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A New Model to Simulate Energy Performance of VRF Systems

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ABSTRACT

This paper presents a new model to simulate energy performance of variable refrigerant flow (VRF) systems in heat pump operation mode (either cooling or heating is provided but not simultaneously). The main improvement of the new model is the introduction of the evaporating and condensing temperature in the indoor and outdoor unit capacity modifier functions. The independent variables in the capacity modifier functions of the existing VRF model in EnergyPlus are mainly room wet-bulb temperature and outdoor dry-bulb temperature in cooling mode and room dry-bulb temperature and outdoor wet-bulb temperature in heating mode. The new approach allows compliance with different specifications of each indoor unit so that the modeling accuracy is improved. The new VRF model was implemented in a custom version of EnergyPlus 7.2. This paper first describes the algorithm for the new VRF model, which is then used to simulate the energy performance of a VRF system in a Prototype House in California that complies with the requirements of Title 24 – the California Building Energy Efficiency Standards. The VRF system performance is then compared with three other types of HVAC systems: the Title 24-2005 Baseline system, the traditional High Efficiency system, and the EnergyStar Heat Pump system in three typical California climates: Sunnyvale, Pasadena and Fresno. Calculated energy savings from the VRF systems are significant. The HVAC site energy savings range from 51 to 85%, while the TDV (Time Dependent Valuation) energy savings range from 31 to 66% compared to the Title 24 Baseline Systems across the three climates. The largest energy savings are in Fresno climate followed by Sunnyvale and Pasadena. The paper discusses various characteristics of the VRF systems contributing to the energy savings. It should be noted that these savings are calculated using the Title 24 prototype House D under standard operating conditions. Actual performance of the VRF systems for real houses under real operating conditions will vary.

INTRODUCTION

Buildings consume more than one-third of the world's primary energy, of which about one-third is consumed by HVAC systems. Reducing energy use by HVAC systems is a key strategy to energy savings and reduction of carbon emissions, and VRF (Variable Refrigerant Flow) systems present a potential opportunity for such energy savings. VRF systems can vary refrigerant flow to meet zonal cooling and heating loads, which leads to high efficient operations during part-load conditions, and have minimal or no ductwork, which may reduce heat losses [Liu 2010]. In addition to energy benefits, VRF systems have smaller indoor fans that significantly reduce indoor noise. A typical VRF system has one outdoor unit serving multiple indoor units. Each indoor unit can have its own thermostat to control its operation. An

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indoor unit can be turned off if a zone is not occupied. This flexibility of zoning and control collectively contribute to potential of energy savings for buildings (such as residences) with diversified zonal loads.

This paper presents a new set of algorithms to model energy performance of heat-pump type VRF systems using EnergyPlus [DOE 2012]. Compared with the existing VRF model in EnergyPlus, the new model provides more flexibility and better accuracy. The new VRF model is applied to a prototype house in California, and the VRF system energy performance is evaluated and compared to that of three traditional standard and high efficiency HVAC systems to determine energy savings.

METHODOLOGY

Computer based building energy modeling and simulation [Hong 2000] has been demonstrated as an effective way to evaluate energy and cost benefit of building technologies. In this study, EnergyPlus was chosen to simulate the energy performance of VRF systems for residential buildings in California. There were three steps to accomplish the goal: 1) research and development of the new VRF model, 2) development the energy models of the house with four comparable HVAC systems, and 3) simulation of the home's energy performance and evaluation of VRF system energy savings.

The Prototype House

The Prototype House D from the 2008 California Title 24 Residential Alternate Calculation Method (ACM) Manual was selected to represent the typical new single-family house in California with the potential for a VRF systems for space cooling and heating. The House has two floors, total floor area of 250 m^2 (2700 ft^2), 4 bedrooms and 3 bathrooms. The House complies with Package D of the 2008 Title 24 (Table 1). Base case space-cooling is provided by a split direct expansion (DX) system, and space-heating is provided by a central gas furnace. The total air infiltration rate is 23.6 L/s (50 cfm). Window-wall-ratio is about 20%. The total internal heat gains for the House are: sensible loads of 60,500 Btu/day (63.8 MJ/day), and latent loads of 14.7 kg/day (32.4 lb/day). The leakage rate of the supply and return air ducts is 3%.

