Title

Energy Use of High-efficiency Motor and Drive System Retrofits in Commercial Packaged Rooftop Heating, Ventilation and Air Conditioning Units

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Energy Use of High-Efficiency Motor and Drive System Retrofits in Commercial Packaged Rooftop Heating, Ventilation, and Air Conditioning Units

By

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Abstract

Previous research indicates that variable and stepped speed fan motor and drives increase energy efficiency in packaged rooftop units. California established energy efficiency standards for all buildings, including variable speed fan motor capabilities, to promote lower energy consumption. This paper evaluates the energy savings of not only the California building code for packaged rooftop units, but also how specific high efficiency motor and drive pairs increase energy efficiency for commercial spaces. High-efficiency motor and drive pairs underwent laboratory testing to measure performance and efficiency. The resulting data was then used to simulate buildings following California's building code with the high-efficiency motor and drive pairs. The simulations were then compared with simulations using the minimum efficiency requirements for California buildings. The high-efficiency motor and drive pairs were confirmed to save greater energy than the base California building code compliance and offers a solution to further reduce statewide energy consumption. The high-efficiency motors and drives were found to save anywhere from 2070-27,00 kWh of source energy beyond the California Code minimum compliance depending on the climate zone and motor and drive pair selected.

Thus, we recommend that California promote these motor and drive products, for both the utility cost savings and carbon dioxide emissions reductions.

Nomenclature

Abbreviation	**Full Term**
AC	Alternating Current
ANSI	American National Standards Institute
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
CAV	Constant Air Volume
DoE	(U.S.) Department of Energy
DC	Direct Current
EIA	Energy Information Administration
HP	Horsepower
HVAC	Heating, Ventilation, and Air Conditioning
kWh	Kilowatt hour
Lbs.	Pounds
nm	Newton meters
NEMA	National Electrical Manufacturers Association
RPM	Rotations Per Minute
Sq ft	Square foot
SMC	Software Motor Company
VAV	Variable Air Volume
VFD	Variable Frequency Drive

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Introduction

In laboratory work we measured the efficacy of high-efficiency motors and drives under conditions expected for rooftop units. The resulting data was input to the building energy software, EnergyPlus, to assess commercial-building energy use across California to explore the energy saving potential of a high-efficiency motor and drive pair retrofits for RTU's.

Relevance of Work

In 2021 global energy-related carbon dioxide emissions reached 36.3 billion metric tons, the highest amount ever in a year [1]. The 36.6 billion metric tons of emissions refers to solely energy-based carbon dioxide and does not include other carbon dioxide sources or the emissions of other greenhouse gases such as methane. In 2014 the United States of America accounted for 15% of all carbon dioxide emissions while representing only 4.5% of the global population [2]. California as the most populous state consumes 259.5 terawatt hours of electricity annually and emitted 418.2 million metric tons of carbon dioxide in 2018 [3]. California attributes 70% of its electricity consumption and a quarter of its greenhouse gases to buildings [4]. Mechanical and lighting systems in these building account for the majority of energy consumption [4]. The primary mechanical energy expenditure for a building is the heating, ventilation, and air conditioning (HVAC).

The U.S. Energy Information Administration (EIA) estimates that in 2021 space cooling alone consumed 389 billion kWh of electricity between the residential and commercial sectors. That value accounts for 10% of annual national energy consumption [5]. Space cooling is just one part of HCAV energy consumption, meaning national energy expenditure on HVAC exceeds at least 10% of total electricity consumption [6]. This paper addresses an energy conservation measure which will maintain air conditioning and ventilation standards while reducing energy consumption [6]. In the United States HVAC units are sized based on design load days which represent the greatest 0.4% of potential heating loads and cooling loads [7]. Unfortunately, most rooftop-unit (RTU) fan motors operate at a single speed which generates a constant air volume (CAV). This means that the fan motors are sized to constantly blow enough air to meet the building's most extreme loads even when actual loads are much lower [8]. Additionally the U.S. Department of Energy (DoE) estimated that in 2011, 58% of all industrial, commercial, and residential electricity was consumed by devices using electric motors [9]. To address blowing more air than is necessary a multi-speed motor and a compatible variable frequency drive (VFD) can be installed to vary airflow, producing a variable air volume (VAV) system. To combat high energy consumption California instituted some of the U.S.'s strictest building energy efficiency codes, including VAV capabilities in commercial buildings [10]. This paper clarifies how much energy Title 24 VAV compliance conserves, as well as the energy that can be conserved using high efficiency motor and drive products that surpass the minimum efficiency standards of Title 24. The ability to vary the fan speed and air flow offers significant energy savings, particularly with highly efficiency motor systems, which can aid California and all regions in reducing electricity and consumption and therefore reduce greenhouse gas emissions.

Work Addressed

This paper investigates the energy saving potential of high-efficiency motor and drive pairs, particularly as they apply to CAV to VAV retrofits for non-residential buildings. To move air through a duct an electric motor must rotate a fan to push the air. To describe the relationship between fan power draw and air flow, the fan affinity laws are used. The fan affinity laws act as guides for how changes in fan diameter, fan speed, fan torque, and air pressure are mathematically related.

The first fan affinity law: $q_2 = \left(\frac{RPM_2}{RPM_1}\right) \times q_1$ where q_2 is final volumetric flow q_1 is initial volumetric flow, RPM_2 is final fan rotational speed and RPM_1 is initial fan rotational speed.

The second fan affinity law: $pa_2 = pa_1 \times \left(\frac{RPM_2}{RPM_1}\right)^2$ where pa_2 is final pressure, pa_1 is initial pressure, RPM_2 is final fan rotational speed and RPM_1 is initial fan rotational speed.

The third fan affinity law: $P_2 = P_1 \times \left(\frac{RPM_2}{RPM_1}\right)^3$ where P_2 is final power draw, P_1 is initial power draw, RPM_2 is final fan rotational speed and RPM_1 is initial fan rotational speed [11].

While fan rotational speed is directly proportional to the air's volumetric flow rate, any change in rotational speed has a cubic relationship to change in power consumption [11]. This occurs due to the buildup of pressure, where the pressure buildup is proportional to the square of the fan rotational speed as seen in the second fan affinity law [12]. Therefore, the relationship between the volumetric flow rate of air and the power needed to move that air is theoretically cubic, greatly incentivizing lower fan and air speed capabilities. VAV systems offer energy saving potentials due to their ability to reduce fan speed or torque to the minimum airflow requirements. Thus reducing energy consumption when the air flow requirement is lower than that at maximum design loads [13].

Literature review

A similar study by the National Renewable Energy Laboratory in 2012 studied retrofits for commercial buildings, simulating energy savings from installing either discrete multispeed or continuously variable speed capabilities into rooftop packaged units. This study simulated sites across the United States and found total building energy savings ranging from 0.7%-8.4% when adding stepped or variable speed capabilities to the building's rooftop units [14]. This paper also found that heating demands were increased in all buildings with stepped speed fan retrofits due to the fans imparting less mechanical energy into the airflow. Despite the higher heating demands the National Renewable Energy Laboratory recommended that all large retail buildings consider stepped speed fan retrofits. Implementation into only 10% of all retail space across the United States would save 332 gigawatt hours of electricity a year which translates to 28.8 million dollars in utility savings [14].

Another study on variable frequency drive evaluation found that variable frequency drives did not save energy during peak load operation due to losses by the drive which often operate at 97% efficiency or lower [15]. This study investigates those losses by evaluating high-efficiency motor and drive pairs which may offer higher system efficiency than standard motor and drive pairs.

In a similar vein, a paper on how to not overestimate the energy savings from a variable frequency drive found that at lower air speeds, a fan motor is likely less efficient, creating energy losses that might be overlooked [16]. Fan motor efficiency tends to drop off when the load dips below 50%. Similarly, duct and piping energy losses increase at lower reduced airflow rates. Other common causes for overestimating energy savings from variable frequency drives include, ineffective or miscalculated dynamic control systems for the variable frequency drive, and misleading energy consumption on motor and drive nameplates. Fan motor efficiency drops off at nameplate ratings for multiple reasons and many high-efficiency motors are most efficient at 80% of their nameplate load [17]. The primary causes for motor efficiency losses in order of magnitude are stator resistance loss, rotor resistance loss, core loss, and stray load loss. Stator resistance loss is due to internal electrical resistances of the stator and can be combatted by increasing wire width or stator length, which would increase the cost of conductors for a motor [18].

Outline

The following chapters discuss the laboratory testing of high-efficiency motor and drive pairs. Next the process of simulating CAV compared to VAV HVAC system throughout California will be discussed. Finally, the implementation of the laboratory results as motor and drive retrofits for the buildings covered in energy simulations will be discussed.

Motor Testing

To measure the efficacy of high-efficiency motor and drive pairs laboratory testing was performed to measure the power consumption of the motor systems at various speeds and torque loadings, chosen to be representative of what should be encountered in typical operation conditions. Motor sizes for testing were chosen by the California Energy Commission. All tested motors were rated for a nominal speed of 1800 rpm, a nominal power output of 7.5 horsepower (HP), and to conform to NEMA standards for 213T frames.

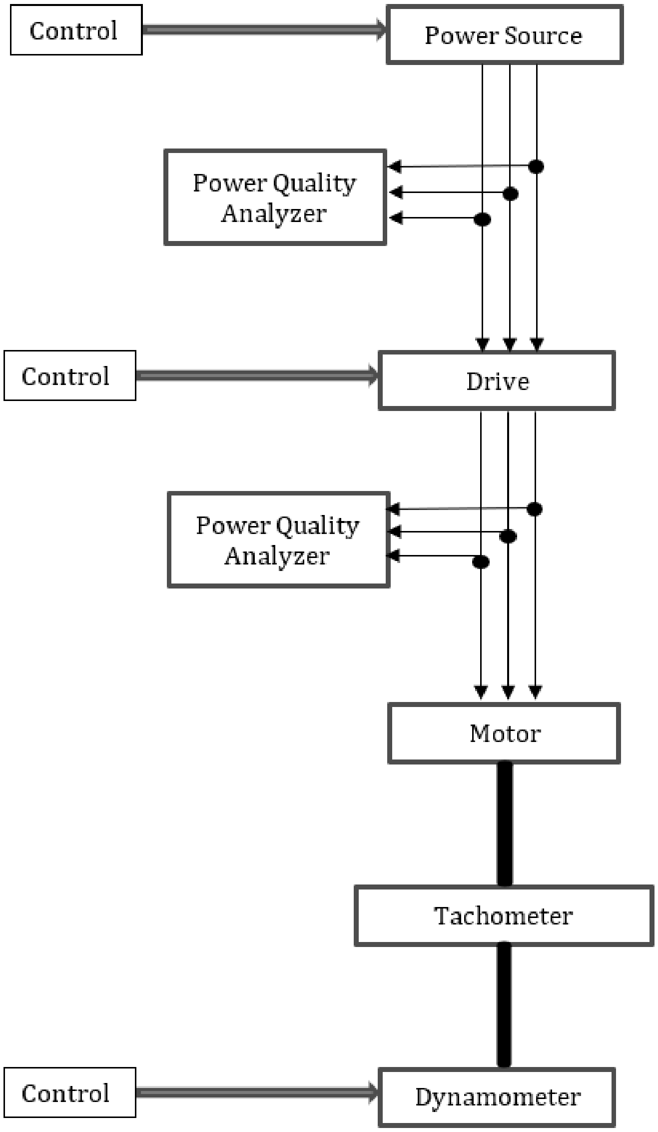
Test Apparatus Construction

Motor testing was performed in a controlled environment on a dynamometer constructed over 9 months for this experiment as shown in Figure 1. The tested motor and drive pair were wired such that power was fed through a 480-volt stationary transformer, to a 0-480V variable transformer to adjust output voltage before feeding into the power analyzer and then the test drive. This allowed for power stabilization and for checking the quality of power supplied to the tested drive. The drive was then wired back into the power analyzer before wiring into the test motor, allowing for a quality check on the power supplied from the test drive to the test motor. The test drive was controlled manually to establish the desired speed. The test motor's shaft was coupled to a tachometer and a torque applying load motor. The load supplying motor was controlled by its own drive with control systems accessed in LabVIEW and applied torque opposite to that of the test motor, to replicate the increase in torque as fan speed and airflow increase as would occur in a duct. Power for the load drive came directly from the building power supply. The test motor was set to a desired speed while the load motor was set to a desired opposing torque and the motors were run for 300 seconds of data collection at each test condition. The load motor and drive also connect to a braking resistor to dissipate heat during the testing process.

Data taken in the power analyzer included voltage, total harmonic distortion of voltage, power, and current into the test drive, as well as voltage, total harmonic distortion of voltage, power, and current into the test motor. Data taken by the tachometer connecting the load and test motors included motor speed, motor torque, and mechanical power output. Additional data points taken and processed by LabVIEW included ambient room temperature and motor temperature.

