Performance Evaluation of Three RTU Energy Efficiency Technologies

Korbaga Woldekidan, Daniel Studer, and Ramin Faramarzi

Produced under direction of ComEd by the National Renewable Energy Laboratory (NREL) under Technical Services Agreement TSA-19-01159

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List of Acronyms

AC	air conditioning
BHP	brake horsepower
DC	direct current
DOE	U.S. Department of Energy
HVAC	heating, ventilating, and air conditioning
IEER	integrated energy efficiency ratio
NREL	National Renewable Energy Laboratory
RTU	rooftop unit
SCE	Southern California Edison
SRM	switched reluctance motor
VFD	variable frequency drive
WC	water column

Executive Summary

This project was part of an effort by ComEd to evaluate the energy saving potential of emerging technologies in the Chicago area. This project focused on the evaluation of energy and peak demand savings potentials of emerging technologies related to rooftop units (RTUs).

According to the Commercial Building Energy Consumption Survey, close to 52% of commercial buildings use packaged air conditioning units like RTUs for providing space cooling (U.S. Energy Information Administration 2012). Even if ANSI/ASHRAE/IES Standard 90.1-2016 requires direct-expansion units with cooling capacity greater than 110,000 Btu/h to have either two-speed or variable-speed fan control, the majority of installed RTUs employ single- or two-stage compressors with a constant-speed supply fan (Cai and Braun 2018).

Recently, RTUs with variable-speed compressors and variable-speed fans with an improved efficiency have become available on the market. In addition to their improved efficiency, their ability to modulate their speed as needed can reduce short cycling issues. However, more research is needed to quantify their energy savings potential for different building types as well as different geographic locations.

This study considered three technology upgrades to a baseline RTU with a single-stage compressor and constant-speed supply fan. EnergyPlus®, the U.S. Department of Energy's (DOE's) building simulation platform, was used for evaluation of the technologies. Energy savings were estimated for six different building types: stand-alone retail, small office, strip mall, warehouse, fast-service restaurant, and full-service restaurant. The savings estimations were based on Typical Meteorological Year 3 (TMY3) weather data for Chicago. Technology upgrades simulated included:

- Replacing the single-speed compressor with a two-stage compressor and adding a variable frequency drive (VFD) to the supply fan
- Replacing the single-speed compressor with a variable-speed compressor and adding a VFD to the supply fan
- Replacing the constant-speed induction motor of the supply fan with a high rotor pole switched reluctance motor (SRM).

The simulation results revealed that upgrading the RTU with a variable-speed compressor and SRM supply fan can result in annual energy savings from 3% to 23%. Among the building types, the stand-alone retail building had the highest total energy savings (23%), while the warehouse had the least (3%). Comparing between the two-stage and variable-speed compressor RTUs, there was an average of 1.5% extra total building energy savings. The use of SRM resulted in an average of 2.5% extra total building energy savings compared to the use of a VFD.

In addition to building energy savings, the upgrades also resulted in peak demand (kW) reduction. A peak demand reduction as high as 11% was estimated for stand-alone retail buildings. In all building types, upgrading the RTU with the variable-speed compressor and SRM supply fan resulted in considerable peak kW savings.

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1 Project Description

This project was part of an effort by ComEd to evaluate the energy saving potential of emerging technologies related to rooftop units (RTUs) in the Chicago area.

An RTU with a single-stage compressor and a constant-speed supply fan with an induction motor was selected as a baseline for the technology comparison. Three retrofit strategies were investigated. The first two involved replacing the single-stage compressor of the RTU with either a two-stage or variable-speed compressor and adding a variable frequency drive (VFD) to the constant speed fan. The use of a multi-/variable-stage compressor improves the part-load efficiency of the compressor, which will ultimately result in annual energy savings, as well as peak demand shaving in some cases where the design capacity of the RTU is larger than the maximum cooling load of the building space that it is serving. The third technology investigated was the use of a high rotor pole switched reluctance motor (SRM) as a replacement for the constant-speed supply fan. The SRM was applied in single-speed, two-stage, and variable-speed compressor RTUs. SRM motors run via reluctance torque. Their stator poles are driven by direct current (DC) power and require an inverter as well as active control when using alternating current power. This inherent property results in high efficiency over a range of operating conditions. It also exhibits higher efficiency compared to VFDs since its switching frequency is much slower (Southern California Edison [SCE] 2018).

The three technologies investigated are summarized below:

- Replacing the single-speed compressor with a two-stage compressor and adding a VFD to the supply fan
- Replacing the single-speed compressor with a variable-speed compressor and adding a VFD to the supply fan
- Replacing the constant-speed induction motor of the supply fan with a high rotor pole SRM.

The U.S. Department of Energy's (DOE's) building simulation platform EnergyPlus (https://energyplus.net) and its graphical user interface OpenStudio® (https://www.openstudio.net) were used to evaluate the energy-saving potential of upgrading RTUs by leveraging experimental data from previous research.

2 Definition of the Baseline RTU

A new 10-ton RTU with a single-stage compressor for cooling, a gas furnace for heating, and a constant-speed induction motor supply fan was selected as the baseline RTU. Its rated performance was based on ASHRAE's latest performance requirement (ANSI/ASHRAE/IES-90.1-2016). For a 10-ton packaged RTU with gas heat, ASHRAE 90.1-2016 requires an integrated energy efficiency ratio (IEER) of at least 12.7. EnergyPlus uses a series of performance curves normalized to a rated coefficient of performance when representing the air conditioning portion of the RTU—the compressor and condenser fan—but ASHRAE only specifies IEER, which is composed of weighted performance at a variety of loading conditions (DOE 2018). To find the rated coefficient of performance, the RTU model was simulated for various coefficients of performance values, and the one that resulted in the specified IEER was picked. The supply air fan efficiency was assumed to be 25% at a fan pressure rise of 440 Pa (SCE 2018).

Part-load performance characteristics of the baseline RTU were assumed to be similar to the part-load performance characteristics of the second-stage compressor of the two-stage RTU used in this study. Further detail is provided in Section 4. Assumptions regarding economizer type and heating efficiency were taken from previous research done at the National Renewable Energy Laboratory (NREL) (Studer et al. 2012).

The performance properties of the baseline RTU are summarized in Table 1.

Table 1. Baseline RTU Properties

IEER	12.7
Coefficient of Performance	4.1
Fan Pressure Rise (psi)	0.064
Fan Mechanical Efficiency (%)	25
Fan Motor Type	Induction
Heating Source	Gas
Heating Efficiency	80%
Economizer Control	Fixed Dry Bulb Temperature
Economizer Lock Point Temperature (^oF)	65
Integrated Economizer and Mechanical Cooling Allowed?	Yes

3 Simulation Scenarios

Six different simulation scenarios were considered to evaluate the effect of the three technologies in different combinations:

- Baseline: Single-Stage Compressor and Constant-Speed Induction Motor Supply Fan
- Case 1: Two-Stage Compressor and Variable-Speed Induction Motor Supply Fan
- Case 2: Variable-Speed Compressor and Variable-Speed Induction Motor Supply Fan
- Case 3: Single-Stage Compressor and Variable-Speed SRM Supply Fan
- Case 4: Two-Stage Compressor and Variable-Speed SRM Supply Fan
- Case 5: Variable-Speed Compressor and Variable-Speed SRM Supply Fan.

4 Modeling Approaches

Six different building types were selected by ComEd for this study. OpenStudio measures were used to generate ASHRAE 90.1-2013 code-compliant DOE prototype baseline models for each building type. The total conditioned area, the number of conditioned zones, and the peak cooling demand for each building are summarized in Table 2.

Table 2. Selected DOE Prototype Buildings

Building Type	Small Office	Stand-Alone Retail	Warehouse	Strip Mall	Fast-Service Restaurant	Full-Service Restaurant
Conditioned Area (ft^2)	5,502	24,692	52,045	22,500	2,501	5,502
Number of Conditioned Zones	5	4	3	10	2	2
Total Fan Brake Horsepower (BHP)	3.5	25	5	23	7	11
Design Cooling Load (Ton)	8.5	65	13	69	20	33

To evaluate the energy-saving potential of each technology, the baseline prototype models were modified using OpenStudio measures. OpenStudio measures are software scripts that can make changes to an OpenStudio building energy model. Three major updates were made to the prototype building models:

1. Replacing the existing constant-speed fans with SRM variable-speed fans or VFD fans and updating their performance curves
2. Replacing the existing single-speed RTUs with two-stage/variable-speed RTUs and updating their performance curves
3. Updating the control strategies based on the modes of operation.

EnergyPlus requires five performance curves for an air conditioning unit and one performance curve for a variable-speed fan to evaluate their energy consumption at different working conditions (DOE 2018). Data from prior research, discussed below, were used to generate these performance curves.

Prior experimental data from SCE's Emerging Products group was used to populate performance curves for induction and SRM supply fans. The SCE Emerging Products group collected the data by running the RTU's supply fan (fan/motor/drive) over three fixed-resistance conditions in inch of water column (WC) (0.4" WC, 1" WC, and 1.5" WC) at seven different fan speeds in a controlled laboratory environment. The lab setup is shown in Figure 1.