Table 1. Key Efficiency Requirements of the Title 24-2008 Residential Package D

Component	Climate Zone 4	Climate Zone 9	Climate Zone 13
Wall Insulation	R13	R13	R19
Ceiling Insulation	R30	R30	R38
Windows, U-factor / SHGC	0.4 / 0.4	0.4 / 0.4	0.4 / 0.4
Space Heating, gas furnace, AFUE	78%	78%	78%
Space Cooling, split DX, SEER	13	13	13
Duct Insulation	R6	R6	R6

Three Typical California Climates

For Title 24 code compliance purposes, California is split into 16 climate zones. Three typical climates were selected for the study: Climate Zone 4 represented by the city Sunnyvale, a mild climate in San Francisco Bay Area; Climate Zone 9 represented by the city Pasadena, a warm and humid climate in the South Coast; and Climate Zone 13 represented by the city Fresno, a hot climate in the Central Valley area of California. The design conditions and weather data for the three climate zones, defined in the Title 24 ACM manuals, were used to calculate peak loads and to run EnergyPlus simulations.

Metrics of Energy Savings

Energy savings of the VRF systems, compared with the alternate systems, were calculated in terms of annual total site energy, annual major end uses in site energy, and annual total TDV energy. The TDV (Time Dependent Valuation) energy is the energy metric used in Title 24 to demonstrate code compliance. The TDV energy represents the life cycle cost of energy considering the escalation rate of utility cost, transmission and distribution loss for electricity. The TDV multipliers vary by time of the day, day of the year, climate, energy sources (electricity, natural gas, propane), and building type (residential and commercial). TDV energy is used to evaluate cost effectiveness of energy efficiency measures for Title 24 during the three-year update cycle. In TDV energy, the electricity use during summer peak demand hours cost much more than during summer off-peak hours or winter.

VRF SYSTEMS MODELING

A VRF system is a refrigerant system that varies the refrigerant flow rate with the help of a variable speed compressor and electronic expansion valves (EEVs) located in each indoor unit to match the space cooling or heating load in order to maintain the zone air temperature at the indoor set temperature [Aynur 2008, 2010]. In cooling mode, the outdoor unit heat exchanger acts as condenser through the four-way valve, while the indoor unit heat exchanger acts as evaporator. The discharged refrigerant from the compressor flows into the outdoor unit, releases heat, and becomes high-pressure low-temperature refrigerant. It is then throttled to low pressure by the EEV, absorbing heat from the indoor air through the indoor unit and superheating. Finally, the superheated refrigerant returns back to the compressors. In heating mode, the four-way valve reverses the refrigerant path and turns the outdoor unit into evaporator and the indoor unit into condenser. Thus the indoor unit rejects heat to the indoor air and heats it up.

The main advantages of a VRF system over the conventional multi-split system are wide-range capacity modulation, individual room setpoint control, and—for the heat recovery type VRF systems—the simultaneous cooling and heating capability [Amarnath 2008, Goetzler 2007], which collectively lead to better energy performance and indoor comfort. The VRF systems are residential systems that operate either in cooling mode or heating mode but not simultaneous cooling and heating. Small VRF systems have one compressor, while large systems typically include two to three compressors with fitted for variable speed capability, thus enabling wide capacity modulation. The inverter yields high part-load efficiency because HVAC systems often operate in the range 40% to 80% of its maximum capacity, while the single speed units have to cycle on and off causing efficiency losses. Heat recovery is readily accomplished when simultaneous heating and cooling occurs, which leads to energy savings. The inverter technology used in the VRF system can maintain precise room temperature control, generally within ±0.55°C (±1°F).