All testing was performed in accordance with the motor and electrical testing standards outlined by ASHRAE and ANSI in ASHRAE Standard 222 [19]. Notable testing conditions met include tachometer precision greater than or equal to 1 rpm, total no-load harmonic distortion not exceeding 3%, and root mean square (RMS) voltage and frequency within tolerance of ±0.5%.

Figure 1 – Diagram of Test Apparatus for Remote Complete Drive Systems [20]



Test Procedure

Motor speed and torque tests points are decided using fan affinity laws for corresponding speeds and torques expected for common percent of airflow operation points for fan duty cycles in VAV systems, as described by the 2012 ASHRAE handbook on HVAC Systems and

Equipment [21]. Each motor and drive pair was tested at each speed and each torque producing a matrix of results. From this the torque and speed test points that matched the expected speed and torque load for common airflow points in a duct system were used to construct a performance curve for expected percent airflow versus percent power draw.

The airflow points selected were: 100%, 90%, 80%, 65%, 50%, and 30%. These operating points represent the most frequent airflow points in VAV systems, as well as encompass a wide test range for accurate motor efficacy exploration [21]. This airflow testing spectrum from 30% airflow to 100% covers 96.9% of all RTU fan duty cycles according to *ASHRAE Handbook: Heating, Ventilating, and Air-Conditioning SYSTEMS AND EQUIPMENT* [21]. Due to the first fan law percent airflow and percent air speed are proportional so percent airflow can be set to equal percent fan speed [11]. However, due to the third fan law, power is proportional to the cube of the percent airflow ratio and can be solved for accordingly. Thus, because power is the product of torque and speed [12], we solved for the torque expected at each airflow point using the known power draw and speed, resulting in the common airflow points seen in Table 1.

Fan Power Equation: $Power = Torque \times Speed \rightarrow Torque = Power \div Speed$

Table 1 – Speed and Torque Test Points for Common Airflows

Percent Airflow [%]	**Percent Fan Speed [%]**	**Percent Torque [%]**	**Percent Theoretical Power Draw [%]**
100	100	100	100
90	90	81	72.9
80	80	54	51.2
65	65	42	27.6
50	50	25	12.5
30	30	9	2.7

The data points in Table 1 were then regressed to create a quartic curve to determine the expected power draw of each motor and drive pair operating at 66% airflow, which will be used later in the analysis. It should also be noted that in real VAV systems the theoretical fan laws are not perfectly followed. The power is more likely to be proportionate to the air flow ratio to the 2.4 power. This occurs due to losses when VAV partially closed dampers lead to increased static duct pressure, which when paired with a fan controlled to maintain a constant duct pressure wastes energy[22].

Test Results

The first motor tested, was manufactured by the Turntide Software Motor Company (SMC). The SMC motor, as with all tested motors, was an 1800 rpm, 7.5 hp motor, that fit into a NEMA 213T frame. The SMC motor came with its own unique drive. The motor data sheet claimed a peak motor and drive pair efficiency of 93% [23]. The SMC motor is a switched reluctance motor, a direct current (DC) motor design which utilizes windings on stator poles [24]. Unidirectional, or DC, electric current run through one or more stator poles generates an magnetomotive force which attracts a nearby rotor pole and pulls the rotor [25]. The stator pole(s) through which current is run then alternates to create a constant magnetic torque on the rotor causing it to rotate. The motor could not be wired to other drives because the motor and drive connected through 6 specially made DC wires intended only for this motor and drive pair. Due to the special wires used to join the motor and drive they were evaluated only at the system scale and no voltage or current metering was possible between the motor and drive. The specialized drive for this motor required remote control and was controlled using the producer's iPhone application (Turntide Technician).

After testing across the potential speed and torque load spectrum, the test points corresponding to expected airflow conditions were brought together to evaluate the system efficiency and fractional power draw at these conditions. The SMC motor and drive pair, while less efficient than advertised, still achieved the highest system efficiency of any tested motor and drive pair.

Table 2 – Laboratory Test Results for the SMC Motor paired with the SMC Drive

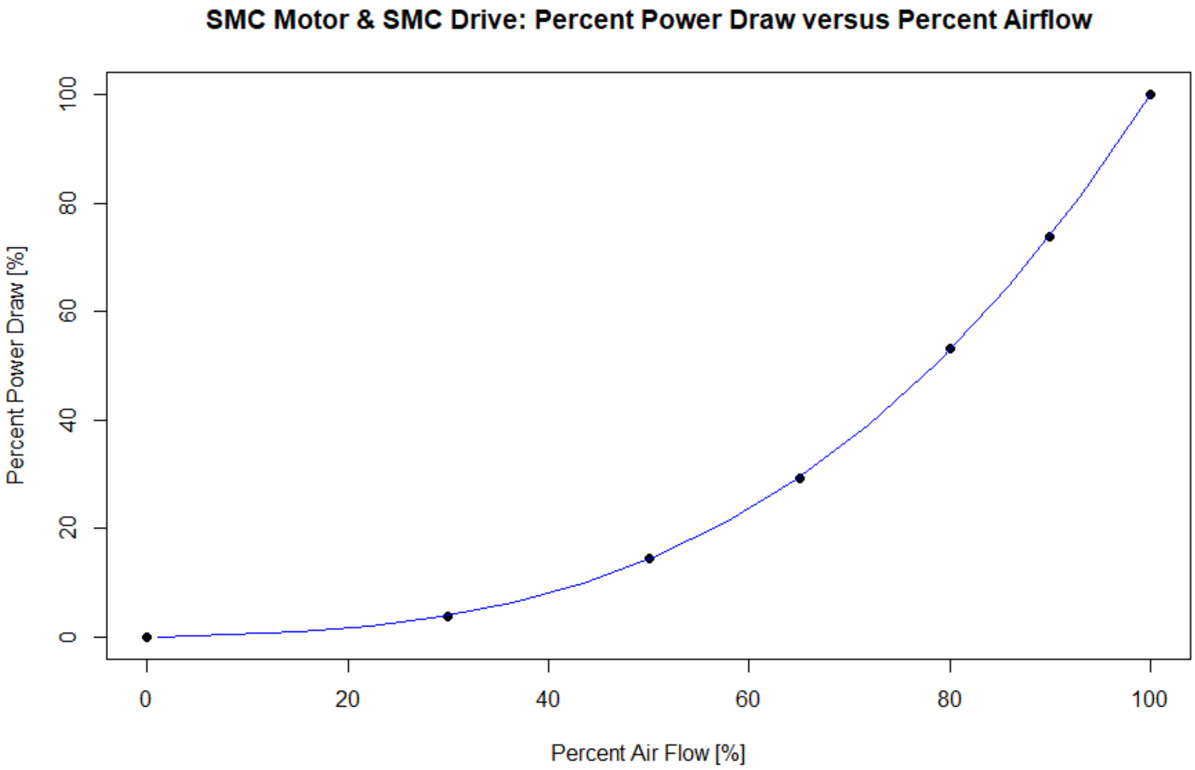
Percent Air Volume [%]	**Speed [rpm]**	**Torque [nm]**	**System Efficiency [%]**	**Percent Power Draw [%]**
100	1,800	29.7	91.9%	100.0%
90	1,620	24.3	91.2%	73.8%
80	1,140	19.2	90.2%	53.2%
65	1,170	12.6	87.4%	29.3%
50	900	7.5	82.1%	14.4%
30	540	2.7	67.3%	3.9%

The results in Table 2 were regressed to produce the quartic curve in Figure 2 with a R squared value of 0.999. The curve's equation was

$$y = -3.262 * 10^{-6} + 4.808x * 10^{-2} - 4.269x^2 * 10^{-2} + 1.084x^3 - 8.965x^4 * 10^{-2}$$

The percent power draw at 66% air flow was found to be 30.8%. The motor data was input into multiple polynomial regression models from linear to sextic; and, quartic was selected as the best option due to superior R squared values. To maintain consistency all other motor data was also regressed into quartic polynomials and reported high R squared values.

Figure 2 – SMC Airflow Data and Quartic Curve



The second motor and drive pair tested, the Marathon motor and Schneider drive, received approval from both product producers as a compatible pair for testing. The Schneider drive was controlled using its front facing control panel. This motor and drive pair was connected with 8-gauge wires. The wires go from the drive into the power analyzer and then into the motor, allowing for motor and drive efficiency to be monitored individually, as well combined into system efficiency. The Marathon motor tested is a permanent magnet synchronous motor. Permanent magnet synchronous motors operate by running alternating current (AC) through a stator winding to create an electromagnetic force which creates a torque on the permanent magnets in the rotor [26].

The peak system efficiency for this motor and drive pair was measured to be 89.5% as seen in Table 3.

Table 3 – Laboratory Test Results for the Marathon Motor paired with the Schneider Drive

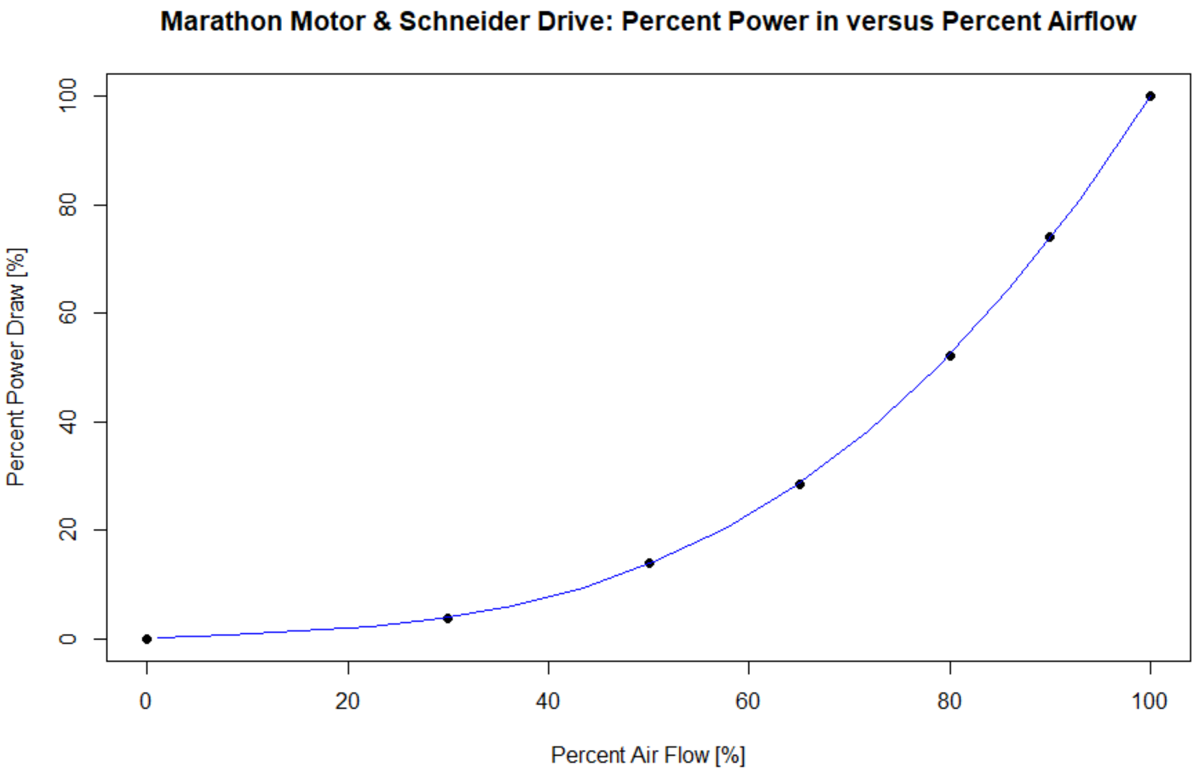
Percent Air Volume [%]	**Speed [rpm]**	**Torque [nm]**	**System Efficiency [%]**	**Percent Power Draw [%]**
100	1800.00	29.7	89.5%	100.0%
90	1620.00	24.3	89.8%	76.2%
80	1140.00	19.2	89.0%	53.8%
65	1170.00	12.6	86.9%	29.4%
50	900.00	7.5	81.2%	14.4%
30	540.00	2.7	62.9%	4.0%

The results seen in Table 3 was found to result in the quartic curve visible in Figure 3. The curve's equation was

$$y = -2.138 * 10^{-4} + 2.521x * 10^{-1} - 1.1621x^2 + 2.946x^3 - 1.033x^4$$

The regressed curve returned a R squared value of 0.999 and found the percent power draw at 66 percent air flow to be 31.1%.

Figure 3 – Marathon Airflow Data and Quartic Curve



The third motor and drive pair tested was the Nidec motor with the Schneider drive. These products received approval from both product producers as a compatible pair for testing. The Nidec motor tested is a 3-phase induction motor. Induction motors use AC run through stator coils to create an electromagnetic force which excites a current in the rotor windings, magnetizing the rotor and creating a torque force [27].

This motor was controlled and wired to the Schneider drive similar to how the Marathon motor was connected to the system, allowing for power quality analysis between the motor and drive. The peak tested efficiency for the system was 86.4% (Table 4). The Nidec motor and Schneider drive performed with the worst across the spectrum efficiency of the three motors.