Performance data collected in a test facility at NREL were used for the two-stage and variable-speed RTUs (Wheeler, Kozubal, and Judkoff 2018). The performance data were collected by running the RTU at different combinations of air flow, outdoor dry bulb temperature, and inlet air dry/wet-bulb temperature combinations. The temperature and flow ranges were selected to cover the full spectrum of the RTU's operating range. For the variable-speed RTU, the performance data were collected at four distinct compressor speeds (25%, 50%, 75%, and 100%) to characterize its performance at different compressor speeds. EnergyPlus treats variable-speed compressors as a multi-staged compressor and captures the overall performance by assigning a set of performance curves corresponding to each stage.

Figure 1. Laboratory setup for fan performance characterization

Image credit: SCE

Figure 2. Laboratory setup for RTU performance characterization at NREL

Apart from the RTU's designed performance conditions, the way it is controlled plays a large role in its overall energy consumption. In this study, a custom EnergyPlus measure was applied to control the fan and the AC unit's operation. Based on the space and outdoor air conditions, the RTU was programmed to run in three different modes: ventilation mode, cooling mode, and heating mode. The summary of the control logic used for each technology is given in the sections below (4.1 to 4.5). Graphical representations of each mode of operation for each simulated case are shown in Appendix A.

4.1 Ventilation Mode

Ventilation mode was activated when the space temperature was lower than the cooling setpoint and greater than the heating setpoint. During this mode, the following control strategies were used for each technology:

Single-Stage Compressor and Constant-Speed Fan (Baseline)

- The cooling and heating coils were turned off
- The outdoor air flow rate was set to the minimum ventilation air flow rate
- The supply air flow rate was set to the design value (constant-speed supply fan).

Single-Stage Compressor and Variable-Speed Fan (Case 3)

- The cooling and heating coils were turned off
- The outdoor air flow rate was set to the minimum ventilation air flow rate
- The supply air flow rate was set to the minimum ventilation air flow rate. Note that the minimum ventilation rate is building/zone dependent and different buildings/zones can have different minimum ventilation air flow rates.

Two-Stage Compressor and Variable-Speed Fan (Case 1, Case 4)

- The cooling and heating coils were turned off
- The outdoor air flow rate was set to the minimum ventilation air flow rate
- The supply air flow rate was set to the minimum ventilation air flow rate.

Variable-Speed Compressor and Variable-Speed Fan (Case 2, Case 5)

- The cooling and heating coils were turned off
- The outdoor air flow rate was set to the minimum ventilation air flow rate
- The supply air flow rate was set to the minimum ventilation air flow rate.

4.2 Cooling Mode

Cooling mode was activated when the space temperature was greater than the cooling setpoint. In cooling mode, the RTU was allowed to run in one of the two different modes: Economizer and Mechanical Cooling or Mechanical Cooling Only. To avoid cooling coil freezing, whenever mechanical cooling was activated, the minimum supply fan speed was limited to 60% for two-stage RTU (Case 1 and Case 4) and 40% for variable-speed RTU (Case 2 and Case 5).

4.2.1 Economizer and Mechanical Cooling

Economizer and Mechanical Cooling was activated when the space temperature was greater than the cooling setpoint and the outdoor air temperature was appropriate for economizing (outdoor air temperature between 55°F and 65°F). A value of 65°F was used as a lock point temperature for economizer operation instead of the ASHRAE Standard 90.1-recommended value of 70°F for climate zone 5A (Chicago area) to reflect what is most practical in the field. During this mode, the following control strategies were used for each technology:

Single-Stage Compressor and Constant-Speed Fan (Baseline)

- The outdoor air flow rate/outdoor air damper was allowed to modulate from its minimum to maximum values proportional to the difference between the space temperature and the cooling setpoint
- If the outdoor air flow rate was at maximum and the conditioned space needed more cooling (if cooling setpoint was not met), the cooling coil (compressor) was activated
- The RTU remained in this mode until the space temperature was lower than the cooling setpoint by 0.5°F, at which point ventilation mode was activated.

Single-Stage Compressor and Variable-Speed Fan (Case 3)

- The supply air flow rate was allowed to modulate from minimum to maximum supply fan capacity proportional to the difference between the space temperature and the cooling setpoint. Every minute, for each 1°F of difference between the space temperature and the cooling setpoint, the fan speed was allowed to increase by 5% .
- The outdoor air flow rate was set to be equal to the supply air flow rate (the outdoor air damper was set to fully open)
- If the RTU air flow rate was at its maximum and the conditioned space needed more cooling, the cooling coil (compressor) was activated
- The RTU remained in this mode until the space temperature was lower than the cooling setpoint by 0.5°F, at which point ventilation mode was activated.

Two-Stage Compressor and Variable-Speed Fan (Case 1, Case 4)

- The supply air flow rate was allowed to modulate from minimum to maximum supply fan capacity proportional to the difference between the space temperature and the cooling setpoint. Every minute, for each 1°F of difference between the space temperature and the cooling setpoint, the fan speed was allowed to increase by 5% .
- The outdoor air flow rate was set to be equal to the supply air flow rate (the outdoor air damper was set to fully open)
- If the supply flow rate was at its maximum capacity and the conditioned space needed more cooling:
    - The first-stage cooling was activated, and the supply fan was set to the first-stage maximum air flow rate until the space temperature fell below the cooling setpoint by 0.5°F, at which point ventilation mode was activated
    - If the space temperature was greater than the cooling setpoint by 0.5°F, second-stage cooling was activated
- In second-stage cooling, the RTU air flow rate was allowed to modulate from the first-stage maximum to second-stage maximum air flow rate in proportion to the difference between the space temperature and the cooling setpoint. Every minute, for each 1°F of difference between the space temperature and the cooling setpoint, the fan speed was allowed to increase by 5%.

- The RTU remained in second-stage cooling until the space temperature fell below the cooling setpoint by 0.25°F, at which point the second-stage cooling was set to off.

- The RTU remained in this mode until the space temperature was lower than the cooling setpoint by 0.5°F, at which point ventilation mode was activated.

Variable-Speed Compressor and Variable-Speed Fan (Case 2, Case 5)

- The outdoor air damper was set to fully open
- The supply air flow rate was allowed to modulate from minimum to maximum supply fan capacity proportional to the difference between the space temperature and the cooling setpoint
- If the supply fan flow rate was at maximum and the conditioned space called for more cooling:
  - First-stage cooling was activated, and the supply fan flow rate was set to the first-stage maximum air flow rate
  - After the first-stage cooling was activated, if the space temperature fell below the cooling setpoint by 0.5°F, ventilation mode was activated
  - After first-stage cooling was activated, if the space temperature was greater than the cooling setpoint by 0.15°F, second-stage cooling was activated
  - In second-stage cooling, the RTU air flow rate was allowed to modulate from the first-stage maximum to second-stage maximum air flow rate in proportion to the difference between the space temperature and the cooling setpoint
  - The RTU remained in second-stage cooling until the space temperature fell below the cooling setpoint by 0.25°F, at which point the unit was set to first-stage cooling
  - After the second-stage cooling was activated, if the space temperature was greater than the cooling setpoint by 0.35°F, third-stage cooling was activated
  - In third-stage cooling, the RTU air flow rate was allowed to modulate from the second-stage maximum to third-stage maximum air flow rate in proportion to the difference between the space temperature and the cooling setpoint
  - The RTU remained in third-stage cooling until the space temperature fell below the cooling setpoint by 0.25°F, at which point the unit was set to first-stage cooling
  - After third-stage cooling was activated, if the space temperature was greater than the cooling setpoint by 0.5°F, fourth-stage cooling was activated
  - In fourth-stage cooling, the RTU air flow rate was allowed to modulate from the third-stage maximum to fourth-stage maximum air flow rate (design air flow rate) in proportion to the difference between the space temperature and the cooling setpoint
  - The RTU remained in fourth-stage cooling until the space temperature fell below the cooling setpoint by 0.25°F, at which point the unit was set to first-stage cooling.

- The RTU remained in this mode until the space temperature was lower than the cooling setpoint by 0.5°F, at which point the ventilation mode was activated.

4.2.2 Mechanical Cooling Only

Mechanical cooling only was activated when the space temperature was greater than the cooling setpoint and outdoor air was not convenient for economizing (outdoor air temperature greater than 65ºF). During this mode, the following control strategies were used for each technology:

Single-Stage Compressor and Constant-Speed Fan (Baseline)

- The outdoor air flow rate was set to the minimum ventilation flow rate
- The cooling coil was activated
- The RTU remained in this mode until the space temperature was lower than the cooling setpoint by 0.5ºF, at which point the ventilation mode was activated.

Single-Stage Compressor and Variable-Speed Fan (Case 3)

- The outdoor air flow rate was set to the minimum ventilation flow rate
- The cooling coil was activated
- The supply fan flow rate was kept at the maximum flow rate
- The RTU remained in this mode until the space temperature was lower than the cooling setpoint by 0.5ºF, at which point the ventilation mode was activated.

Two-Stage Compressor and Variable-Speed Fan (Case 1, Case 4)

- The outdoor air flow rate was set to the minimum ventilation flow rate
- The first-stage compressor was activated
- The supply fan flow rate was allowed to modulate between the minimum and the first-stage maximum flow rate based on the difference between the space temperature and the cooling setpoint
- The RTU remained in first-stage cooling until the space temperature was lower than the cooling setpoint by 0.5ºF, at which point the ventilation mode was activated
- After the first-stage compressor was on, if the space temperature rose above the cooling setpoint by 0.5ºF, the second-stage compressor was engaged
- In second-stage cooling, the supply fan air flow rate was allowed to modulate between the first-stage maximum and second-stage maximum air flow rate based on the difference between the space temperature and the cooling setpoint
- The RTU remained in second-stage cooling until the space temperature was below the cooling setpoint by 0.25ºF, at which point the unit was set to first-stage cooling.

