub-meter: HVAC	Building electricity
Improper time delay setting in occupancy sensors	Sub-meter: Lighting	VAV reheat coil capacity	Sub-meter: Heating (elec)	Sub-meter: HVAC	Building electricity
Lighting setback error	Sub-meter: Lighting	VAV reheat coil capacity	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)

(orange)	Basic sensor set
(green)	Moderate sensor set
(cream)	Rich sensor set
Black lettering	Building level meter
Orange lettering	Building sub-meter
Purple lettering	RTU sensors
Blue lettering	VAV box sensors

Table A2. Prioritized Sensor List for Each Fault in Cooling Season.

Fault	Prioritized Sensors for Cooling Season				
	1st Sensor	2nd Sensor	3rd Sensor	4th Sensor	5th Sensor
HVAC setback error	Sub-meter: Heating (elec)	RTU economizer status	RTU outdoor air fraction	Sub-meter: HVAC	RTU fan power
Thermostat measurement bias	Sub-meter: Heating (elec)	Sub-meter: HVAC	RTU fan air flow rate	Building electricity	RTU fan power
Economizer opening stuck	RTU outdoor air fraction	RTU cooling coil capacity	Sub-meter: Cooling	Sub-meter: HVAC	Building electricity
Supply air duct leakages	Sub-meter: Heating (elec)	RTU fan air flow rate	RTU fan power	RTU outdoor air fraction	RTU mixed air temp
Return air duct leakages	RTU outdoor air fraction	RTU cooling coil capacity	Sub-meter: Cooling	Sub-meter: HVAC	RTU cooling coil runtime fraction
Excessive infiltration	Sub-meter: Heating (elec)	Zone relative humidity	Sub-meter: HVAC	RTU cooling coil capacity	Sub-meter: Cooling
Oversized equipment at design	RTU cooling coil runtime fraction	Sub-meter: Cooling	Sub-meter: HVAC	Building electricity	Sub-meter: Heating (elec)
Biased economizer sensor: mixed air temperature	-	-	-	-	-
Biased economizer sensor: outdoor air temperature	RTU outdoor air fraction	RTU cooling coil capacity	Sub-meter: Cooling	RTU cooling coil runtime fraction	Zone relative humidity
AHU fan motor degradation	RTU fan power	Sub-meter: HVAC	Building electricity	Sub-meter: Cooling	RTU cooling coil capacity
Duct fouling	RTU fan power	Sub-meter: HVAC	Building electricity	RTU cooling coil capacity	Sub-meter: Cooling
Condenser fan degradation	Sub-meter: Cooling	Sub-meter: HVAC	Building electricity	-	-
Condenser fouling	Sub-meter: Cooling	Sub-meter: HVAC	Building electricity	RTU cooling coil runtime fraction	Sub-meter: Heating (elec)
Refrigerant liquid-line restriction	Sub-meter: Cooling	Sub-meter: HVAC	Building electricity	RTU cooling coil runtime fraction	Zone relative humidity
Presence of noncondensable	Sub-meter: Cooling	Sub-meter: HVAC	Building electricity	RTU cooling coil runtime fraction	Sub-meter: Heating (elec)
Nonstandard refrigerant charging	Sub-meter: Cooling	RTU cooling coil runtime fraction	Sub-meter: HVAC	Building electricity	Zone relative humidity
Improper time delay setting in occupancy sensors	Sub-meter: Lighting	Sub-meter: Heating (elec)	Building electricity	Zone relative humidity	Sub-meter: Cooling
Lighting setback error	Sub-meter: Lighting	Sub-meter: Heating (elec)	Building electricity	Sub-meter: Cooling	RTU cooling coil capacity

(orange)	Basic sensor set
(green)	Moderate sensor set
(cream)	Rich sensor set
Black lettering	Building level meter
Orange lettering	Building sub-meter
Purple lettering	RTU sensors
Blue lettering	VAV box sensors

Table A3. Prioritized Sensor List for Each Fault in Shoulder Season.

Fault	Prioritized Sensors for Shoulder Season				
	1st Sensor	2nd Sensor	3rd Sensor	4th Sensor	5th Sensor
HVAC setback error	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU heating coil capacity	VAV reheat coil capacity	Sub-meter: Heating (elec)
Thermostat measurement bias	VAV reheat coil capacity	Sub-meter: Heating (elec)	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU heating coil capacity
Economizer opening stuck	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU outdoor air fraction	RTU cooling coil capacity
Supply air duct leakages	VAV reheat coil capacity	Sub-meter: Heating (elec)	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)
Return air duct leakages	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU outdoor air fraction	RTU cooling coil capacity
Excessive infiltration	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	VAV reheat coil capacity	Sub-meter: Heating (elec)
Oversized equipment at design	RTU heating coil runtime fraction	RTU cooling coil runtime fraction	Sub-meter: Cooling	RTU cooling coil capacity	Zone relative humidity
Biased economizer sensor: mixed air temperature	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU heating coil capacity	RTU outdoor air fraction	RTU cooling coil runtime fraction
Biased economizer sensor: outdoor air temperature	RTU outdoor air fraction	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU cooling coil capacity
AHU fan motor degradation	RTU fan power	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU heating coil capacity	Sub-meter: HVAC
Duct fouling	RTU fan power	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	RTU heating coil capacity	Sub-meter: HVAC
Condenser fan degradation	Sub-meter: Cooling	Sub-meter: HVAC	Building electricity	-	-
Condenser fouling	Sub-meter: Cooling	Sub-meter: HVAC	Building electricity	RTU cooling coil runtime fraction	RTU cooling coil capacity
Refrigerant liquid-line restriction	Sub-meter: Cooling	RTU cooling coil runtime fraction	Sub-meter: HVAC	Building electricity	Zone relative humidity
Presence of noncondensable	Sub-meter: Cooling	RTU cooling coil runtime fraction	Sub-meter: HVAC	Building electricity	RTU cooling coil capacity
Nonstandard refrigerant charging	RTU cooling coil runtime fraction	Sub-meter: Cooling	Sub-meter: HVAC	Building electricity	Zone relative humidity
Improper time delay setting in occupancy sensors	Sub-meter: Lighting	VAV reheat coil capacity	Sub-meter: Heating (elec)	RTU heating coil capacity	RTU heating coil runtime fraction
Lighting setback error	Sub-meter: Lighting	RTU heating coil capacity	RTU heating coil runtime fraction	Sub-meter: Heating (gas)	VAV reheat coil capacity

(orange fill)	Basic sensor set
(green fill)	Moderate sensor set
(light yellow fill)	Rich sensor set
Black lettering	Building level meter
Orange lettering	Building sub-meter
Purple lettering	RTU sensors
Blue lettering	VAV box sensors