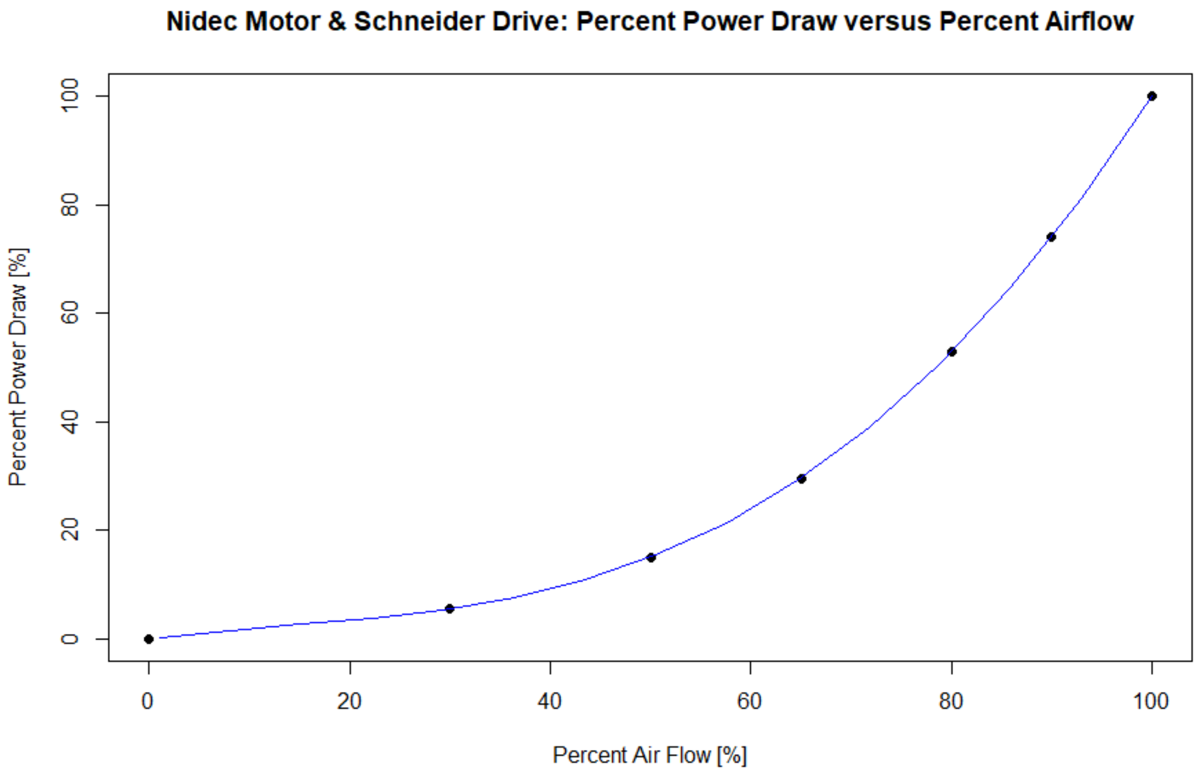
The Nidec motor and Schneider drive also reported the highest percent power draw for each testing point.

Table 4 – Laboratory Test Results for the Nidec Motor paired with the Schneider Drive

Percent Air Volume [%]	**Speed [rpm]**	**Torque [nm]**	**System Efficiency [%]**	**Percent Power Draw [%]**
100	1800.00	29.7	86.4%	100.0%
90	1620.00	24.3	85.9%	79.8%
80	1140.00	19.2	84.6%	57.0%
65	1170.00	12.6	80.4%	31.9%
50	900.00	7.5	72.1%	16.3%
30	540.00	2.7	42.6%	5.9%

The results seen in Table 4 was found to result in the quartic curve visible in Figure 4. The Nidec motor and Schneider drive curve's equation was $y = -3.42 * 10^{-4} + 5.994x * 10^{-1} - 2.754x^2 + 5.551x^3 - 2.392x^4$. The regressed equation returned a R squared value of 0.999 and found the percent power draw at 66 percent air flow to be 33.8%.

Figure 4 – Nidec Airflow Data Graphed and Resulting Quartic Curve



Chapter Summary

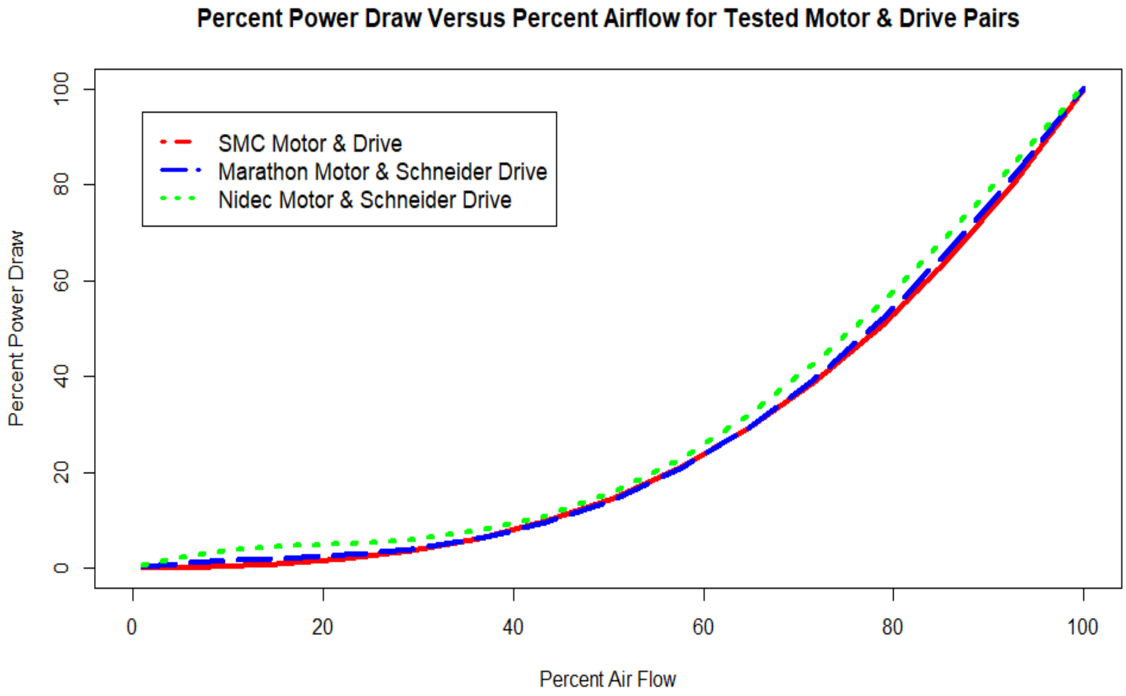
The SMC motor and drive pair returned the highest efficiency of all pairs tested at the design load of 100% airflow conditions. This may be attributed to the packaged SMC motor and drive pair. Additionally, as the newest motor by design, the SMC had access to the newest technology and the greatest motor and drive pair compatibility. The Nidec motor with the Schneider drive had the lowest efficiency at all levels of testing. The Nidec and Marathon motors may have suffered drive compatibility losses when compared to the SMC system; but, the Schneider Drive was approved by both Nidec and Marathon as an appropriate drive pairing. The motor test data is summarized in Table 5.

Table 5 – Summary of All Motor Test Results

Motor Manufacturer	SMC	Marathon	Nidec
Motor Type	Switched Reluctance	Permanent Magnet Synchronous	3-Phase Induction
Drive Manufacturer	SMC	Schneider	Schneider
System Efficiency at 100% Airflow	91.9%	89.5%	86.4%
Power Draw at 100% Airflow	100.0%	100.0%	100.0%
Power Draw at 90% Airflow	73.8%	76.2%	79.8%
Power Draw at 80% Airflow	53.2%	53.8%	57.0%
Power Draw at 65% Airflow	29.3%	29.4%	31.9%
Power Draw at 50% Airflow	14.4%	14.4%	16.3%
Power Draw at 30% Airflow	3.9%	4.0%	5.9%

The results were used to establish expected power draws for each motor and drive pair when operating at any airflow rate. In this analysis the expected power draw of each motor and drive pair at 66% air volume flow rate will be used for later simulations. The expected power draws are as follows: SMC 30.8%, Marathon 31.1%, and Nidec 33.8%. The motor and drive power draw curves are illustrated in Figure 5.

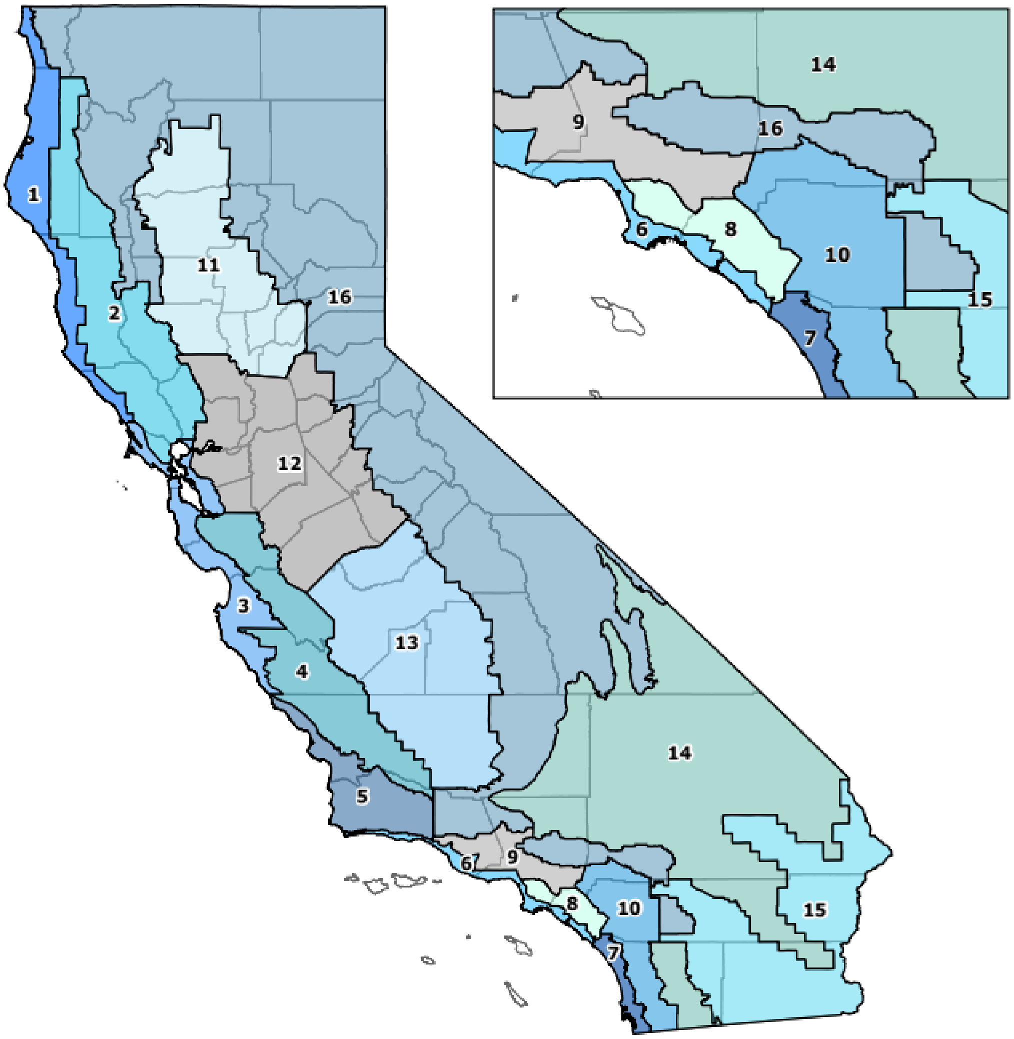
Figure 5 – Percent Power Draw Versus Percent Airflow for Tested Motor & Drive Pairs



Simulation of Energy Savings

To assess the potential energy savings from high-efficiency motor and drive pairs, the laboratory data was used in simulations of prototype buildings across California. EnergyPlus, a whole-building energy simulation software sponsored by the U.S. Department of Energy was used for the simulations [28]. Stand-alone retail building was selected for modeling due to its common usage of RTU's that can accept variable speed drives. The prototype buildings were selected from the U.S. Department of Energy's reference building page [29]. Prototype buildings come with three available construction vintages: pre-1980, post-1980, and post-2004. Each of these vintages was modeled separately. To simulate building energy use across California, all 16 of California's climate zones (Figure 6) were simulated separately[30].