Variable-Speed Compressor and Variable-Speed Fan (Case 2, Case 5)

- The outdoor air flow rate was set to the minimum ventilation air flow rate
- The first-stage compressor was activated
- The supply fan flow rate was allowed to modulate between the minimum and the first-stage maximum flow rate based on the difference between the space temperature and the cooling setpoint
- The RTU remained in first-stage cooling until the space temperature was lower than the cooling setpoint by 0.5ºF, at which point ventilation mode was activated
- If the space temperature was greater than the cooling setpoint by 0.15ºF, the second-stage compressor was engaged

- In second-stage cooling, the supply fan flow rate was allowed to modulate between the first-stage maximum and second-stage maximum air flow rate based on the difference between the space temperature and the cooling setpoint
- The RTU remained in second-stage cooling until the space temperature was below the cooling setpoint by 0.25ºF, at which point the unit was set to first-stage cooling
- If the space temperature was greater than the cooling setpoint by 0.35ºF, the third-stage compressor was engaged
- In the third-stage cooling, the supply fan flow rate was allowed to modulate between the second-stage maximum and third-stage maximum air flow rate based on the difference between the space temperature and the cooling setpoint
- The RTU remained in third-stage cooling until the space temperature was below the cooling setpoint by 0.25ºF, at which point the unit was set to first-stage cooling
- If the space temperature was greater than the cooling setpoint by 0.5ºF, the fourth-stage compressor was engaged
- In fourth-stage cooling, the RTU air flow rate was allowed to modulate between the third-stage maximum and fourth-stage maximum air flow rate based on the difference between the space temperature and the cooling setpoint
- The RTU remained in fourth-stage cooling until the space temperature was below the cooling setpoint by 0.25ºF, at which point the unit was set to first-stage cooling
- The RTU remained in mechanical cooling until the space temperature was below the cooling setpoint by 0.5ºF, at which point the ventilation mode was activated.

4.3 Heating Mode

Heating mode was activated when the space temperature was lower than the heating setpoint. All the technologies shared similar control logic during heating mode, summarized below:

- The outdoor air flow rate was set to minimum ventilation flow rate
- The supply fan flow rate was set to the maximum flow rate
- The heating coil was on
- The RTU remained in this mode until the space temperature was greater than the heating setpoint by 0.5ºF, at which point the ventilation mode was activated.

5 Simulation Results and Savings Summary

A total of 36 simulations were performed (the baseline models plus five different retrofit options across six building types) using Typical Meteorological Year 3 weather data for Chicago. Key simulation results and findings are presented in the subsections below.

5.1 Annual Electricity Use

Table 3 through Table 8 show the summary of annual energy consumption as well as annual peak kW demand for each building type. Both gross and normalized (by conditioned area and tonnage) energy consumption and peak demand data are provided. The tables also provide energy consumption by end use (AC and supply fan).

Table 3. Electricity Consumption Summary for Fast-Service Restaurant Building

Fast-Service Restaurant	Baseline	Case 1	Case 2	Case 3	Case 4	Case 5
Total Building Annual kWh	151,757	140,610	136,565	138,665	136,420	132,666
Annual AC (Compressor + Condenser Fan) kWh	8,926	8,461	5,550	8,090	7,917	7,490
Annual Supply Fan kWh	38,159	27,489	23,558	25,917	23,847	20,572
Peak Building kW	38.0	38.0	36.1	36.9	37.1	35.4
Total Building Annual kWh/ft^2	61	56	55	55	55	53
Total Building Annual kWh/ton	7,588	7,031	6,828	6,933	6,821	6,633
(AC + Supply Fan) kWh/ft^2	19	14	12	14	13	11
(AC + Supply Fan) kWh/ton	2,354	1,798	1,455	1,700	1,588	1,403
Peak W/ft^2	15.2	15.2	14.5	14.7	14.8	14.1
Peak KW/ton	1.90	1.90	1.81	1.84	1.86	1.77

Table 4. Electricity Consumption Summary for Full-Service Restaurant Building

Full-Service Restaurant	Baseline	Case 1	Case 2	Case 3	Case 4	Case 5
Total Building Annual kWh	269,217	249,369	246,035	247,790	242,756	239,674
Annual AC (Compressor + Condenser Fan) kWh	17,210	16,142	16,356	15,666	15,867	15,997
Annual Supply Fan kWh	60,039	41,195	36,467	40,221	34,910	30,508
Peak Building kW	65	65	61	63	64	60
Total Building Annual kWh/ft^2	49	45	45	45	44	44
Total Building Annual kWh/ton	8,158	7,557	7,456	7,509	7,356	7,263
(AC + Supply Fan) kWh/ft^2	14	10	10	10	9	8
(AC + Supply Fan) kWh/ton	2,341	1,737	1,601	1,694	1,539	1,409
Peak W/ft^2	11.8	11.8	11.2	11.5	11.6	10.9
Peak KW/ton	1.97	1.97	1.86	1.92	1.93	1.82

Table 5. Electricity Consumption Summary for Small Office Building

Small Office	Baseline	Case 1	Case 2	Case 3	Case 4	Case 5
Total Building Annual kWh	49,233	44,626	44,477	45,311	43,679	43,516
Annual AC (Compressor + Condenser Fan) kWh	3,706	3,766	3,558	3,355	3,719	3,493
Annual Supply Fan kWh	8,946	4,582	4,642	5,374	3,681	3,745
Peak Building kW	17	17	16	17	17	15
Total Building Annual kWh/ft^2	8.9	8.1	8.1	8.2	7.9	7.9
Total Building Annual kWh/ton	5,861	5,313	5,295	5,394	5,200	5,180
(AC + Supply Fan) kWh/ft^2	2.30	1.52	1.49	1.59	1.35	1.32
(AC + Supply Fan) kWh/ton	1,506	994	976	1,039	881	862
Peak W/ft^2	3.1	3.1	2.9	3.1	3.0	2.8
Peak KW/ton	2.03	2.02	1.88	2.01	1.99	1.83

Table 6. Electricity Consumption Summary for Stand-Alone Retail Building

Retail Stand-Alone	Baseline	Case 1	Case 2	Case 3	Case 4	Case 5
Total Building Annual kWh	321,677	257,243	256,706	270,515	248,947	248,230
Annual AC (Compressor + Condenser Fan) kWh	33,722	29,110	29,316	29,832	28,596	28,614
Annual Supply Fan kWh	103,744	43,713	43,621	55,876	35,929	35,890
Peak Building kW	98	96	89	94	93	87
Total Building Annual kWh/ft^2	13	10	10	11	10	10
Total Building Annual kWh/ton	4,949	3,958	3,949	4,162	3,830	3,819
(AC + Supply Fan) kWh/ft^2	5.6	2.9	3.0	3.5	2.6	2.6
(AC + Supply Fan) kWh/ton	2,115	1,120	1,122	1,319	993	992
Peak W/ft^2	4.0	3.9	3.6	3.8	3.8	3.5
Peak KW/ton	1.5	1.5	1.4	1.4	1.4	1.3

Table 7. Electricity Consumption Summary for Strip Mall Building

Strip Mall	Baseline	Case 1	Case 2	Case 3	Case 4	Case 5
Total Building Annual kWh	350,318	295,878	292,421	302,649	285,632	281,631
Annual AC (Compressor + Condenser Fan) kWh	31,094	27,738	27,629	28,917	27,388	27,780
Annual Supply Fan kWh	105,100	54,006	50,660	59,596	44,109	39,736
Peak Building kW	114	112	106	114	109	104
Total Building Annual kWh/ft^2	15.6	13.2	13.0	13.5	12.7	12.5
Total Building Annual kWh/ton	5,077	4,288	4,238	4,386	4,140	4,082
(AC + Supply Fan) kWh/ft^2	6.1	3.6	3.5	3.9	3.2	3.0
(AC + Supply Fan) kWh/ton	1,974	1,185	1,135	1,283	1,036	978
Peak W/ft^2	5.1	5.0	4.7	5.1	4.9	4.6
Peak KW/ton	1.65	1.62	1.54	1.65	1.59	1.51

Table 8. Electricity Consumption Summary for Warehouse Building

Warehouse	Baseline	Case 1	Case 2	Case 3	Case 4	Case 5
Total Building Annual kWh	181,139	176,205	176,402	174,407	173,848	174,009
Annual AC (Compressor + Condenser Fan) kWh	1,666	1,648	1,698	1,483	1,624	1,664
Annual Supply Fan kWh	19,327	14,409	14,557	12,777	12,077	12,198
Peak Building kW	47	47	47	46	46	46
Total Building Annual kWh/ft^2	3.5	3.4	3.4	3.4	3.3	3.3
Total Building Annual kWh/ton	13,934	13,554	13,569	13,416	13,373	13,385
(AC + Supply Fan) kWh/ft^2	0.40	0.31	0.31	0.27	0.26	0.27
(AC + Supply Fan) kWh/ton	1,615	1,235	1,250	1,097	1,054	1,066
Peak W/ft^2	0.90	0.90	0.90	0.89	0.89	0.89
Peak KW/ton	3.60	3.60	3.60	3.56	3.56	3.56

5.2 Annual Whole Building Electricity Savings

Table 9 and Figure 3 show annual energy savings in percentages corresponding to each building type. Based on the simulation results, all upgrade types (Case 1 to Case 5) are predicted to result in energy savings ranging from 3%–23% compared to the baseline energy consumption. The stand-alone retail building type is observed to benefit the most from the upgrades, while the warehouse building type exhibited the least savings, due to the relative contribution of heating, ventilating, and air conditioning (HVAC) to overall energy consumption in each building type: only 11% for the warehouse building, in contrast to 42% for the stand-alone retail building. Enhanced part-load efficiencies from two-stage/variable-speed compressor and variable-speed supply fans contributed to the annual energy savings. Of all the retrofit types, Case 5 showed the highest savings for most of the building types. The normalized energy savings in kWh/ton and kWh/ft^2 compared to the baseline are shown in Table 10. The savings ranged from 0.1–7.6 kWh/ft^2 and from 364–1,146 kWh/ton.