EnergyPlus version 7.2 can model the heat pump type and heat recovery type VRF systems. The object *AirConditioner:VariableRefrigerantFlow* describes the outdoor unit which connects to the zone terminal units (indoor units). Zone terminal units operate to meet the zone sensible cooling or heating requirements as determined by the zone thermostat schedule.

The actual operation mode is determined based on the master thermostat priority control type. There are five algorithms available: *LoadPriority*, *ZonePriority*, *ThermostatOffsetPriority*, *MasterThermostatPriority*, and *Scheduled*. *LoadPriority* uses the total zone load to choose the operation mode as either cooling or heating. *ZonePriority* uses the number of zones requiring cooling or heating to determine the operation mode. *ThermostatOffsetPriority* uses the zone farthest from the room setpoint to determine the operation mode. The *MasterThermostatPriority* operates the system according to the zone load where the master thermostat is located. *Scheduled* operates the VRF system either in cooling or heating based on schedule. When the system is running in cooling mode, the cooling coils will be enabled only in the terminal units where cooling is required. In heating mode, the heating coils only response to the zones with heating load.

The indoor unit supply fan can be modeled in two operation modes: cycling fan cycling coil (AUTO fan mode) or continuous fan cycling coil (Fan ON mode). To model the AUTO fan mode, only the *Fan:OnOff* object can be used. For the Fan ON mode, both *Fan:OnOff* and *Fan:ConstantVolume* objects can be used.

The main improvement of the new VRF model is the introduction of the evaporating and condensing temperature in the indoor and outdoor unit capacity modifier functions. The independent variables in the existing capacity modifier functions are mainly room wet bulb temperature and outdoor dry bulb temperature in cooling mode, and room dry bulb temperature and outdoor wet bulb temperature in heating mode. The new approach allows compliance with different specifications of each indoor unit so that the modeling accuracy is improved. For instance, for the same indoor wet bulb temperature, at different load conditions, the evaporating temperatures of the indoor units can be different. While the existing approach results in the same power consumption, the new approach can capture the difference in power consumption due to the different evaporating temperature requirements. Another improvement in the new model is to allow the use of *Fan:VariableVolume* object in the indoor unit to model the continuous modulation of the indoor air flow.

Figure 1 compares the VRF system modeling approach currently used in EnergyPlus with the newly proposed method. It should be noted that Figure 1 only lists the main equations but does not necessarily include all the equations actually used in the calculation. Each simulation time step, EnergyPlus performs a zone air heat balance to determine the zone load and then the VRF system operation mode is determined according to the specified master thermostat priority control. EnergyPlus uses equation (1) and (2) to calculate the actual output of each indoor unit. Then the capacity required by the outdoor unit is calculated using equation (3) taking into account of the pipe length and height correction with equation (4).

The total power consumption is computed using equation (7) to (10) that incorporate the modifiers correlated with average room wet bulb temperature, outdoor dry bulb temperature, and the part-load ratio. The new approach first calculates the evaporating and condensing temperature using equation (11) to (15). The total power consumption is then computed using equation (17).

Existing algorithms in EnergyPlus

$$Q_{tot,in} = Q_{rate,in} \cdot CapFT_{in} \quad (1)$$

$$CapFT_{in} = a_1 + a_2 T_{wb,i} + a_3 T_{wb,i}^2 + a_4 T_{db,o} + a_5 T_{db,o}^2 + a_6 T_{wb,i} T_{db,o} \quad (2)$$

$$Q_{out} = \sum_{k=1}^{n} Q_{tot,in,k} / CapF_{Pipe} \quad (3)$$

$$CapF_{Pipe} = b_1 + b_2 L + b_3 L + b_4 H \quad (4)$$

$$Q_{out,avail} = Q_{rate,out} \cdot CapFT_{out} \quad (5)$$

$$CapFT_{out} = c_1 + c_2 T_{wb,i,avg} + c_3 T_{wb,i,avg}^2 + c_4 T_{db,o} + c_5 T_{db,o}^2 + c_6 T_{wb,i,avg} T_{db,o} \quad (6)$$