Figure 6 – Climate Zone Map of California [31]



Simulating CAV Buildings

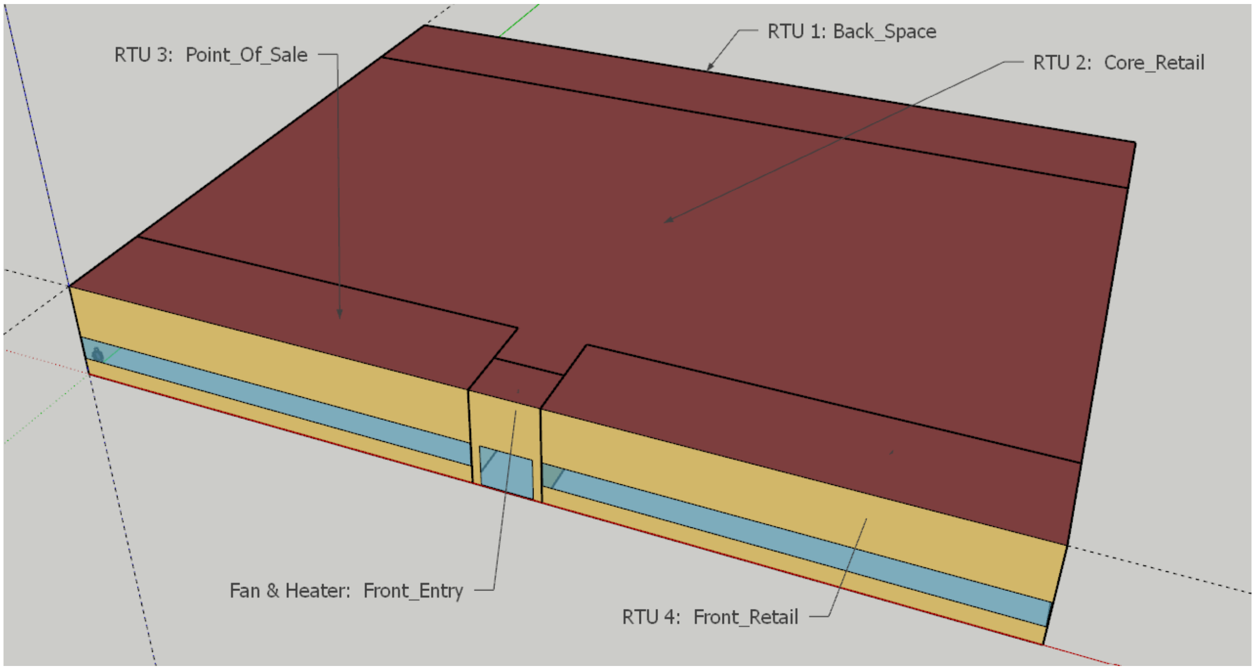
To establish a baseline simulation the prototype stand-alone retail building files were downloaded and then given the appropriate location and weather data. It is important to use both the correct design load and correct weather files when using EnergyPlus. Design load day is an object contained in the building file while the weather data is a separate file selected at simulation start. The design load day inputs are used by EnergyPlus for zone, system, and plant sizing, which occur before simulations. While there are other ways to input design load data, the design load days input is the EnergyPlus default. The weather files are used during the energy simulations, providing relevant hourly data such as temperature and humidity throughout the year. The prototype buildings come with multiple location options across the U.S. The only available reference cities located in California were San Francisco and Los Angeles. To fit the available locations to the desired California climate zones a reference was supplied by Lawrence Berkeley National Laboratory (Table 6) through personal contact [32]. The reference indicates which national location to use for each California location before altering the design load days and location to the desired California climate zone. Once location and design load days were determined, simulations were run to create a baseline energy consumption for constant-air-volume systems using the Department of Energy’s assumed base motor efficiencies. When modeling baseline CAV energy consumption no edits were made to the building description data besides correcting the design load days, correcting location, and using the correct weather file.

Table 6 – California Climate Zone Representative Cities and the Department of Energy Reference City used for their simulations with corrected design load days

Climate Zone	Climate Zone Representative City	Representative City's County	Reference City Altered for Simulation
1	Arcata	Humbolt County, CA	Seattle, WA
2	Santa Rosa	Sonoma County, CA	San Francisco, CA
3	Oakland	Alameda County, CA	San Francisco, CA
4	San Jose	Santa Clara County, CA	San Francisco, CA
5	Santa Maria	Santa Barbara County, CA	San Francisco, CA
6	Torrance	Los Angeles County, CA	Los Angeles, CA
7	San Diego	San Diego County, CA	Los Angeles, CA
8	Fullerton	Orange County, CA	Los Angeles, CA
9	Burbank-Glendale	Los Angeles County, CA	Los Angeles, CA
10	Riverside	Riverside County, CA	Los Angeles, CA
11	Red Bluff	Tehama County, CA	Las Vegas, NV
12	Sacramento	Sacramento County, CA	Las Vegas, NV
13	Fresno	Fresno County, CA	Las Vegas, NV
14	Palm Dale	Los Angeles County, CA	Las Vegas, NV
15	Palm Spring	Riverside County, CA	Las Vegas, NV
16	Blue Canyon	Placer County, CA	Las Vegas, NV

The default model for the stand-alone retail building had four HVAC zones served by four packaged rooftop units as well as one front entrance fan with an electric heater. The four HVAC zones include a large central zone as well as three smaller perimeter zones, all with natural gas heating in their respective rooftop units. The central HVAC zone is significantly larger than the other HVAC zones. When auto sizing components EnergyPlus found the central zone required 4 to 5 times the ventilation, heating, and cooling capacity of the other three individual zones. The building was single story, rectangular in layout, with a floor area of 24,962 square feet. A visualization of the building including HVAC zones is shown in Figure 7.

Figure 7- 3D Rendering of stand-alone retail building and its HVAC Zones



Alteration Process to make Buildings VAV & Simulations

When editing the base CAV building models to VAV all EnergyPlus component values were left untouched, or had explicit sizing copied over if a component had to be replaced with a comparable component that was VAV compatible in EnergyPlus. The only numerical values directly changed were number of fan motor speeds and establishing the Title 24 compliance for airflow and power fraction. All objects replaced are due to EnergyPlus requiring explicit VAV compatibility. All replaced objects are identical to their CAV counterparts in practice and as such have all applicable designations set identically to the default CAV system.

To begin editing the prototype file a UnitarySystemPerformance:Multispeed object that defines the discrete fan speeds for heating and cooling was created so that the fans operate at maximum air flow if the heating or cooling coils are active. This component is not a physical object but is required for EnergyPlus to accept other multispeed components. The next modification to the prototype file was to replace fans stored in the Fan:OnOff category of the file with fans with updated information in the Fan:SystemModel section. This allows for a greater number of inputs and controls for the fan motors. The replacement of the fans was done so that the motor test data could be input as the original fan objects are single speed in EnergyPlus. The existing AirTerminal:SingleDuct:ConstantVolume:NoReheat objects were then replaced by AirTerminal:SingleDuct:VAV:NoReheat objects to accept the variable air volume. Replacing the airducts with functionally identical air ducts, with VAV designation, is necessary for EnergyPlus to run VAV components. Then the ZoneHVAC:AirDistributionUnit object was altered to accept the new duct designation. This edit is done by selecting what type of airduct is connected to the air distribution unit. The Coil:Cooling:Dx:Singlespeed objects were then replaced with Coil:Cooling:Dx:Multispeed to accept the VAV system. EnergyPlus will not allow single speed cooling coils to be joined with VAV components, so the coil had to be replaced. The two speeds necessary to establish the multi-speed coil objects were both set to full operation when airflow was at maximum, effectively creating a single speed cooling coil that EnergyPlus accepted as VAV compatible. AirLoopHVAC:UnitarySystem objects replaced the AirLoopHVAC:UnitaryHeatCool objects. These objects are functionally identical with the Unitary system accepting VAV capabilities. In Sizing:System the airflow control switched from

CAV to VAV. Then the Controller:OutdoorAir objects were altered so that the lockout type was set to lockout with heating. EnergyPlus will interpret the heating lockout and the forced single-speed cooling coil so that heating and cooling operations will be performed with full air flow and fan speed. The resulting system will then handle thermal loads similar to a single speed system, cycling heating and cooling components on and off, each with a single operation point which always coincides with full fan airflow. Ventilation with no active heating or cooling will be performed at the lower fan speed.

Table 7 details which EnergyPlus components were altered or replaced and their respective purposes in EnergyPlus [33]. Table 8 summarizes how the components were altered or replaced so that EnergyPlus would simulate the building as VAV.

Table 7 – Altered & Removed Components with their Purposes in EnergyPlus

Original Component	**Component Purpose**
SizingPeriod:DesignDay	Provide Design load information for EnergyPlus sizing operations before simulation
UnitarySystemPerformance:Multispeed	Required for multi speed heating and cooling, determines airflow ratio at discrete operation speed
Fan:OnOff	Constant Volume Fan
AirTerminal:SingleDuct:ConstantVolume:NoReheat	Central Air System Terminal with Single duct, CAV, no reheat coil
ZoneHVAC:AirDistributionUnit	Central Air Distribution Unit
Coil:Cooling:Dx:Singlespeed	Single Speed DX cooling coil
AirLoopHVAC:UnitaryHeatCool	Unitary System for CAV heating and cooling
Sizing:System	Specifies input needed for sizing of air system
Controller:OutdoorAir	Controller to set outdoor flow rate

Table 8 – Summary of Building Alterations in EnergyPlus to Accommodate VAV

Original Component	**Alteration Performed**
SizingPeriod:DesignDay	Correct climate zone design load day swapped in
UnitarySystemPerformance:Multispeed	Created
Fan:OnOff	Replaced by Fan:SystemModel, Motor Data updated when needed
AirTerminal:SingleDuct:ConstantVolume:NoReheat	Replaced by AirTerminal:SingleDuct:VAV:NoReheat
ZoneHVAC:AirDistributionUnit	Accept VAV
Coil:Cooling:Dx:Singlespeed	Replaced by Coil:Cooling:Dx:Multispeed
AirLoopHVAC:UnitaryHeatCool	AirLoopHVAC:UnitarySystem
Sizing:System	Set to Accept VAV
Controller:OutdoorAir	Lockout with Heating

To analyze HVAC energy consumption the following variables were included: fan energy, cooling energy, heating energy from electricity, and heating energy from natural gas. To verify proper ventilation and airflow standards fan mass flow rate and fraction of outdoor air were also recorded. Each listed variable was recorded for each of the four rooftop units and their serviced zones, as well as the front entry heater and fan. The results were then summed across each zone and the entry fan every hour to produce a summary of the building total HVAC energy consumption from fans, heating, and cooling.

When enabling VAV capabilities for a building it is important to determine a method of minimum airflow to be maintained during ventilation only operation periods. Due to the large floorspace of the stand-alone retail building, the default method of outdoor airflow in EnergyPlus is outdoor air flow per zone floor area. The simulated buildings will make sure to always blow at least the designated outdoor airmass flow during all operation modes.

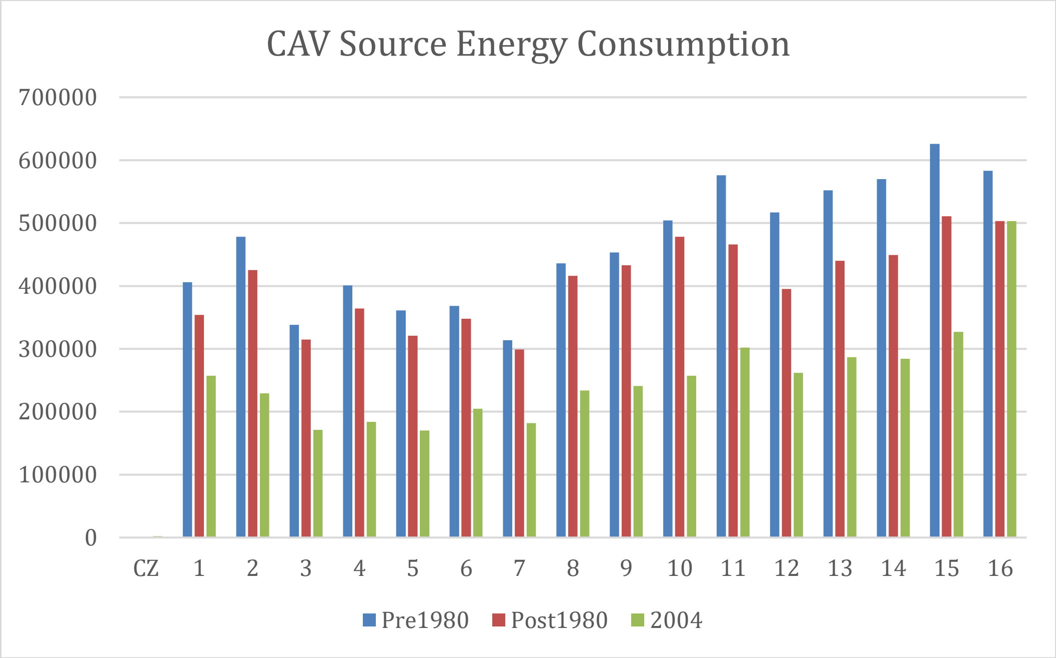
Simulation of VAV with High-Efficiency Motor and Drive Pairs

To implement the results from the laboratory motor testing into simulation efforts, the expected speed-torque airflow test points for a duct were used to construct quartic curves using the linear regression function in the software Rstudio [34]. A quartic curve is a 4^{th} degree polynomial, in this cased used as a curve describing the relationship between airflow and power fraction for the tested motors and drives. Quartic curves are also an object type in EnergyPlus and as such can be easily implemented into simulations. These curves describe the percent airflow versus percent power draw for the motor and drive pairs. From these curves the Title 24 compliance point at 66% airflow was selected to find the corresponding fractional power draw of each high-efficiency motor and drive pair at that airflow point. The air flow and power draw point was then put into the fan:SystemModel objects in the VAV models. Additionally, the static motor efficiency was changed from default values to the appropriate measured motor and drive system efficiency at nominal conditions. Then all vintages and climate zones were simulated again for each motor and drive pair. We assumed that for each motor tested earlier in the project there exists a motor of comparable efficiency at or near the auto sized motor capacities in EnergyPlus.