Table 9. Annual Percentage Building Electricity Savings

Case Type	Fast-Service Restaurant	Full-Service Restaurant	Small Office	Stand-Alone Retail	Strip Mall	Warehouse
Case 1	7%	7%	9%	20%	16%	3%
Case 2	10%	9%	10%	20%	17%	3%
Case 3	9%	8%	8%	16%	14%	4%
Case 4	10%	10%	11%	23%	18%	4%
Case 5	13%	11%	12%	23%	20%	4%

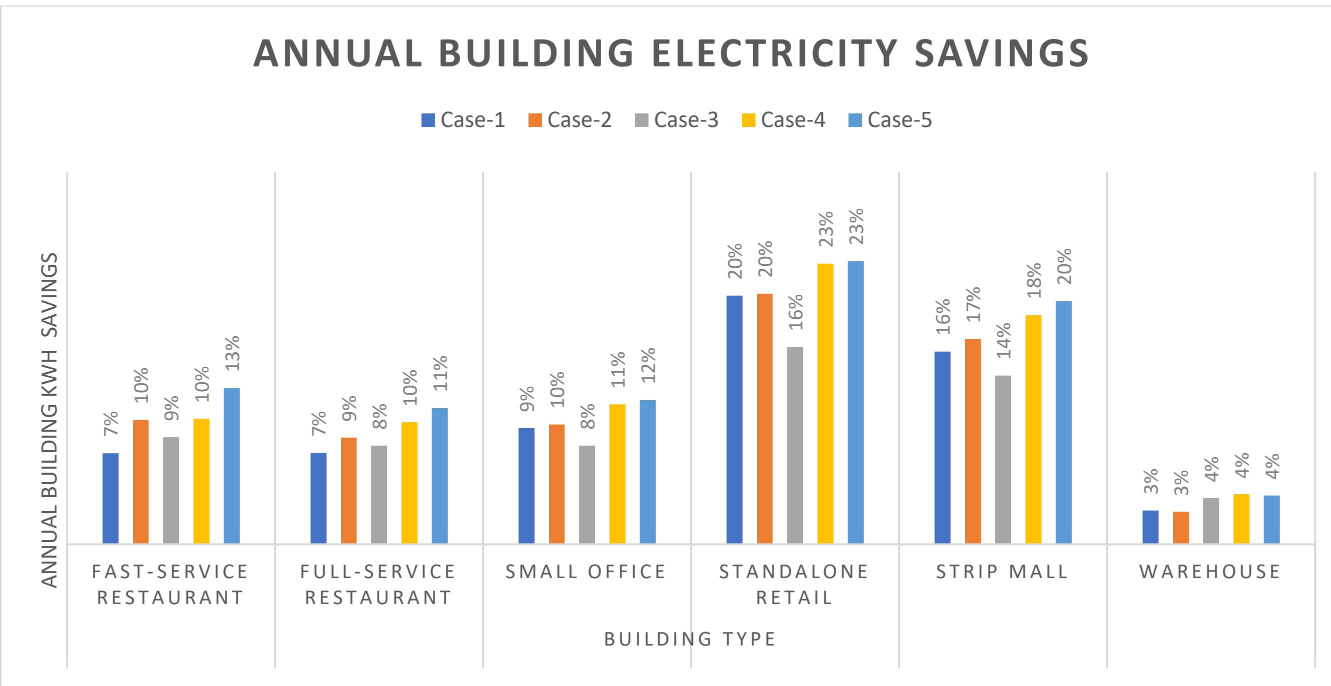

Figure 3. Annual percentage building electricity savings

Table 10. Annual Building Electricity Savings in kWh/ft^2 and kWh/ton

		Case 1	Case 2	Case 3	Case 4	Case 5
Fast-Service Restaurant	**(kWh/ft^2)**	4.5	6.1	5.2	6.1	7.6
	(kWh/Ton)	557.3	759.6	654.6	766.8	954.6
Full-Service Restaurant	**(kWh/ft^2)**	3.6	4.2	3.9	4.8	5.4
	(kWh/Ton)	601.4	702.5	649.3	801.8	895.2
Small Office	**(kWh/ft^2)**	0.8	0.9	0.7	1.0	1.0
	(kWh/Ton)	548.5	566.2	466.9	661.2	680.6
Stand-Alone Retail	**(kWh/ft^2)**	2.6	2.7	2.1	2.9	3.0
	(kWh/Ton)	989.9	1,026.6	787.1	1,120.3	1,146.9
Strip Mall	**(kWh/ft^2)**	2.4	2.6	2.1	2.9	3.1
	(kWh/Ton)	789.0	839.1	690.9	937.5	995.5
Warehouse	**(kWh/ft^2)**	0.1	0.1	0.1	0.1	0.1
	(kWh/Ton)	379.6	364.4	517.9	560.9	548.5

5.3 Annual HVAC Electricity Savings

Considering only HVAC systems (AC and supply fan), annual electricity savings ranging from 23%–53% were predicted (Table 11 and Figure 4). Stand-alone retail and warehouse building types exhibited the highest and lowest annual HVAC energy savings, respectively. As the electricity savings in the building comes from upgrading the supply fan and compressor types, the normalized HVAC energy savings in kWh/ft^2 and kWh/ton were similar to the building level savings as indicated in Table 10.

Table 11. Annual HVAC Electricity Savings

Case Type	Fast-Service Restaurant	Full-Service Restaurant	Small Office	Stand-Alone Retail	Strip Mall	Warehouse
Case 1	24%	26%	34%	47%	40%	24%
Case 2	38%	32%	35%	47%	43%	23%
Case 3	28%	28%	31%	38%	35%	32%
Case 4	33%	34%	42%	53%	48%	35%
Case 5	40%	40%	43%	53%	50%	34%

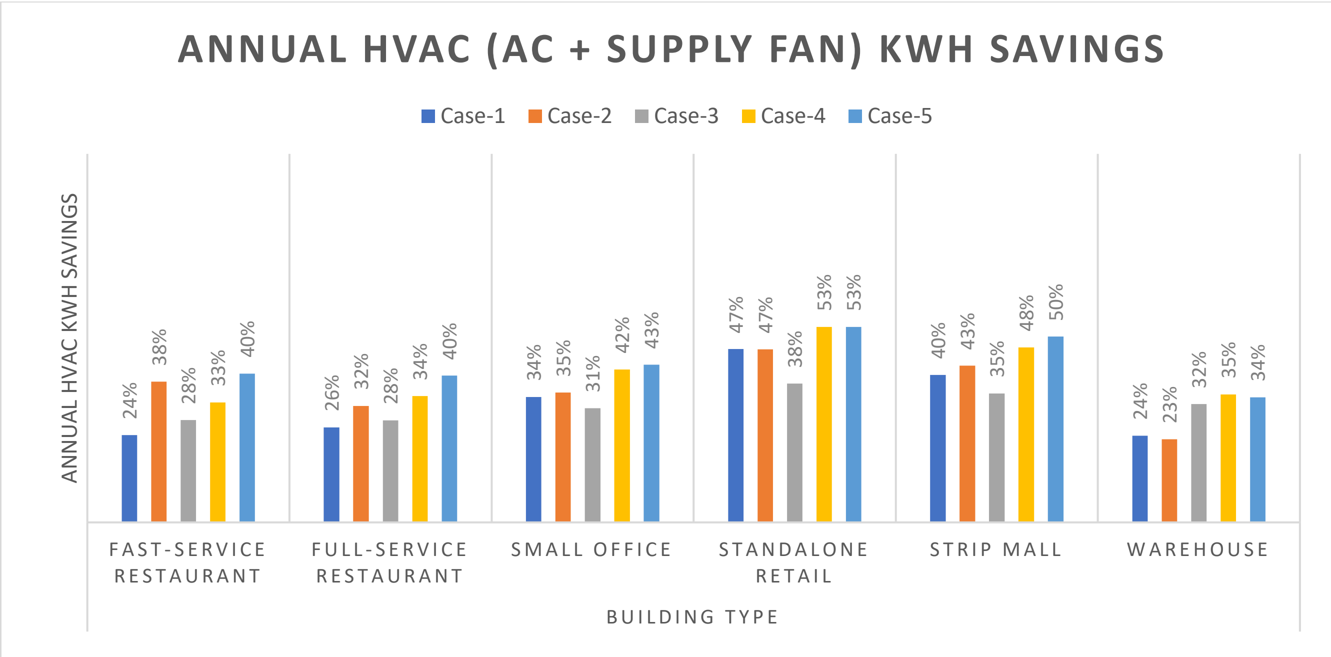

Figure 4. Annual HVAC electricity savings

5.4 Annual Fan Electricity Savings

Table 12 and Figure 5 show the predicted annual fan energy savings for each upgrade type compared to the baseline constant-speed fan energy consumption. Energy savings ranging from 25%–65% were predicted. Use of the SRM supply fan for two-stage/variable-speed compressor RTUs (Case 4 and Case 5) is also predicted to result in around 9% extra fan energy savings on average compared to conventional supply fan with variable frequency drive induction motors (Case 1). Normalized annual supply fan energy savings in kWh/BHP are shown in Table 13 and Figure 6. Savings ranging from 954 kWh/BHP–2,842 kWh/BHP were predicted.