$$N = \sum_{k=1}^{n} N_{in,k} + N_{out} \quad (7)$$

$$N_{out} = N_{rate,out} \cdot PCF_{Temp} \cdot PCF_{PLR} \quad (8)$$

$$PCF_{Temp} = d_1 + d_2 T_{wb,i} + d_3 T_{wb,i}^2 + d_4 T_{db,o} + d_5 T_{db,o}^2 + d_6 T_{wb,i} T_{db,o} \quad (9)$$

$$PCF_{PLR} = e_1 + e_2 PLR + e_3 PLR^2 \quad (10)$$

New algorithms for VRV

$$Q_{tot,in} = Q_{rate,in} \cdot f(\Delta T_{in}) \cdot f(Ga_{in}) \cdot f(SCH_{in}) \quad (11)$$

$$\Delta T_{in} = Ta_{in} - Te_{req,in} \text{ for cooling}$$
$$\Delta T_{in} = Tc_{req,in} - Ta_{in} \text{ for heating} \quad (12)$$

$$T_e = \min(Te_{req,in}) \text{ and } T_c = \max(Tc_{req,in}) \quad (13)$$

$$Q_{out} = Q_{rate,out} \cdot f(\Delta T_{out}) \cdot f(Ga_{out}) \cdot f(SCH_{out}) \quad (14)$$

$$\Delta T_{out} = Tc_{req} - Ta_{out} \text{ for cooling}$$
$$\Delta T_{out} = Ta_{out} - Te_{req} \text{ for heating} \quad (15)$$

$$N_{in} = f_1 + f_2 \left(\frac{Ga_{in}}{Ga_{in,rate}}\right)^3 \quad (16)$$

$$N_{out} = g_1 + g_2 \left(\frac{Ga_{out}}{Ga_{out,rate}}\right)^3 + g_3 T_c + g_4 T_e + g_5 T_c^2 + g_6 T_c T_e + g_7 T_e^2 \quad (17)$$

Figure 1. Existing VRF model in EnergyPlus 7.2 vs. the new VRF model.

ENERGY MODELS

This section describes key inputs used to develop the energy models using EnergyPlus for the four design alternatives. For a specific climate zone, the only differences in the four models are the specifications of the HVAC systems, other characteristics of the House remain constant. Across climate zones, the building envelope might be different depending on Title 24 requirements, but the geometry, zoning, internal heat gains, and operating schedules remain constant. Peak loads were calculated using a tool compliant with the ACCA Manual J. HVAC equipment, including the indoor and outdoor units, was sized based on the peak loads and design outdoor conditions.

Thermal zoning of the House

Based on the size of the house and the Title 24-2008 requirements, the House was modeled as four thermal zones - the downstairs Living Area zone and the upstairs Sleeping Area zone. Figure 2 illustrates the zoning and three-dimension view of the House. The Garage is unconditioned. For the VRF models, there are two indoor units (modeled as an equivalent large unit) serving the First Floor, and three indoor units each serving one bedroom on the Second Floor. For the Title 24 Baseline model and the two Alternate System models, the First Floor is modeled as a thermal zone served by a ducted system with split DX cooling and a central gas furnace heating, while the Second Floor is modeled as another ducted system serving the three bedrooms and common areas with the Master Bedroom as the controlled zone (where the thermostat is located). Airflows were considered when doors open between the three bedrooms, and between the upstairs and downstairs. During the night, doors were assumed closed and no airflow occurred.