Results & Comparisons

The first results to discuss are the baseline energy consumptions for each climate zone using the default CAV system which are shown in Figure 8. In each climate zone the older building vintages consumed more energy than their newer counterparts. This was expected as the building vintages follow efficiency and building standards of their respective construction years. The older buildings' envelopes were less thermally insulated, and the older HVAC equipment was slightly less efficient. The data presented in Figure 8 and Tables 9-14 refers to source energy. EnergyPlus automatically calculates both source and site energy. Source energy for electricity is calculated as 1.742 times the site energy. Source energy for natural gas is calculated as 1.092 times the site energy.

Figure 8 – Graph of Total Source Annual HVAC Energy Consumption by climate zone and building vintage



Due to the scale of the energy being reported as well as the number of total buildings, data beyond this point is averaged with equal weighting between the three building vintages and reported in Tables 9 through 14. Data reported from this point on is also presented as rounded to 3 significant figures. Unaveraged data for the source energy consumed by each building simulated is available in the appendix.

Table 9 - Average Annual HVAC Source Energy Consumption Across 3 Building Vintages with CAV

Climate Zone	Fan - Electricity [kWh]	Heating - Electricity [kWh]	Heating - Natural Gas [kWh]	Cooling - Electricity [kWh]	Total HVAC Energy [kWh]
1	118,000	1,900	218,000	950	339,000
2	168,000	1,470	157,000	49,800	377,000
3	142,000	1,030	116,000	15,700	275,000
4	161,000	807	96,300	57,900	316,000
5	145,000	953	115,000	22,300	284,000
6	201,000	344	38,200	67,600	307,000
7	184,000	303	32,400	48,500	265,000
8	220,000	392	38,000	104,000	362,000
9	222,000	471	48,400	104,000	375,000
10	227,000	547	59,100	126,000	413,000
11	196,000	1,420	138,000	112,000	448,000
12	175,000	1,290	137,000	78,500	391,000
13	188,000	1,030	116,000	122,000	426,000
14	194,000	1,010	127,000	112,000	434,000
15	220,000	286	32,600	235,000	488,000
16	187,000	2,710	249,000	31,600	470,000

Comparing the default CAV buildings to the baseline VAV buildings reveals energy savings following the adoption of the minimum level of Title 24 compliance for HVAC energy savings. The energy consumption and thus the savings analyzed, maintain an average and equal weighting between the three building vintages in each climate zone. In Table 10 the default fan system efficiency was used, and the fan is set to use two air speeds. One air speed with 100% airflow and 100% power draw, and a slower speed with 66% airflow and 40% power draw.

Table 10 – Average Source Energy Saved when comparing Baseline Title 24 minimum compliance VAV to CAV by Climate Zone

Climate Zone	**Fan - Electricity [kWh]**	**Heating - Electricity [kWh]**	**Heating - Natural Gas [kWh]**	**Cooling - Electricity [kWh]**	**Total HVAC Energy [kWh]**
1	63,200	(4)	(29,500)	55	33,800
2	85,700	(12)	(25,000)	11,400	72,000
3	70,600	(11)	(20,900)	4,350	54,000
4	84,800	(8)	(18,700)	13,800	79,900
5	72,700	(11)	(18,800)	5,950	59,900
6	101,000	(5)	(11,800)	21,300	110,000
7	88,400	(4)	(11,000)	15,400	92,800
8	114,000	83	(9,710)	30,900	136,000
9	117,000	(5)	(14,600)	24,500	127,000
10	121,000	(5)	(15,900)	27,500	132,000
11	99,300	(7)	(23,900)	17,500	92,900
12	89,600	(7)	(23,100)	15,000	81,400
13	96,100	(6)	(20,500)	20,400	96,000
14	99,600	(8)	(20,500)	16,100	95,300
15	121,000	(3)	(9,310)	37,500	149,000
16	89,900	(11)	(32,200)	5,250	63,000

Table 11 shows the results of simulations using the efficiency and flow fraction versus percent power draw of the SMC motor and drive. It summarizes the percent savings found for each HVAC energy category associated with upgrading from Title 24 minimum efficiency compliance to the SMC motor with minimum compliance for. For the SMC simulations the nominal motor system efficiency was set to 91.9%, while the two air flow speeds were set to 100% airflow with 100% power draw and 66% airflow with 30.8% power draw.

Table 11 – Average Annual Source Energy Savings When Comparing SMC Simulations to Title 24 Base VAV Simulations by Climate Zone

Climate Zone	**Fan - Electricity [kWh]**	**Heating - Electricity [kWh]**	**Heating - Natural Gas [kWh]**	**Cooling - Electricity [kWh]**	**Total HVAC Energy [kWh]**
1	5,820	11	(2,750)	(61)	3,020
2	10,600	12	(2,630)	848	8,800
3	7,080	13	(1,850)	236	5,480
4	10,400	4	(2,110)	1,010	9,340
5	8,160	12	(1,540)	480	7,120
6	12,600	7	(934)	1,420	13,100
7	13,100	(0)	(1,860)	1,180	12,400
8	12,800	(81)	(4,060)	(408)	8,230
9	13,600	7	(1,530)	1,860	14,000
10	15,900	2	(2,070)	2,150	16,000
11	12,800	8	(2,950)	1,790	11,700
12	13,300	(3)	(3,390)	609	10,500
13	12,600	6	(2,550)	1,870	11,900
14	13,100	10	(2,140)	2,000	12,900
15	23,700	4	(1,750)	5,030	27,000
16	10,200	13	(3,590)	980	7,610

Next are the findings from the simulations using the Marathon motor and Schneider drive's efficiency and percent air flow versus percent power draw (Table 12). For the Marathon simulations the nominal motor system efficiency was set to 89.5%, while the two air flow speeds were set to 100% airflow with 100% power draw and 66% airflow with 31.1% power draw.

Table 12 – Average Annual Source Energy Savings when Comparing Marathon Simulations to Base Title 24 VAV Simulations by Climate Zone

Climate Zone	Fan - Electricity [kWh]	Heating - Electricity [kWh]	Heating - Natural Gas [kWh]	Cooling - Electricity [kWh]	Total HVAC Energy [kWh]
1	5,610	11	(2,630)	(62)	2,930
2	10,200	12	(2,500)	815	8,560
3	6,810	13	(1,740)	219	5,300
4	10,100	4	(2,020)	972	9,010
5	7,860	13	(1,440)	460	6,890
6	12,200	7	(866)	1,310	12,700
7	12,700	(0)	(1,800)	1,140	12,000
8	12,300	(81)	(3,990)	(474)	7,740
9	13,200	7	(1,460)	1,790	13,500
10	15,300	2	(1,980)	2,070	15,400
11	12,400	8	(2,830)	1,730	11,300
12	12,800	(3)	(3,270)	566	10,100
13	12,200	6	(2,440)	1,810	11,500
14	12,700	10	(2,040)	1,940	12,600
15	23,100	4	(1,710)	4,930	26,400
16	9,790	13	(3,430)	946	7,330

The last set of simulations used the Nidec motor and Schneider drive’s efficiency and percent air flow versus percent power draw (Table 13). For the Nidec simulations the nominal motor system efficiency was set to 86.4%, while the two air flow speeds were set to 100% airflow with 100% power draw and 66% airflow with 33.8% power draw.

Table 13 –Average Annual Source Energy Savings When Comparing Nidec Simulations to Base Title 24 VAV Simulations by Climate Zone

Climate Zone	Fan - Electricity [kWh]	Heating - Electricity [kWh]	Heating - Natural Gas [kWh]	Cooling Energy [kWh]	Total HVAC Energy [kWh]
1	3,610	11	(1,490)	(65)	2,070
2	9,310	83	(1,120)	351	8,630
3	4,020	13	(800)	97	3,330
4	6,830	4	(1,210)	657	6,280
5	5,160	13	(636)	273	4,810
6	8,090	7	(311)	862	8,650
7	8,840	(0)	(1,250)	798	8,390
8	7,920	(81)	(3,400)	(1,070)	3,360
9	8,500	7	(771)	1,180	8,910
10	10,300	2	(1,230)	1,390	10,500
11	8,280	8	(1,780)	1,240	7,750
12	8,990	(2)	(2,230)	180	6,940
13	8,160	6	(1,550)	1,290	7,910
14	8,570	10	(1,140)	1,390	8,830
15	18,500	4	(1,300)	4,010	21,200
16	6,250	13	(2,050)	682	4,900

Another metric to evaluate energy savings is the energy savings per unit area of floor space. As seen in Table 14 this format makes the data more applicable for scaling out assumptions such as energy savings for similar buildings of known square footage. This data otherwise reflects the same results as previously discussed. The SMC system created the largest savings, the Nidec system generated the least savings, and the coastal climate zones benefited less from retrofits than the inland climate zones. While the data reported in Table 14 is source energy, natural gas and electricity are kept separate for pricing and carbon emission calculation purposes. While Natural Gas consumption increases in all cases, the reduction in electricity outweighs the increase.

Table 14 – HVAC Average Annual Source Energy Savings per square foot of floor area for each motor and drive pair compared to baseline Title 24 VAV compliance

Climate Zone	SMC - Electricity [kWh / sqft]	SMC – Natural Gas [kWh / sqft]	Marathon - Electricity [kWh / sqft]	Marathon – Natural Gas [kWh / sqft]	Nidec – Electricity [kWh / sqft]	Nidec – Natural Gas [kWh / sqft]
1	0.231	(0.110)	0.223	(0.105)	0.142	(0.060)
2	0.458	(0.105)	0.443	(0.100)	0.390	(0.045)
3	0.294	(0.074)	0.282	(0.070)	0.165	(0.032)
4	0.459	(0.085)	0.442	(0.081)	0.300	(0.048)
5	0.347	(0.062)	0.334	(0.058)	0.218	(0.025)
6	0.561	(0.037)	0.543	(0.035)	0.359	(0.012)
7	0.573	(0.075)	0.554	(0.072)	0.386	(0.050)
8	0.492	(0.163)	0.470	(0.160)	0.271	(0.136)
9	0.621	(0.061)	0.599	(0.058)	0.388	(0.031)
10	0.724	(0.083)	0.698	(0.079)	0.470	(0.049)
11	0.586	(0.118)	0.565	(0.113)	0.382	(0.071)
12	0.556	(0.136)	0.537	(0.131)	0.367	(0.089)
13	0.579	(0.102)	0.560	(0.098)	0.379	(0.062)
14	0.604	(0.086)	0.585	(0.082)	0.399	(0.046)
15	1.150	(0.070)	1.125	(0.068)	0.901	(0.052)
16	0.449	(0.144)	0.431	(0.137)	0.278	(0.082)

According to the U.S. Energy Information Administration, the Pacific West, which included California, Oregon, and Washington, designated 11,956 million square feet as commercial floor space in 2018 [35]. The Bureau of Economic Analysis states that in 2018 California accounted for 78% of the total GDP between the Pacific West States [36]. Using the assumption that floor space distribution between each state is directly proportional to the distribution of GDP, California has an estimated 9,364 million square feet of commercial floor space.

Table 15 shows the climate zone and statewide savings in source energy assuming prior Title 24 compliance and an assumed 10% adoption rate. A 10% adoption rate is used because the number of buildings already using motor and drive pairs more efficient than Title 24 requirements is unknown. Furthermore, the number of commercial buildings using electric based heat pumps instead of natural gas heating would affect calculations. The results in Table 15 also assume that commercial floorspace and high-efficiency motor and drive adoption is evenly distributed between each climate zone. For the calculations in Table 15 the potential source energy savings, or increased consumption, for electricity and natural gas were calculated separately and then summed. The resulting data shows that statewide a 10% floorspace adoption rate of the SMC motor and drive could conserve 420 million kWh of source energy. A 10% adoption rate of the Marathon motor would save 406 million kWh of source energy statewide and a 10% adoption rate of the Nidec motor would save 287 million kWh of source energy statewide.