Table 12. Annual Fan Electricity Savings

Case Type	Fast-Service Restaurant	Full-Service Restaurant	Small Office	Stand-Alone Retail	Strip Mall	Warehouse
Case 1	28%	31%	49%	58%	49%	25%
Case 2	38%	39%	48%	58%	52%	25%
Case 3	32%	33%	40%	46%	43%	34%
Case 4	38%	42%	59%	65%	58%	38%
Case 5	46%	49%	58%	65%	62%	37%

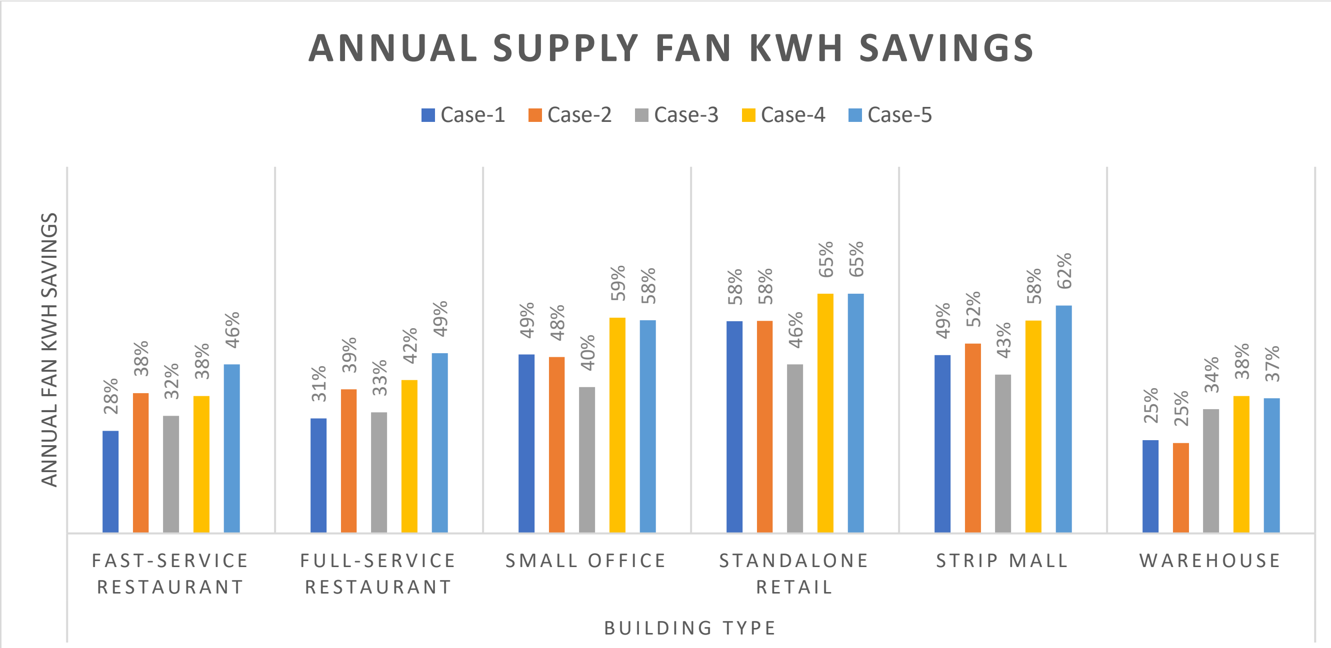

Figure 5. Annual fan electricity savings

Table 13. Normalized Annual Fan Electricity Savings in kWh/BHP

	Fan Energy Savings in kWh/BHP					
Case Type	**Fast-Service Restaurant**	**Full-Service Restaurant**	**Small Office**	**Stand-Alone Retail**	**Strip Mall**	**Warehouse**
Case 1	1,524	1,713	1,247	2,401	2,221	983
Case 2	2,086	2,143	1,230	2,405	2,367	954
Case 3	1,749	1,802	1,020	1,915	1,978	1,310
Case 4	2,045	2,284	1,504	2,713	2,652	1,450
Case 5	2,512	2,685	1,486	2,714	2,842	1,426

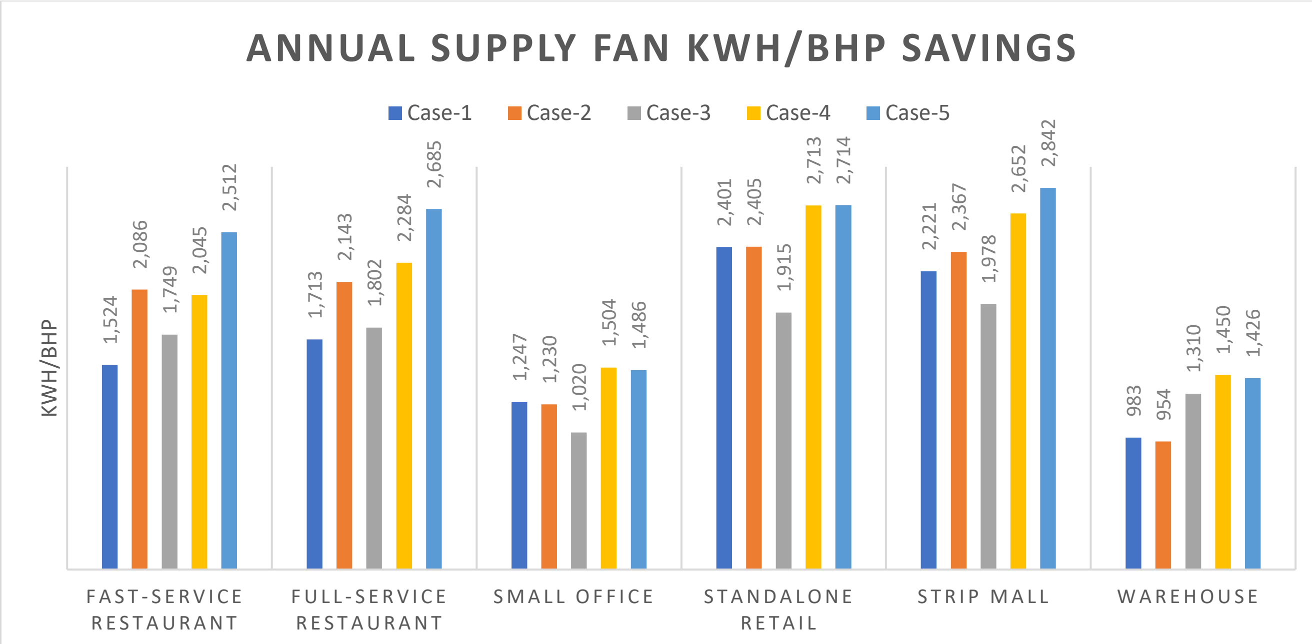

Figure 6. Normalized annual fan electricity savings in kWh/BHP

5.5 Peak kW Demand Reduction

Table 14 and Figure 7 show peak energy demand savings for each building type. The savings predicted ranged from 0% for warehouse to 10% for small office building types. The normalized peak kW savings ranged from 0 W/ft^2–1.1W/ft^2. In terms of normalized kW savings per ton, savings as high as 0.2kW/ton were observed for the small office building type. Only hours between 1 p.m.–5 p.m., Monday to Friday, June through August were considered for peak savings calculation (Illinois Statewide Technical Reference Manual 2019). As expected, Case 5 resulted in the highest energy demand savings for all the building types considered. Use of supply fan SRMs contributed to the peak energy savings both from improved part-load performance and motor efficiency. The normalized peak savings in W/ft^2 and W/ton are shown in Table 15. The savings ranged from 0–1.1 W/ft^2 and from 0–199 W/ton.