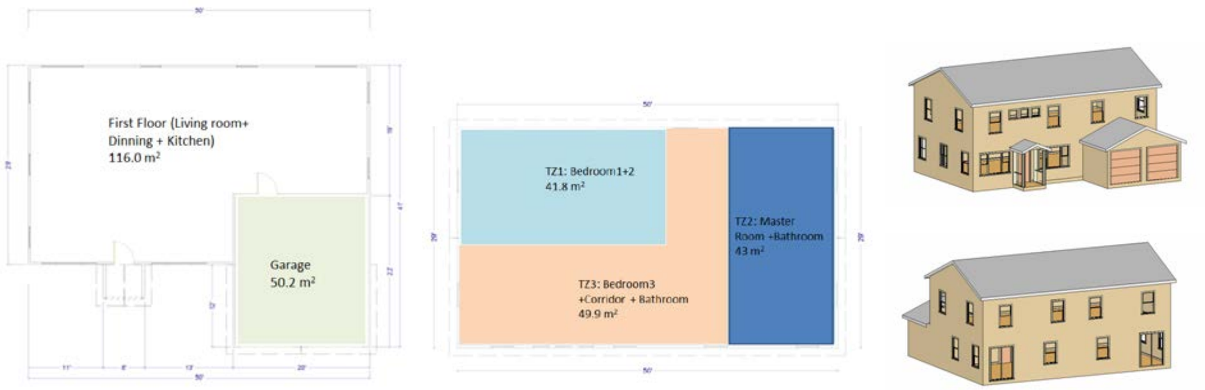

Figure 2. Zoning of the house: First Floor Living Area (left), Second Floor Sleeping Area (middle), 3D View (right)

Internal heat gains

Internal heat gains were calculated based on the Title 24 ACM manual. Section 3.2.6 describes the calculation of total daily sensible heat gains. For the House, the daily total sensible heat gains is 60,500 Btu/day (63.8 MJ/day), the latent load is 14.7 kg/day (32.4 lb/day). The daily heat gains are distributed into hourly heat gains by the heat gains schedules. These hourly schedules are further adjusted by the monthly multipliers to reflect the seasonal variations of heat gains in houses. Title 24 does not regulate the electricity use by lighting or home appliances but their heat gains are considered in the peak loads calculations as well as in the EnergyPlus annual simulations.

Thermostat settings

The hourly profiles of the thermostat settings for the Living Area and the Sleeping Area are shown in Figure 3. Both the cooling and the heating thermostats assume certain extent of setback when a thermal zone is unoccupied.

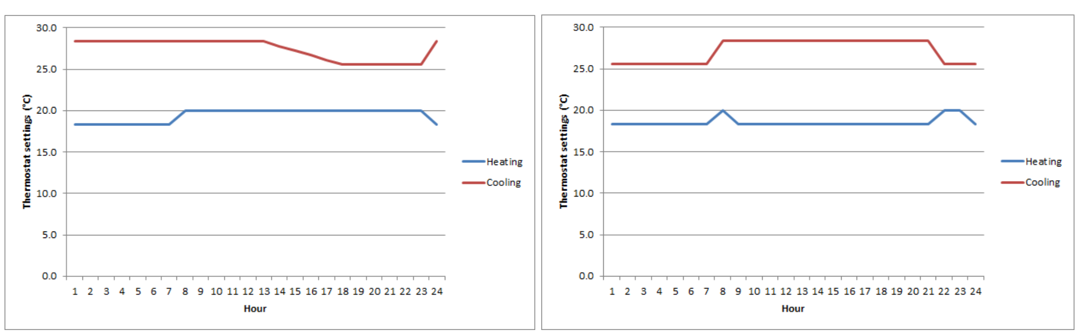

Figure 3. Thermostat settings, Living Area (left) and Sleeping Area (right)

Ventilation and fans

Title 24-2008 refers to ASHRAE Standard 62.2 Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings for ventilation requirement. There are three bathroom exhaust fans (10.2 watt each) with each running half an hour a day between 7:00-7:30am exhausting 23.6 L/s (50 cfm) of air. There is one kitchen exhaust fan (37.2 watt) running an hour a day between 5:30-6:30pm exhausting 47.2 L/s (100 cfm) of air. There is also a whole-house fan (14 watt) running continuously providing constant ventilation air at 30.4 L/s (64.5 cfm). All five fans are assumed to have a total efficiency of 15%.