Table 15 – Climate Zone & Statewide Source Energy Savings from a 10% Adoption Rate on Commercial Floorspace

Climate Zone	**SMC - Source Energy [kWh]**	**Marathon - Source Energy [kWh]**	**Nidec - Source Energy [kWh]**
1	7,080,000	6,880,000	4,850,000
2	20,600,000	20,100,000	20,200,000
3	12,900,000	12,400,000	7,800,000
4	21,900,000	21,100,000	14,700,000
5	16,700,000	16,200,000	11,300,000
6	30,600,000	29,700,000	20,300,000
7	29,200,000	28,200,000	19,700,000
8	19,300,000	18,100,000	7,880,000
9	32,700,000	31,600,000	20,900,000
10	37,500,000	36,200,000	24,600,000
11	27,400,000	26,400,000	18,200,000
12	24,600,000	23,800,000	16,300,000
13	27,900,000	27,000,000	18,600,000
14	30,300,000	29,400,000	20,700,000
15	63,200,000	61,800,000	49,700,000
16	17,800,000	17,200,000	11,500,000
State Total	420,000,000	406,000,000	287,000,000

Financial Implications of Energy Savings

An important factor in the adoption of high-efficiency motor and drive pairs is the financial incentive for property owners and managers to save on utility costs. When calculating financial savings from energy savings electricity was valued at an average of 19.2 cents per kWh in California [37] and natural gas was valued at an average of $9.646 per thousand square feet of natural gas which equates to 3.17 cents per kWh in California in 2021 [38]. Calculations for utility cost are based on site energy consumption, not source. Pricing for energy is also based on yearly averages. Real energy pricing is done much more dynamically and would vary based on both time of year and time of day. Our baseline for savings is the savings found from retrofitting a building from CAV to the baseline Title 24 VAV compliance, as seen in Table 16. As expected, the Northern coastal regions see the lowest savings while the inland climate zones that see high peak summer temperatures see significantly greater savings.

Table 16 – Annual Financial Savings from Title 24 VAV Retrofit

Climate Zone	**Fan - Electricity**	**Heating - Electricity**	**Heating - Natural Gas**	**Cooling Energy**	**Total HVAC Energy**
1	$6,970	$(0)	$(855)	$6	$6,120
2	$9,450	$(1)	$(726)	$1,250	$9,970
3	$7,780	$(1)	$(607)	$479	$7,650
4	$9,340	$(1)	$(544)	$1,520	$10,300
5	$8,010	$(1)	$(545)	$655	$8,120
6	$11,100	$(1)	$(344)	$2,350	$13,100
7	$9,740	$(0)	$(318)	$1,700	$11,100
8	$12,600	$9	$(282)	$3,410	$15,800
9	$12,900	$(1)	$(424)	$2,700	$15,200
10	$13,300	$(1)	$(460)	$3,030	$15,900
11	$10,900	$(1)	$(694)	$1,930	$12,200
12	$9,880	$(1)	$(672)	$1,650	$10,900
13	$10,600	$(1)	$(595)	$2,250	$12,200
14	$11,000	$(1)	$(594)	$1,780	$12,200
15	$13,300	$(0)	$(270)	$4,130	$17,100
16	$9,910	$(1)	$(934)	$578	$9,550

The first set of savings comes from the SMC simulations. The results in Table 17 represent the money saved upgrading from the base Title 24 compliancy VAV system to the base compliance using a high-efficiency motor and drive pair, in this case the SMC products. The SMC motor produced a savings from $556 in climate zone 1 to $3,110 in climate zone 15. That translates to the average savings in climate zone 1 going from CAV to SMC VAV of $6,680 annually and the savings for a building going from CAV to SMC VAV in climate zone 15 of $20,210 annually.

Table 17 – Annual Financial Savings going from Base Title 24 VAV Compliance to SMC Retrofit

Climate Zone	Fan - Electricity [$]	Heating - Electricity [$]	Heating - Natural Gas [$]	Cooling - Electricity [$]	Total HVAC Energy [$]
1	$642	$1	$(80)	$(7)	$556
2	$1,160	$1	$(76)	$94	$1,180
3	$780	$1	$(54)	$26	$754
4	$1,150	$0	$(61)	$111	$1,200
5	$900	$1	$(45)	$53	$910
6	$1,390	$1	$(27)	$156	$1,520
7	$1,450	$(0)	$(54)	$130	$1,520
8	$1,410	$(9)	$(118)	$(45)	$1,240
9	$1,500	$1	$(44)	$205	$1,660
10	$1,750	$0	$(60)	$237	$1,930
11	$1,410	$1	$(86)	$197	$1,530
12	$1,460	$(0)	$(98)	$67	$1,430
13	$1,380	$1	$(74)	$206	$1,520
14	$1,440	$1	$(62)	$220	$1,600
15	$2,610	$0	$(51)	$555	$3,110
16	$1,130	$1	$(104)	$108	$1,130

The results in Table 18 represent the financial savings going from the base VAV case to Title 24 compliance using the Marathon motor and Schneider drive. The SMC motor and drive simulations resulted in the greatest average annual savings of all high-efficiency motor and drive pairs. The lowest retrofit saving found going from base VAV to the Marathon motor in climate zone 1 saved $537 annually. Going from base CAV to the Marathon VAV system would result in $6,660 of savings annually. The highest savings were again found in climate zone 15 with a base VAV to Marathon VAV retrofit saving $3,050 annually and a CAV to Marathon VAV retrofit saving of $20,150 annually

Table 18 - Annual Financial Savings going from Base Title 24 VAV Compliance to Marathon Retrofit

Climate Zone	**Fan - Electricity [$]**	**Heating – Electricity [$]**	**Heating - Natural Gas [$]**	**Cooling - Electricity [$]**	**Total HVAC Energy [$]**
1	$619	$1	$(76)	$(7)	$537
2	$1,130	$1	$(73)	$90	$1,150
3	$750	$1	$(50)	$24	$725
4	$1,110	$0	$(59)	$107	$1,160
5	$867	$1	$(42)	$51	$877
6	$1,350	$1	$(25)	$145	$1,470
7	$1,400	$(0)	$(52)	$126	$1,470
8	$1,350	$(9)	$(116)	$(52)	$1,180
9	$1,450	$1	$(42)	$197	$1,610
10	$1,690	$0	$(58)	$229	$1,860
11	$1,360	$1	$(82)	$191	$1,470
12	$1,420	$(0)	$(95)	$62	$1,380
13	$1,340	$1	$(71)	$200	$1,470
14	$1,390	$1	$(59)	$214	$1,550
15	$2,550	$0	$(50)	$544	$3,050
16	$1,080	$1	$(100)	$104	$1,090

The results in Table 19 show the savings upgrading a system from the base Title 24 compliance VAV simulations to the Nidec VAV simulations. Like the other motor and drive pairs, the greatest savings are found in the more extreme inland climate zones while the coastal climates save less when retrofitting. Climate zone 1 saw average annual savings of $349. The CAV to Nidec VAV case would result in $6,470 saved annually. Climate zone 15 saw the greatest savings at $2,440 annually which would be $19,540 going from CAV to Nidec supported VAV.

Table 19 - Annual Financial Savings going from Base Title 24 VAV Compliancy to Nidec Retrofit

Climate Zone	Fan - Electricity [$]	Heating - Electricity [$]	Heating - Natural Gas [$]	Cooling - Electricity [$]	Total HVAC Energy [$]
1	$398	$1	$(43)	$(7)	$349
2	$1,030	$9	$(32)	$39	$1,040
3	$443	$1	$(23)	$11	$432
4	$753	$0	$(35)	$72	$791
5	$568	$1	$(19)	$30	$581
6	$892	$1	$(9)	$95	$979
7	$974	$(0)	$(36)	$88	$1,030
8	$873	$(9)	$(99)	$(118)	$647
9	$936	$1	$(22)	$130	$1,040
10	$1,140	$0	$(36)	$153	$1,260
11	$913	$1	$(52)	$137	$999
12	$991	$(0)	$(65)	$20	$946
13	$900	$1	$(45)	$142	$998
14	$944	$1	$(33)	$153	$1,070
15	$2,040	$0	$(38)	$442	$2,440
16	$688	$1	$(59)	$75	$706

Converting the source energy savings per square foot of floor space from Table 20 to site energy savings per square foot of floor space allows for further financial saving calculations. Using the average annual prices of 19.2 cents per kWh electricity, 3.17 cents per kWh equivalent of natural gas, and the site energy savings from an assumed 10% adoption rate of a given motor and drive pair in California’s commercial floor space, an estimate of statewide savings can be made. Table 20 shows the savings from a 10% adoption rate of high efficiency motors evenly distributed across each climate zone. The SMC system would save 53.5 million dollars annually for building operators statewide. The Marathon System would save 51.7 million dollars annually. The Nidec system would save 36.5 million dollars annually.

Table 20 – Annual Utility Cost Savings for Building Operators Assuming a 10% Floorspace Adoption Rate on all Commercial Buildings

Climate Zone	**SMC [$]**	**Marathon [$]**	**Nidec [$]**
1	$1,300,000	$1,260,000	$861,000
2	$2,770,000	$2,690,000	$2,480,000
3	$1,770,000	$1,700,000	$1,040,000
4	$2,820,000	$2,710,000	$1,890,000
5	$2,130,000	$2,060,000	$1,380,000
6	$3,560,000	$3,440,000	$2,300,000
7	$3,570,000	$3,450,000	$2,440,000
8	$2,900,000	$2,760,000	$1,620,000
9	$3,900,000	$3,760,000	$2,470,000
10	$4,530,000	$4,370,000	$2,980,000
11	$3,580,000	$3,450,000	$2,390,000
12	$3,360,000	$3,240,000	$2,280,000
13	$3,560,000	$3,440,000	$2,380,000
14	$3,750,000	$3,630,000	$2,530,000
15	$7,300,000	$7,140,000	$5,760,000
16	$2,650,000	$2,550,000	$1,710,000
State Sum	$53,500,000	$51,700,000	$36,500,000

Annual carbon dioxide emissions can be estimated using the earlier total source energy savings numbers with 10% adoption. The average carbon dioxide emissions per kWh electricity in California was 0.495 lbs. per kWh [39] in 2020 according to the Energy Information Administration. The EIA also reported a national average carbon dioxide emission of 0.181 lbs [40]. per kWh equivalent of natural gas. The SMC motor and drive would save 420 million kWh of source energy, corresponding 107,000 metric tons of carbon dioxide (Table 21). The Marathon motor and Schneider drive would save 406 million kWh, which is 103,000 metric tons of carbon dioxide. The Nidec motor and Schneider drive would save 287 million kWh in source energy, which is equivalent to 71,900 metric tons of carbon dioxide.

Table 21 – Annual Carbon Dioxide Emission Savings from a 10% Adoption Rate on all California Commercial Floorspace

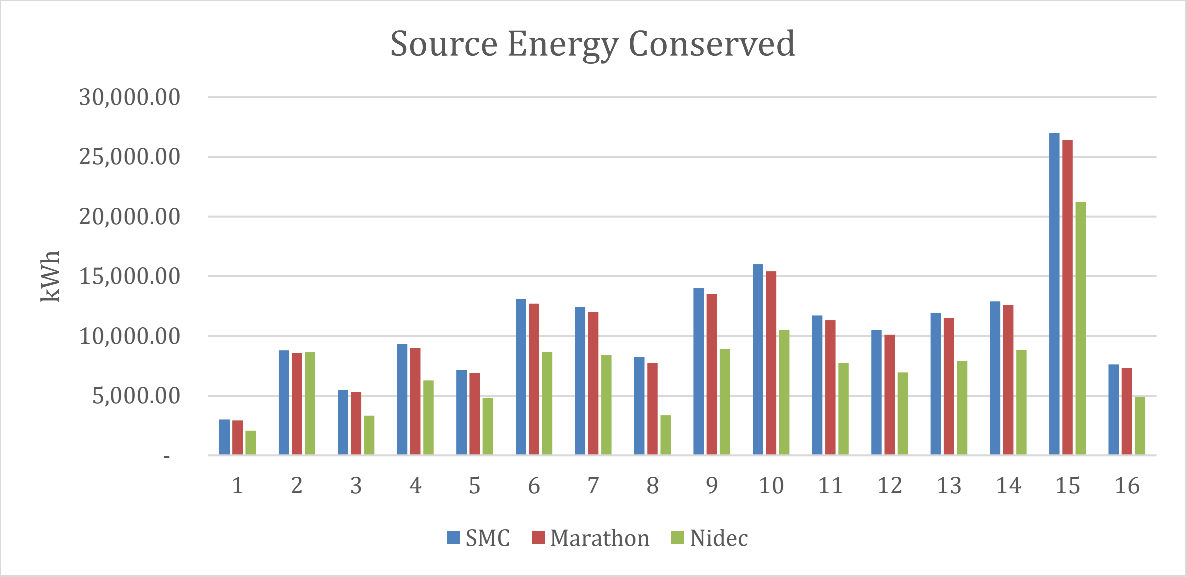
Climate Zone	SMC [Metric Tons Carbon Dioxide]	Marathon [Metric Tons Carbon Dioxide]	Nidec [Metric Tons Carbon Dioxide]
1	2,510	2,420	1,590
2	5,510	5,340	4,920
3	3,500	3,370	2,020
4	5,620	5,420	3,710
5	4,260	4,110	2,740
6	7,190	6,960	4,660
7	7,170	6,930	4,830
8	5,690	5,410	2,910
9	7,860	7,590	4,950
10	9,110	8,790	5,940
11	7,130	6,870	4,680
12	6,650	6,430	4,400
13	7,110	6,880	4,680
14	7,530	7,290	5,030
15	14,800	14,500	11,600
16	5,210	5,000	3,260
State Sum	107,000	103,000	71,900

Chapter Summary

In all climate zones and all vintages of simulated buildings the overall HVAC energy consumption dropped when retrofitting from CAV to VAV with California Title 24 compliance. Additionally, because each high-efficiency motor and drive pair was more efficient and consumed less power at both designated fan speeds, the high-efficiency motor and drive simulations saw even greater energy savings.