Table 14. Peak kW Savings

Case Type	Fast-Service Restaurant	Full-Service Restaurant	Small Office	Stand-Alone Retail	Strip Mall	Warehouse
Case 1	0%	0%	1%	2%	2%	0%
Case 2	5%	5%	8%	9%	7%	0%
Case 3	3%	2%	1%	4%	0%	1%
Case 4	2%	2%	2%	4%	4%	1%
Case 5	7%	7%	10%	11%	9%	1%

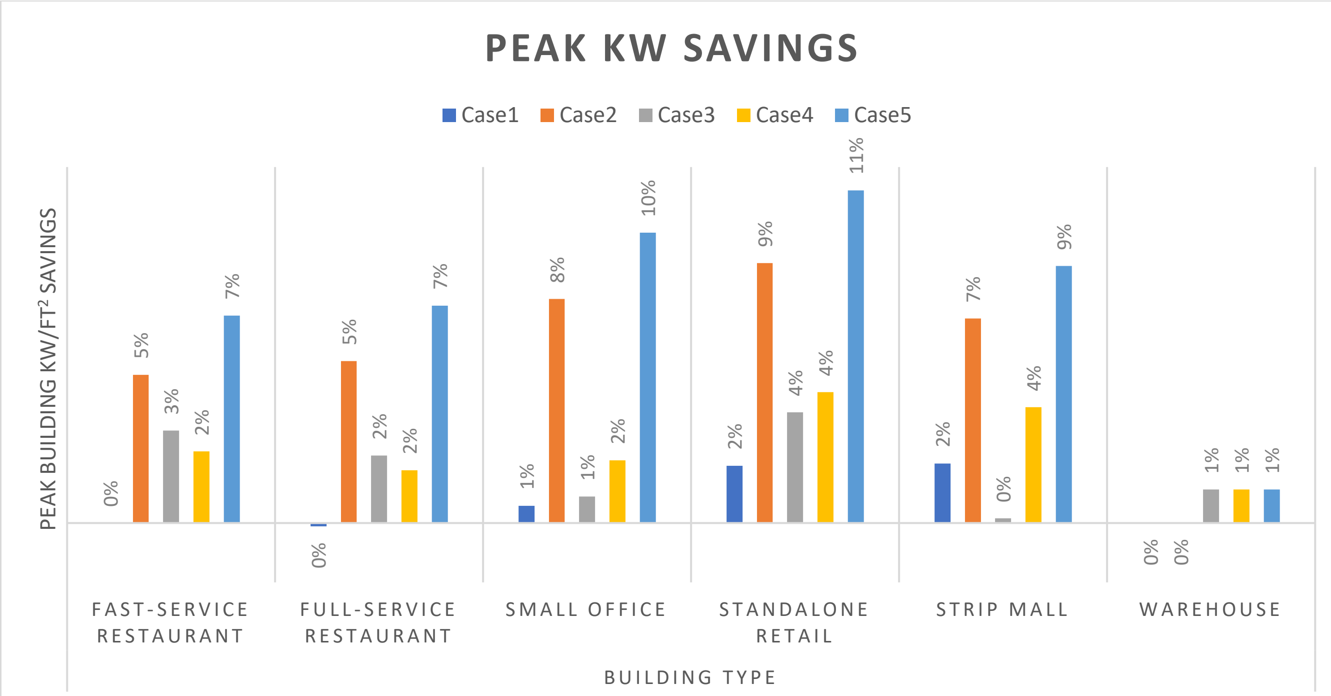

Figure 7. Peak kW savings

Table 15. Normalized Peak Energy Demand Savings in W/ft^2 and W/ton

		Case 1	Case 2	Case 3	Case 4	Case 5
Fast-Service Restaurant	**(W/ft^2)**	0.0	0.8	0.5	0.4	1.1
	(W/Ton)	0.1	95.1	59.3	45.9	133.0
Full-Service Restaurant	**(W/ft^2)**	0.0	0.6	0.3	0.2	0.9
	(W/Ton)	0	107.5	44.8	35.1	144.2
Small Office	**(W/ft^2)**	0.0	0.2	0.0	0.1	0.3
	(W/Ton)	11.9	153.4	18.1	42.9	198.9
Stand-Alone Retail	**(W/ft^2)**	0.1	0.3	0.1	0.2	0.4
	(W/Ton)	29.0	131.6	56.1	66.2	168.5
Strip Mall	**(W/ft^2)**	0.1	0.3	0.0	0.2	0.4
	(W/Ton)	33.2	113.8	2.6	64.3	142.9
Warehouse	**(W/ft^2)**	0.0	0.0	0.01	0.01	0.01
	(W/Ton)	0	0	40.6	40.6	40.6

6 Conclusion

The simulation results predict considerable annual energy savings for all the upgrade scenarios. The following energy-saving ranges were observed:

- Annual total building energy savings from 3%–23%
- Annual total building energy savings from 0.1 kWh/ft^2–7.6 kWh/ft^2
- Annual total building energy savings from 364 kWh/ton–1,146 kWh/ton
- Annual HVAC energy savings ranging from 23%–53%
- Annual supply fan energy savings ranging from 25%–65%
- Annual supply fan energy savings ranging from 954 kWh/BHP–2,842 kWh/BHP
- Peak energy demand savings from 0%–11%
- Peak energy demand savings from 0 W/ft^2–1.1 W/ft^2
- Peak energy demand savings from 0 W/ton–198 W/ton.

As expected, RTUs with a variable-speed compressor (Case 2 and Case 5) showed superior performance compared to RTUs with single-stage and two-stage compressor. This is a result of enhanced part-load performance due to the improved matching of the compressor capacity with the cooling load.

Similarly, supply fans with SRMs exhibited improved performance compared to the constant- and variable-speed induction motor supply fan cases examined. In all building types, the use of SRMs on the RTU supply fans resulted in 9% extra fan energy savings on average, compared to the supply fan with a variable-speed induction motor.

References

ASHRAE (2016). ANSI/ASHRAE/IES-90.1-2016: *Energy Standard for Buildings Except Low-Rise Residential Buildings.* Atlanta, Georgia: ASHRAE.

Cai, J., Braun, J.E., (2018). *Assessments of variable-speed equipment for packaged rooftop units (RTUs) in the United States*. Energy Build. 164, 203–218. https://doi.org/10.1016/j.enbuild.2018.01.007

DOE (2018). *EnergyPlus Version 8.9.0 Documentation: Engineering Reference.* https://energyplus.net/sites/all/modules/custom/nrel_custom/pdfs/pdfs_v8.9.0/EngineeringReference.pdf

DOE (2020). "EnergyPlus." Accessed October 29, 2020. https://energyplus.net/.

DOE (2020). "EnergyPlus Weather Data." Accessed October 29, 2020. https://energyplus.net/weather.

Illinois Statewide Technical Reference Manual (2019). *2019 Illinois Statewide Technical Reference Manual for Energy Efficiency Version 7.0 Volume 1: Overview and User Guide.* https://s3.amazonaws.com/ilsag/IL-TRM_Effective_010119_v7.0_Vol_1-4_Compiled_092818_Final.pdf.

SCE (2018). *Software-Controlled Switch Reluctance Motors.* Emerging Technologies Coordinating Council. https://www.etcc-ca.com/reports/software-controlled-switch-reluctance-motors.

Studer, Daniel, Rachel Romero, Lesley Herrmann, and Kyle Benne (2012). *Energy Implications of Retrofitting Retail Sector Rooftop Units with Stepped-Speed and Variable-Speed Functionality.* Golden, CO: NREL. NREL/TP-5500-51102. https://www.nrel.gov/docs/fy12osti/51102.pdf.

U.S. Energy Information Administration (2012). "2012 Commercial Buildings Energy Consumption Survey." Accessed October 29, 2020. https://www.eia.gov/consumption/commercial/.

Wheeler, Grant, Eric Kozubal, and Ron Judkoff (2018). *Experimental Design and Laboratory Characterization of a Medium- and High-Efficiency Rooftop Unit for Use in Building Energy Simulations.* Golden, CO: NREL. NREL/CP-5500-71133. https://www.osti.gov/biblio/1558884-experimental-design-laboratory-characterization-medium-high-efficiency-rooftop-unit-use-building-energy-simulations.

Appendix A. Details of RTU Operation Modes

Figure A-1 through Figure A-8 show the modes of operation for the different cases considered. The figures show how the modes of operation vary from case to case, as well as when outdoor air is appropriate and not appropriate for economizer operation.