HVAC systems and equipment efficiencies

The Baseline model, compliant with the 2008 Title 24 Package D requirements, has two single-zone air ducted systems with single-stage DX cooling and central gas furnace heating. The cooling efficiency SEER is 13 and the heating efficiency AFUE is 78%. The SEER and AFUE efficiency inputs were converted into appropriate inputs to EnergyPlus. The air distribution system is assumed to have an efficiency of 70% (30% duct heat loss).

The HVAC systems in the High Efficiency model is similar to those in the Baseline model except with higher efficiency: (1) two-stage DX cooling with 18 SEER, (2) condensing gas furnace with 97% AFUE, and (3) sealed air duct with a distribution efficiency of 95%.

The Heat Pump model also has two single zone systems with the DX coils providing both cooling and heating for spaces. The heat pump systems meet EnergyStar efficiency requirement: cooling SEER of 14 and heating HSPF of 8.2.

The VRF model has one VRF system providing both cooling and heating (not simultaneously) for spaces. There is one outdoor unit located outside the House, and four indoor units – one large unit serving the first floor and three units each serving one bedroom on the second floor.

ENERGY SAVINGS ANALYSIS

For each climate, the four energy models, with differences only in their respective HVAC systems, were run with EnergyPlus version 7.2. Tables 2 to 4 summarize the simulated results and the calculated energy savings of the other three system designs compared with the Title 24-2008 Baseline system. It should be noted that the energy use for the domestic hot water is not included in the HVAC Site Energy or TDV Energy in the tables because California Energy Commission required a special tool (not EnergyPlus) to calculate such energy use. Table 5 summarizes the energy savings of the VRF systems compared to the other three systems.

Table 2. Energy Savings for Sunnyvale - Climate Zone 4

	Lighting and Applicances	Space Cooling	Fan	Space Heating		HVAC Site Energy	HVAC Site Energy Savings	TDV Energy	TDV Energy Savings
	Electric kWh	Electric kWh	Electric kWh	Electric kWh	Gas kWh	kWh	%	kWh	%
Title 24-2008 Baseline	1100	770	650	n.a.	13187	14607	n.a.	31698	n.a.
High efficiency system	1100	382	425		7078	7885	46%	19382	39%
Heat pump system	1100	743	848	2818	n.a.	4409	70%	21696	32%
VRV-S system	1100	383	273	1422		2078	86%	12728	60%

Table 3. Energy Savings for Pasadena - Climate Zone 9

	Lighting and Applicances	Space Cooling	Fan	Space Heating		HVAC Site Energy	HVAC Site Energy Savings	TDV Energy	TDV Energy Savings
	Electric kWh	Electric kWh	Electric kWh	Electric kWh	Gas kWh	kWh	%	kWh	%
Title 24-2008 Baseline	1100	1533	700	n.a.	6830	9063	n.a.	27473	n.a.
High efficiency system	1100	780	493		3640	4913	46%	17240	37%
Heat pump system	1100	1479	787	1372	n.a.	3638	60%	21399	22%
VRV-S system	1100	634	268	808		1710	81%	11960	56%

Table 4. Energy Savings for Fresno - Climate Zone 13

	Lighting and Applicances	Space Cooling	Fan	Space Heating		HVAC Site Energy	HVAC Site Energy Savings	TDV Energy	TDV Energy Savings
	Electric kWh	Electric kWh	Electric kWh	Electric kWh	Gas kWh	kWh	%	kWh	%
Title 24-2008 Baseline	1100	2731	1342	n.a.	16050	20123	n.a.	52938	n.a.
High efficiency system	1100	1529	870		8795	11194	44%	32292	39%
Heat pump system	1100	2635	1524	3453	n.a.	7612	62%	39894	25%
VRV-S system	1100	1070	288	1584		2942	85%	17673	67%

Table 5. Summary of VRF System Energy Savings

Climate	HVAC Site Energy Savings (%)			TDV Energy Savings (%)		
	Compared to Title 24 Baseline System	Compared to the High Efficiency System	Compared to the Heat Pump System	Compared to Title 24 Baseline System	Compared to the High Efficiency System	Compared to the Heat Pump System
Sunnyvale - Climate Zone 4	86%	74%	53%	60%	34%	41%
Pasadena - Climate Zone 9	81%	65%	53%	56%	31%	44%
Fresno - Climate Zone 13	85%	74%	61%	67%	45%	56%