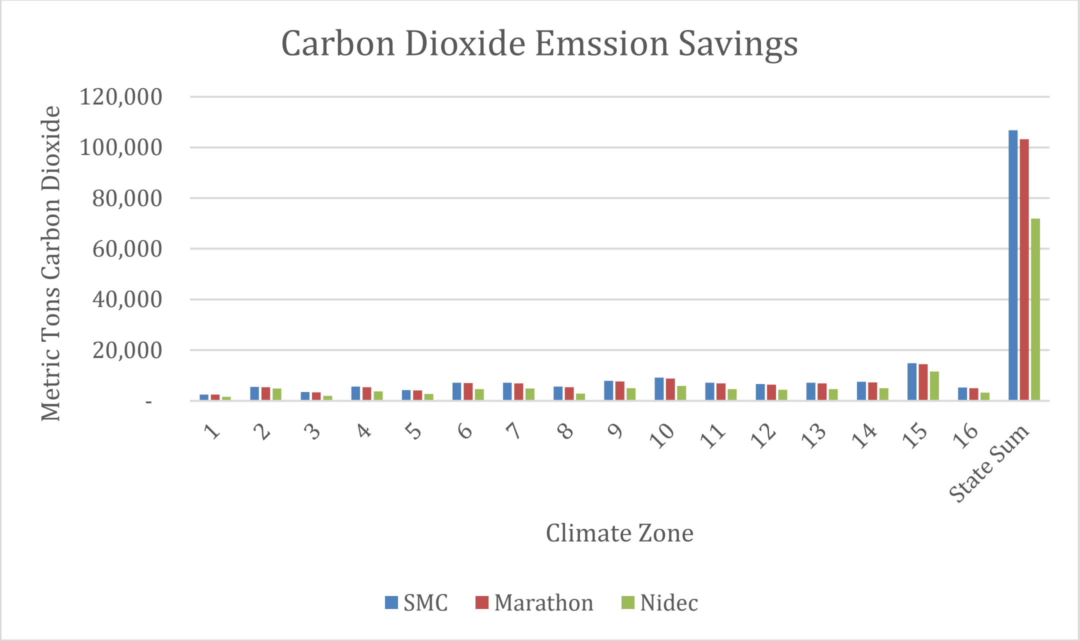
The SMC motor and drive retrofit for Title 24 compliant buildings saw annual source energy savings of 3,020 kWh in climate zone 1 to 27,000 kWh in climate zone 15. The Marathon motor and Schneider drive retrofit for Title 24 compliant buildings saw annual source energy savings of 2,930 kWh in climate zone one to 26,400 kWh in climate zone 15. The Nidec motor and Schneider drive retrofit for Title 24 compliant buildings saw annual source energy savings of 2,070 kWh in climate zone one to 21,200 kWh in climate zone 15. Across all simulations the SMC motor and drive saved the greatest amount of total HVAC energy, then the Marathon system, and the Nidec system saved the least total energy (Figure 9).

Figure 9 – Annual Source Energy Conserved with a 10% Adoption Rate on California Commercial Floorspace



The SMC's superior energy savings also translated into greater cost savings and carbon dioxide emission reductions when scaled for statewide adoption. Figure 10 illustrates the potential carbon dioxide emission reductions for each individual climate zone and the state total from a 10% adoption rate.

Figure 10 – Carbon Dioxide Emission Reductions from a 10% Adoption Rate on California Commercial Floorspace



Summary & Conclusions

Summary

To properly assess the energy impact of high efficiency motor and drive retrofits for commercial RTU's we performed a literature review, laboratory testing, and building energy simulations.

The literature review consisted of reporting previous work relating to RTU energy efficiency, benefits of VAV capabilities, and causes for energy efficiency losses in motor and drive pairs. The literature review also established appropriate testing standards to follow for laboratory work.

Laboratory testing of high efficiency motor and drive pairs took place over a series of months and required the design and construction of a dynamometer. Dynamometer construction took place over several months and resulted in a test setup compliant with motor and electrical testing standards from ASHRAE and ANSI in ASHRAE Standards 222 [19]. The laboratory test points were decided upon using the speed and torque corresponding to common airflows for fans in RTU's as reported by ASHRAE. After testing across a variety of speed and torque points, the motor and drive data was used to construct quartic curves for percent power in versus percent airflow to be used in the building energy simulations.

To perform simulations, reference building files were obtained from the Department of Energy's EnergyPlus reference buildings. Building models were then adjusted to simulate all 16 of California's climate zones. The buildings were run as CAV to establish a baseline of energy consumption. Then buildings were edited to minimum VAV compliance for California's Title 24 to establish a baseline of energy savings. Then the data from laboratory testing was used to model the buildings as if they followed Title 24 minimum airflow standards while utilizing the high efficiency motor and drive pairs. All simulation results were then compared. Energy savings for each scenario were then expanded to cover the potential financial savings and carbon dioxide emission savings

Conclusions

We set out to find how retrofitting RTU's with high-efficiency motor and variable speed drive pairs would impact energy consumption in commercial buildings. We found that adding variable speed capabilities equivalent to the minimum compliance of California's Title 24 saved energy in all simulated building locations and all simulated building vintages. Furthermore, when modeling with high-efficiency motor and drive pairs, all buildings simulated saw even greater energy savings than the baseline VAV compliance simulations. This indicates that California's Title 24 conserves energy statewide, and that more energy can be conserved with the implementation of high efficiency motor and drive pairs into RTU's.

The northwestern most climate zones resulted in the lowest energy savings because the climate is largely stable and lacks extreme weather that causes the oversizing of HVAC capacity for daily operations. On the other end of the weather spectrum, climate zones 10 through 15 are inland and see much greater variance in their weather, notably in their high summer temperatures. Due to the necessity to size systems for extreme conditions, the ability to use a ventilation only speed and matching heating and cooling demands generated huge energy savings.

Carbon dioxide reductions of up to 107,000 metric tons with only a 10% adoption rate is a significant amount of carbon dioxide emissions to reduce. Implementation of high efficiency motor and drive pairs would help reduce financial burdens for property managers, reduce statewide energy consumption, and reduce carbon dioxide emissions. Thus, we recommend that California promote these motor and drive products, for both the utility cost savings and carbon dioxide emissions reductions.

Future Work

The work presented in this thesis will be extended by the UC Davis Western Cooling Efficiency Center as they plan to use the tested motors in an RTU retrofit.

Financial savings could be refined using dynamic prices as opposed to annual average costs. Prices tend to be higher in times of greater demand meaning that the savings are likely lower than predicted in this paper. In addition, California different regions see vast differences in energy costs. Payback period calculations would be important to investigate. Payback period was not covered in this report due to the assumptions made on comparable high-efficiency motor and drive pairs existing at each EnergyPlus auto sized motor's sizing designation. A future report may look for high-efficiency motors of all sizes and create a comprehensive collection of energy efficiency products.

The sensitivity of the results to EnergyPlus' autosizing feature for HVAC components should be investigated. For example, the baseline VAV model for climate zone 12 was studied using autosized HVAC components and then using the nearest real motor sizing to investigate the potential impact of autosizing optimism. Across the three building vintages fan and total HVAC energy never changed by greater than 3.0% or 1.5% respectively. Those results led us to believe that in this case motor sizing was negligible, but a more thorough investigation may provide further insight to appropriate sizing and payback periods. In addition, continuous controls of a the VAV system, simulating other building types, and expanding to other states and US regions would provide useful information.

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Appendix

Table 22 – Source Energy Consumed by each Base CAV HVAC building simulated

Climate Zone	Building Vintage	Fan Electricity [kWh]	Heating Electricity [kWh]	Heating - Natural Gas [kWh]	Cooling - Electricity [kWh]	Total HVAC Energy [kWh]
1	**pre1980**	149,959	2,318	252,839	1,001	406,116
1	**post1980**	120,327	1,596	231,546	781	354,249
1	**2004**	82,712	1,786	171,082	1,067	256,646
2	**pre1980**	227,375	1,864	182,285	66,042	477,567
2	**post1980**	199,101	1,221	169,544	54,727	424,593
2	**2004**	78,367	1,333	120,500	28,614	228,814
3	**pre1980**	185,191	1,318	131,644	20,037	338,190
3	**post1980**	173,527	834	123,290	17,226	314,877
3	**2004**	66,276	943	93,892	9,984	171,094
4	**pre1980**	212,321	1,116	112,729	74,441	400,607
4	**post1980**	198,088	603	98,914	66,611	364,215
4	**2004**	73,834	703	77,224	32,651	184,412
5	**pre1980**	191,690	1,301	137,903	30,462	361,356
5	**post1980**	175,746	731	120,617	23,763	320,857
5	**2004**	68,409	827	87,786	12,531	169,553
6	**pre1980**	235,643	513	48,381	83,151	367,688
6	**post1980**	229,980	254	41,088	76,798	348,120
6	**2004**	136,822	264	25,014	42,954	205,054
7	**pre1980**	214,526	441	40,458	58,576	314,000
7	**post1980**	208,286	240	35,763	54,379	298,668
7	**2004**	128,287	227	20,980	32,640	182,134
8	**pre1980**	259,965	574	48,683	126,454	435,675
8	**post1980**	254,819	312	40,607	119,897	415,634
8	**2004**	143,966	292	24,741	64,810	233,810
9	**pre1980**	264,610	670	60,372	126,858	452,510
9	**post1980**	258,716	380	52,485	121,067	432,649
9	**2004**	144,124	362	32,392	64,421	241,299
10	**pre1980**	274,806	780	74,355	153,876	503,817
10	**post1980**	266,906	440	63,593	147,247	478,185
10	**2004**	140,662	422	39,379	76,849	257,313
11	**pre1980**	261,269	1,717	162,622	150,238	575,846
11	**post1980**	204,007	1,323	146,537	114,289	466,156
11	**2004**	122,538	1,221	105,466	72,437	301,662
12	**pre1980**	242,580	1,617	161,849	110,971	517,017

12	**post1980**	175,147	1,127	143,729	75,364	395,367
12	**2004**	106,905	1,111	104,554	49,129	261,699
13	**pre1980**	252,370	1,237	134,976	163,700	552,284
13	**post1980**	194,032	925	122,696	122,225	439,878
13	**2004**	116,351	937	90,628	79,419	287,335
14	**pre1980**	260,052	1,401	159,310	149,204	569,966
14	**post1980**	202,307	817	131,116	114,558	448,798
14	**2004**	119,711	807	91,278	72,146	283,942
15	**pre1980**	280,666	429	41,849	302,597	625,540
15	**post1980**	234,686	204	30,407	245,744	511,040
15	**2004**	143,776	227	25,667	157,044	326,714
16	**pre1980**	247,004	3,145	289,111	44,062	583,322
16	**post1980**	195,816	2,750	273,687	30,531	502,784
16	**2004**	117,605	2,223	184,517	20,235	324,580

Table 23 – Source Energy Consumed by all Title 24 base Compliance buildings simulated

Climate Zone	**Building Vintage**	**Fan Electricity [kWh]**	**Heating Electricity [kWh]**	**Heating - Natural Gas [kWh]**	**Cooling - Electricity [kWh]**	**Total HVAC Energy [kWh]**
1	**pre1980**	75,385	2,319	287,137	1,073	365,914
1	**post1980**	59,367	1,599	262,042	770	323,778
1	**2004**	28,599	1,795	194,689	841	225,924
2	**pre1980**	111,054	1,866	214,141	51,933	378,994
2	**post1980**	100,224	1,226	198,906	42,588	342,944
2	**2004**	36,457	1,362	134,319	20,808	192,946
3	**pre1980**	95,421	1,318	156,894	16,051	269,684
3	**post1980**	85,739	836	149,603	12,834	249,012
3	**2004**	32,038	973	105,041	5,327	143,379
4	**pre1980**	102,845	1,116	135,855	57,692	297,508
4	**post1980**	92,835	605	121,766	50,250	265,456
4	**2004**	34,213	726	87,415	24,258	146,612
5	**pre1980**	98,034	1,301	160,791	24,027	284,152
5	**post1980**	86,456	733	143,882	17,459	248,530
5	**2004**	33,231	858	97,952	7,429	139,470
6	**pre1980**	118,043	513	61,548	59,728	239,832
6	**post1980**	113,856	254	54,049	53,385	221,545
6	**2004**	68,077	278	34,402	25,924	128,681
7	**pre1980**	113,078	440	52,706	42,526	208,751
7	**post1980**	108,271	240	47,674	38,492	194,677
7	**2004**	64,627	240	29,701	18,434	113,001