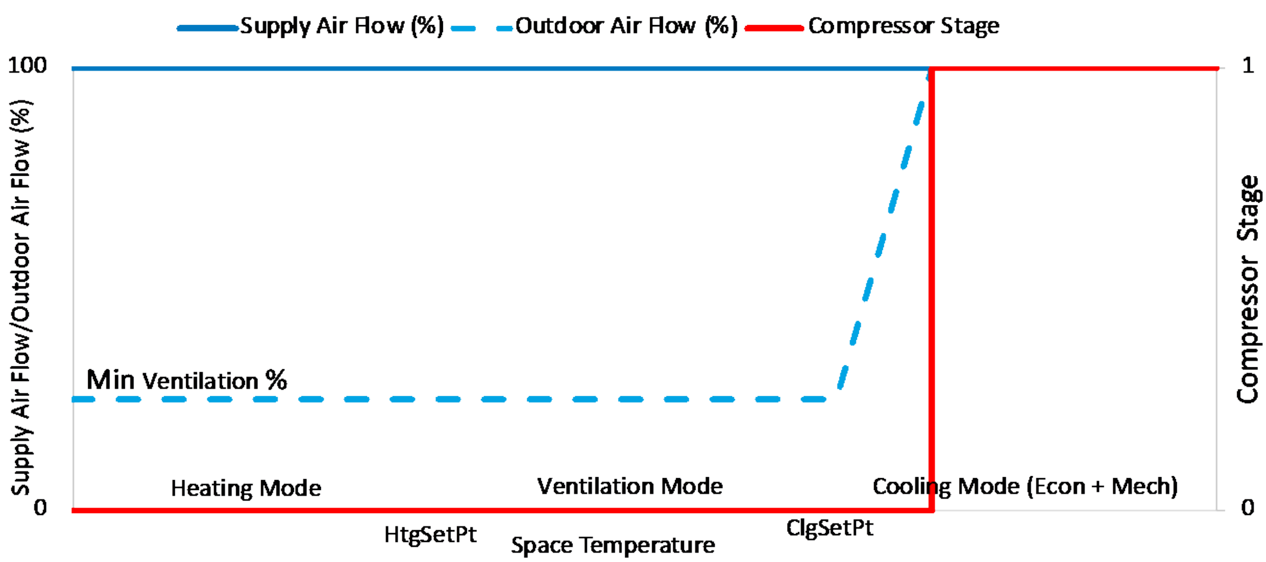

Figure A-1. Sequence of operations for baseline when outdoor air temperature is appropriate for economizer operation

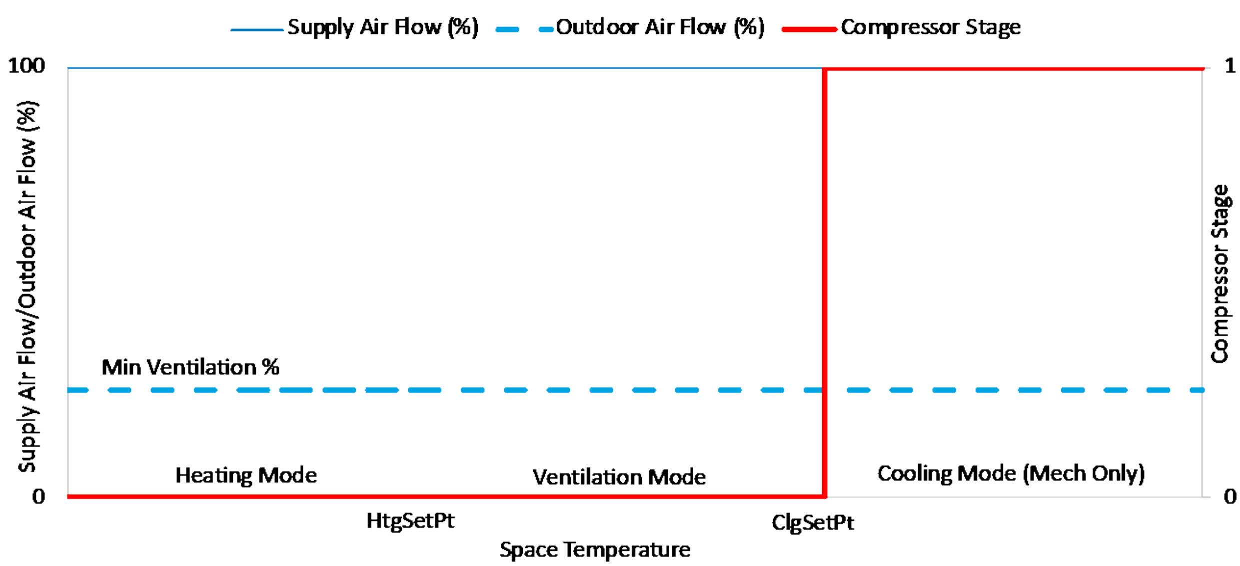

Figure A-2. Sequence of operations for baseline when outdoor air temperature is not appropriate for economizer operation

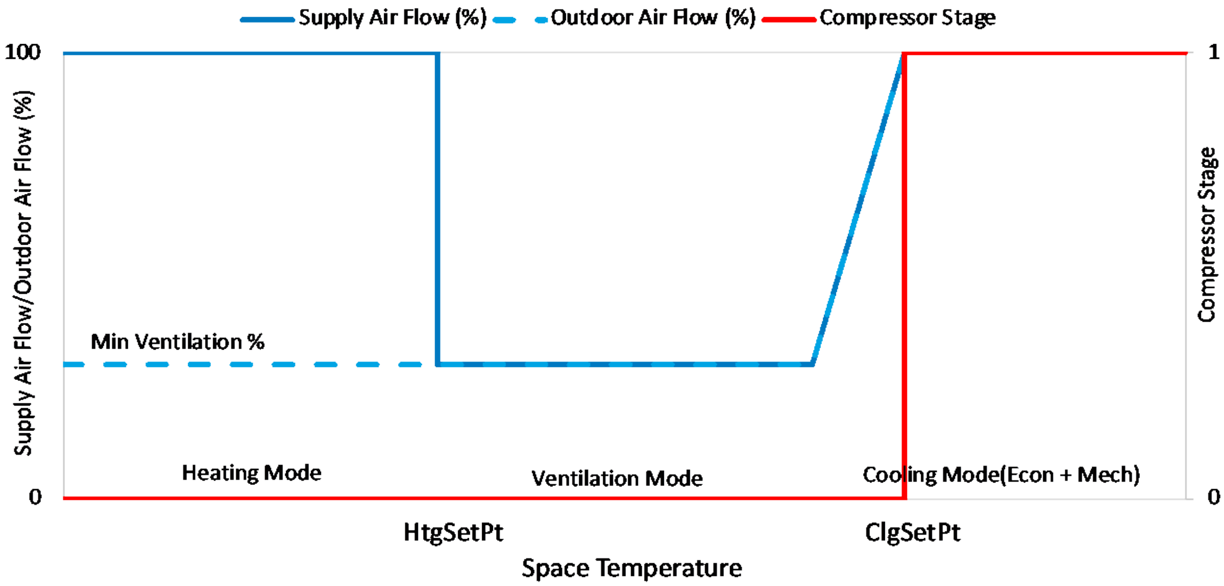

Figure A-3. Sequence of operations for Case 3 when outdoor air temperature is appropriate for economizer operation

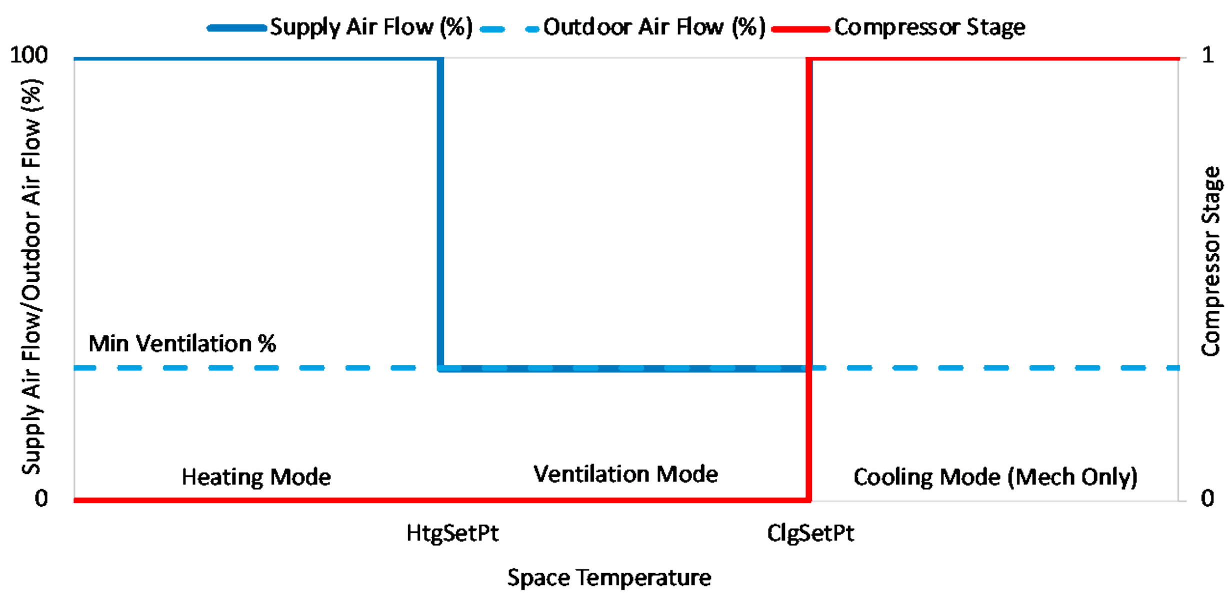

Figure A-4. Sequence of operations for Case 3 when outdoor air temperature is not appropriate for economizer operation