The following can be observed from the results: 1) compared to the Title24-2008 Baseline Systems, the VRF systems save significant amount of HVAC site energy (81-86%) as well as TDV energy (56-67%), 2) Compared to the High Efficiency Systems, the VRF systems also save significant amount of HVAC site energy (65-74%) as well as TDV energy (31-45%), 3) compared to the EnergyStar Heat Pump Systems, the VRF systems also save significant amount of HVAC site energy (53-61%) as well as TDV energy (41-56%), 4) The largest savings are in Fresno climate where it is hot during summer requiring lots of cooling, and cold during winter requiring heating.

The energy savings of the VRF systems are driven by various factors: (1) no air duct losses, (2) variable speed compressor operating efficiently under part-load conditions, (3) small and efficient indoor fans, (4) dynamic temperature controls to meet zone loads, (5) heat pump mode for heating, and (6) better zoning controls – an indoor unit can be completely turned off if a space is not occupied. Because TDV energy values electricity consumed during peak summer hours much more than other hours, the electricity saved by the VRF systems in cooling mode translates into much more TDV energy savings during summer peak hours.

CONCLUSION

Energy savings calculated using the new VRF models in a custom version of EnergyPlus 7.2 for the VRF systems, compared with the other three systems, are significant. The HVAC site energy savings range from 53 to 86%, while the TDV energy savings range from 31 to 67%. It should be noted that the energy use for the domestic hot water is not included in the energy savings calculations. When included, the whole house energy savings (site or TDV energy) in percentage will be lower.

The largest energy savings observed are for the Fresno climate, followed by Sunnyvale and Pasadena. Various characteristics (design and operation) of the VRF systems contribute to the energy savings. It should be noted that these savings are calculated using the Title 24 prototype House D under standard operating conditions. Actual performance of the VRF systems for real houses under real operating conditions will vary, for example when considering pressure drop or heat loss in the piping, defrost cycle in heating operation, and effect of fan power to the capacity in cooling operation.

The second phase of the project will analyze the actual performance data from VRF system installed in an actual house in Stockton. The collected data will be used to validate the VRF model and to calibrate the developed energy models and algorithms.

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NOMENCLATURE

$HL =$	Heat load	$CapFT =$	Capacity modification function of temperature
$Q =$	Capacity	$PCF =$	Power modification function
$C =$	Coefficient	$PLR =$	Partial load ratio
$SCH =$	Superheat or subcool	$Ga =$	Air flow rate
$Ta =$	Air temperature	$A =$	Capacity correction coefficient
$N =$	Electric power	$a - g =$	Equation coefficients
$Te =$	Evaporating temperature	$Tc =$	Condensing temperature
$L =$	Equivalent refrigerant pipe length	$H =$	Refrigerant pipe vertical height
$SHR =$	Sensible Heat Ratio	$h =$	Enthalpy
$w =$	Humidity ratio	$P =$	Pressure
$\Delta P =$	Pressure drop	$COP =$	Coefficient of Performance

Subscripts

$in, i =$	Indoor unit	$out, o =$	Outdoor unit
$rate =$	Capacity at rating condition	$Temp =$	Temperature
$PLR =$	Partial load ratio	$Pipe =$	Refrigerant pipe
$req =$	Required capacity	$wb =$	Wet bulb temperature
$db =$	Dry bulb temperature	$avail =$	Available capacity
$tot =$	Total capacity at actual operating condition, including sensible and latent capacities	$avg =$	Average value
$ADP =$	Apparatus dew point	$Tin,wADP =$	Air at indoor air temp and humidity ratio at ADP
$e =$	Evaporating or evaporator	$c =$	Condensing or condenser
$s =$	Suction	$comp =$	Compressor
$rps =$	Compressor speed		

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