8	**pre1980**	122,809	312	54,617	87,211	264,949
8	**post1980**	122,809	312	54,617	87,211	264,949
8	**2004**	69,711	305	33,940	43,890	147,847
9	**pre1980**	125,712	670	77,008	98,687	302,077
9	**post1980**	122,064	381	68,970	92,661	284,075
9	**2004**	68,372	376	43,112	47,461	159,322
10	**pre1980**	129,611	780	92,784	121,409	344,585
10	**post1980**	123,906	440	81,670	114,320	320,336
10	**2004**	66,994	437	50,427	59,671	177,529
11	**pre1980**	127,216	1,719	192,476	125,755	447,166
11	**post1980**	100,557	1,325	172,062	96,433	370,377
11	**2004**	62,150	1,239	121,821	62,325	247,535
12	**pre1980**	118,518	1,619	191,951	88,174	400,262
12	**post1980**	85,264	1,129	167,660	61,729	315,781
12	**2004**	51,981	1,128	119,964	40,706	213,779
13	**pre1980**	122,744	1,239	160,872	134,356	419,211
13	**post1980**	94,447	926	144,429	102,531	342,334
13	**2004**	57,323	950	104,444	67,126	229,843
14	**pre1980**	126,213	1,402	183,911	127,338	438,864
14	**post1980**	97,528	818	153,775	97,487	349,607
14	**2004**	59,505	827	105,408	62,680	228,421
15	**pre1980**	126,924	429	52,813	252,725	432,891
15	**post1980**	105,823	204	40,031	206,701	352,759
15	**2004**	64,795	235	32,996	133,545	231,570
16	**pre1980**	128,841	3,149	328,765	37,268	498,023
16	**post1980**	99,906	2,754	309,126	25,207	436,993
16	**2004**	61,891	2,248	205,995	16,613	286,747

Table 24 - Source Energy Consumed by all SMC Motor & SMC Drive buildings simulated

Climate Zone	**Building Vintage**	**Fan Electricity [kWh]**	**Heating Electricity [kWh]**	**Heating - Natural Gas [kWh]**	**Cooling - Electricity [kWh]**	**Total HVAC Energy [kWh]**
1	**pre1980**	69,321	2,295	289,558	1,246	362,419
1	**post1980**	51,914	1,589	265,620	819	319,942
1	**2004**	24,653	1,796	196,941	802	224,192
2	**pre1980**	97,696	1,852	217,226	50,724	367,498
2	**post1980**	86,246	1,221	202,675	41,468	331,610
2	**2004**	32,106	1,346	135,341	20,592	189,384
3	**pre1980**	86,747	1,304	158,938	15,679	262,668
3	**post1980**	75,990	830	152,493	12,431	241,744

3	**2004**	29,217	954	105,646	5,392	141,210
4	**pre1980**	89,914	1,107	138,195	56,329	285,545
4	**post1980**	79,704	601	124,409	49,008	253,722
4	**2004**	28,956	726	88,769	23,837	142,287
5	**pre1980**	87,532	1,287	162,417	23,287	274,524
5	**post1980**	75,543	727	146,309	16,814	239,394
5	**2004**	30,151	840	98,504	7,374	136,869
6	**pre1980**	103,251	506	62,468	57,892	224,116
6	**post1980**	99,155	249	55,175	51,714	206,293
6	**2004**	59,825	269	35,159	25,186	120,439
7	**pre1980**	97,936	440	54,821	41,082	194,280
7	**post1980**	93,569	240	49,714	37,135	180,658
7	**2004**	55,090	240	31,139	17,685	104,154
8	**pre1980**	109,732	567	64,356	91,676	266,331
8	**post1980**	106,847	308	56,165	84,955	248,274
8	**2004**	60,432	297	34,824	42,906	138,460
9	**pre1980**	109,383	662	78,707	96,271	285,023
9	**post1980**	105,566	377	70,789	90,419	267,150
9	**2004**	60,313	368	44,172	46,543	151,395
10	**pre1980**	108,534	781	95,847	118,506	323,667
10	**post1980**	105,984	436	83,694	111,790	301,905
10	**2004**	58,239	434	51,547	58,651	168,872
11	**pre1980**	109,414	1,710	196,134	123,377	430,635
11	**post1980**	87,260	1,320	175,318	94,894	358,793
11	**2004**	54,785	1,230	123,752	60,878	240,644
12	**pre1980**	100,241	1,619	196,688	86,251	384,799
12	**post1980**	72,277	1,145	171,266	60,520	305,208
12	**2004**	43,439	1,119	121,777	42,009	208,344
13	**pre1980**	105,606	1,231	164,061	131,932	402,829
13	**post1980**	81,260	923	147,219	100,918	330,319
13	**2004**	49,952	944	106,113	65,553	222,562
14	**pre1980**	108,794	1,388	186,265	124,718	421,165
14	**post1980**	83,539	813	156,353	95,714	336,420
14	**2004**	51,688	815	106,892	61,086	220,481
15	**pre1980**	84,960	423	56,100	244,874	386,357
15	**post1980**	87,522	202	41,207	203,189	332,119
15	**2004**	54,038	230	33,795	129,803	217,866
16	**pre1980**	115,987	3,130	332,823	36,128	488,069
16	**post1980**	88,695	2,748	313,457	24,342	429,242
16	**2004**	55,330	2,235	208,377	15,678	281,621

Table 25 - Source Energy Consumed by all Marathon Motor & Schneider Drive buildings simulated

Climate Zone	Building Vintage	Fan Electricity [kWh]	Heating Electricity [kWh]	Heating - Natural Gas [kWh]	Cooling - Electricity [kWh]	Total HVAC Energy [kWh]
1	**pre1980**	69,547	2,295	289,412	1,246	362,499
1	**post1980**	52,187	1,589	265,473	819	320,069
1	**2004**	24,779	1,796	196,867	803	224,246
2	**pre1980**	98,095	1,852	217,066	50,772	367,784
2	**post1980**	86,653	1,221	202,519	41,510	331,903
2	**2004**	32,282	1,346	135,284	20,604	189,516
3	**pre1980**	87,115	1,304	158,796	15,700	262,916
3	**post1980**	76,315	830	152,359	12,451	241,955
3	**2004**	29,348	954	105,593	5,403	141,298
4	**pre1980**	90,422	1,107	138,076	56,379	285,984
4	**post1980**	80,185	601	124,292	49,054	254,132
4	**2004**	29,127	726	88,724	23,851	142,428
5	**pre1980**	87,978	1,287	162,296	23,315	274,877
5	**post1980**	75,871	727	146,202	16,837	239,638
5	**2004**	30,278	840	98,457	7,382	136,958
6	**pre1980**	103,594	506	62,419	58,024	224,543
6	**post1980**	99,602	249	55,063	51,798	206,712
6	**2004**	60,106	269	35,116	25,273	120,764
7	**pre1980**	98,420	440	54,752	41,129	194,741
7	**post1980**	94,125	240	49,645	37,180	181,191
7	**2004**	55,382	240	31,091	17,709	104,423
8	**pre1980**	110,436	567	64,279	91,755	267,038
8	**post1980**	107,199	308	56,091	85,032	248,630
8	**2004**	60,832	297	34,781	42,948	138,857
9	**pre1980**	109,820	662	78,639	96,355	285,476
9	**post1980**	106,201	377	70,710	90,499	267,787
9	**2004**	60,661	368	44,116	46,583	151,729
10	**pre1980**	109,223	781	95,745	118,601	324,349
10	**post1980**	106,666	436	83,593	111,881	302,578
10	**2004**	58,584	434	51,487	58,696	169,201
11	**pre1980**	110,042	1,710	195,984	123,461	431,197
11	**post1980**	87,762	1,320	175,196	94,947	359,226
11	**2004**	55,060	1,230	123,671	60,909	240,870
12	**pre1980**	100,834	1,619	196,532	86,314	385,299
12	**post1980**	72,699	1,145	171,148	60,559	305,551
12	**2004**	43,693	1,119	121,703	42,037	208,553

13	**pre1980**	106,156	1,231	163,919	132,018	403,323
13	**post1980**	81,694	923	147,107	100,975	330,699
13	**2004**	50,211	944	106,047	65,589	222,791
14	**pre1980**	109,283	1,388	186,149	124,802	421,622
14	**post1980**	84,039	813	156,233	95,774	336,858
14	**2004**	51,969	816	106,832	61,116	220,732
15	**pre1980**	85,567	423	56,049	244,997	387,036
15	**post1980**	88,134	202	41,153	203,306	332,794
15	**2004**	54,397	230	33,763	129,870	218,261
16	**pre1980**	116,567	3,130	332,609	36,176	488,482
16	**post1980**	89,105	2,748	313,277	24,377	429,508
16	**2004**	55,590	2,235	208,277	15,697	281,799

Table 26 – Source Energy Consumed by all Nidec Motor & Schneider Drive buildings simulated

Climate Zone	**Building Vintage**	**Fan Electricity [kWh]**	**Heating Electricity [kWh]**	**Heating - Natural Gas [kWh]**	**Cooling - Electricity [kWh]**	**Total HVAC Energy [kWh]**
1	**pre1980**	71,898	2,295	287,962	1,239	363,394
1	**post1980**	54,687	1,589	264,165	827	321,267
1	**2004**	25,937	1,796	196,206	814	224,753
2	**pre1980**	102,890	1,851	215,593	51,181	371,516
2	**post1980**	91,078	1,221	201,081	41,870	335,250
2	**2004**	25,826	1,133	134,043	21,227	182,229
3	**pre1980**	90,739	1,304	157,630	15,861	265,534
3	**post1980**	79,769	830	151,177	12,609	244,386
3	**2004**	30,632	953	105,131	5,451	142,167
4	**pre1980**	94,640	1,107	137,042	56,804	289,593
4	**post1980**	84,091	601	123,293	49,451	257,436
4	**2004**	30,668	726	88,325	23,974	143,693
5	**pre1980**	91,524	1,287	161,269	23,577	277,658
5	**post1980**	79,125	728	145,218	17,065	242,135
5	**2004**	31,600	840	98,045	7,454	137,938
6	**pre1980**	108,453	506	61,784	58,572	229,315
6	**post1980**	104,289	250	54,432	52,326	211,297
6	**2004**	62,951	269	34,716	25,553	123,489
7	**pre1980**	102,814	440	54,125	41,552	198,932
7	**post1980**	98,372	240	49,043	37,579	185,233
7	**2004**	58,273	240	30,664	17,929	107,106
8	**pre1980**	115,394	567	63,620	92,479	272,060
8	**post1980**	112,262	308	55,424	85,728	253,722

8	**2004**	63,921	297	34,345	43,320	141,882
9	**pre1980**	115,532	662	77,840	97,097	291,131
9	**post1980**	111,388	377	69,929	91,217	272,910
9	**2004**	63,739	368	43,634	46,962	154,702
10	**pre1980**	115,416	780	94,840	119,454	330,490
10	**post1980**	112,412	436	82,739	112,695	308,282
10	**2004**	61,664	433	51,001	59,095	172,193
11	**pre1980**	115,778	1,710	194,617	124,184	436,288
11	**post1980**	91,746	1,320	174,078	95,432	362,577
11	**2004**	57,557	1,230	122,995	61,169	242,951
12	**pre1980**	106,225	1,619	195,138	86,878	389,860
12	**post1980**	76,487	1,145	170,086	60,914	308,632
12	**2004**	46,076	1,119	121,047	42,277	210,518
13	**pre1980**	111,708	1,230	162,713	132,767	408,418
13	**post1980**	85,658	923	146,198	101,490	334,268
13	**2004**	52,664	944	105,471	65,884	224,964
14	**pre1980**	114,783	1,388	185,037	125,608	426,816
14	**post1980**	88,310	813	155,230	96,321	340,674
14	**2004**	54,454	815	106,236	61,416	222,921
15	**pre1980**	90,785	423	55,610	246,104	392,922
15	**post1980**	93,557	202	40,687	204,355	338,800
15	**2004**	57,761	230	33,432	130,487	221,909
16	**pre1980**	121,248	3,130	330,827	36,540	491,745
16	**post1980**	92,861	2,748	311,770	24,648	432,028
16	**2004**	57,790	2,235	207,426	15,853	283,304