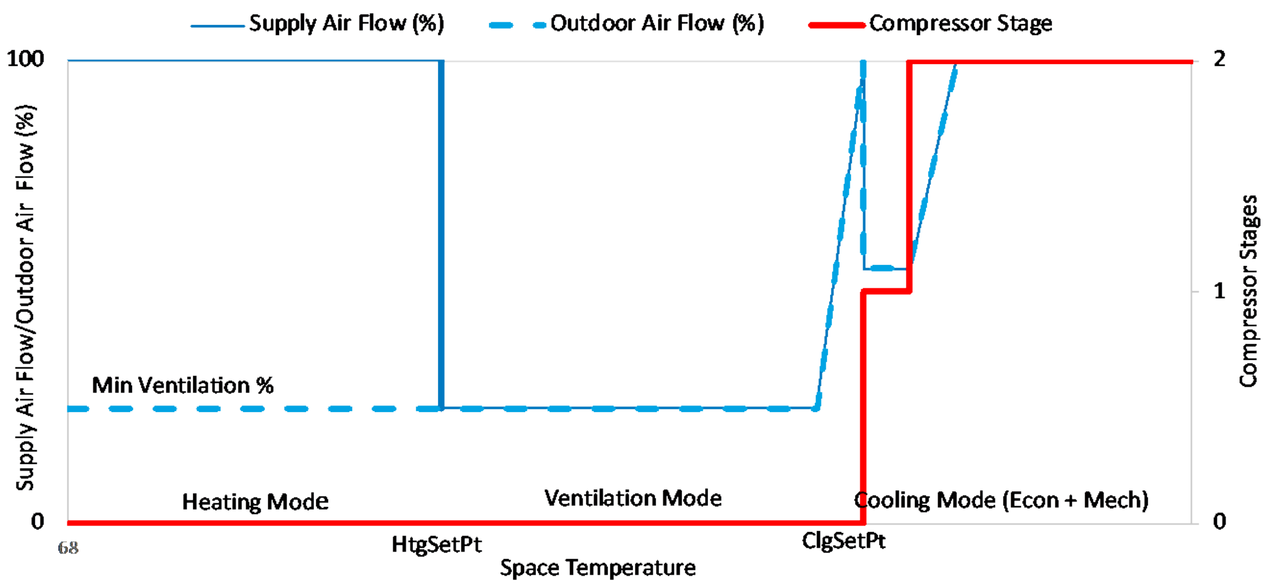

Figure A-5. Sequence of operations for Case 1 and Case 4 when outdoor air temperature is appropriate for economizer operation

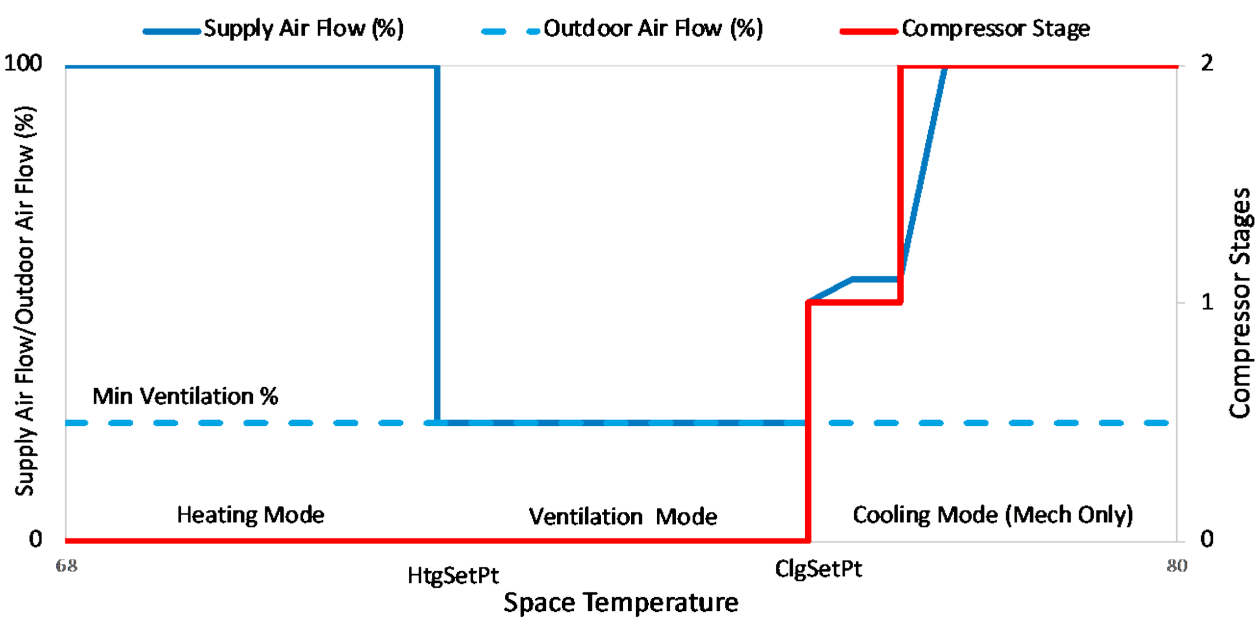

Figure A-6. Sequence of operations for Case 1 and Case 4 when outdoor air temperature is not appropriate for economizer operation

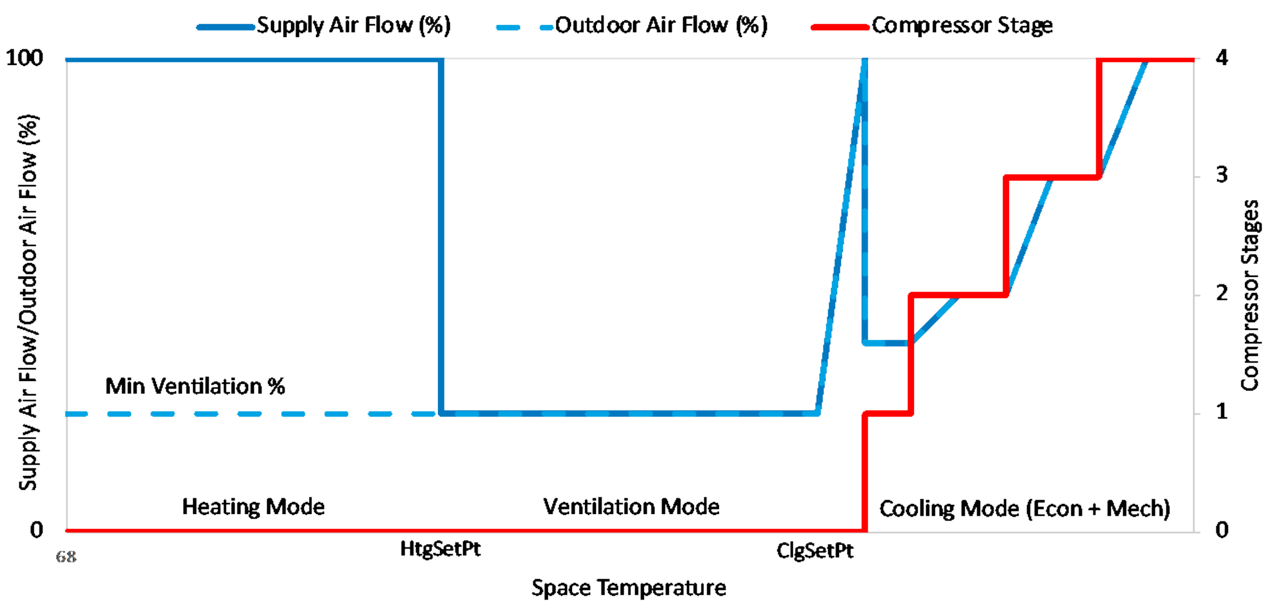

Figure A-7. Sequence of operations for Case 2 and Case 5 when outdoor air temperature is appropriate for economizer operation

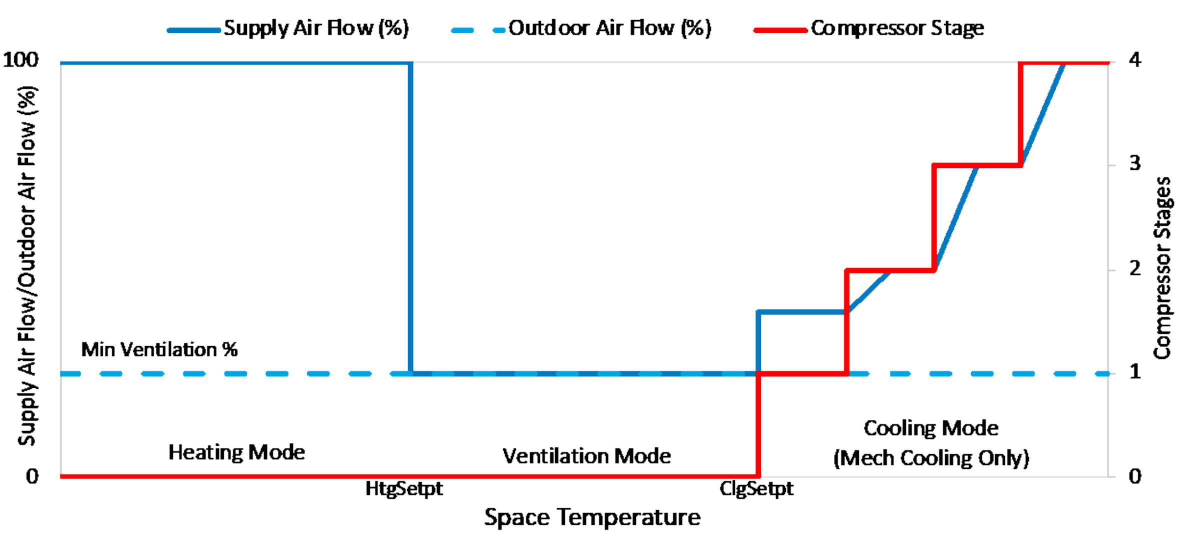

Figure A-8. Sequence of operations for Case 2 and Case 5 when outdoor air temperature is not appropriate for economizer operation