Work Paper SCE17HC039

**Revision 0**

**Southern California Edison**

**VFD Retrofit to Central Plant Systems**

# At-a-Glance Summary

|  |  |
| --- | --- |
| **Measure Codes** | AC-14365, AC-91987, AC-55411, AC-18931, and AC-18932. |
| **Measure Description** | Variable Speed Drive on Cooling Tower (CT) Fan Control  Variable Speed Drive on Chilled Water (CHW) Pump Control  Variable Speed Drive on Condenser Water (CW) Pump Control |
| **Base Case Description** | Source: Existing Custom Equipment/Title 24  CT Fan Control – Single speed/two-speed depending on vintage  CHW Pump Control – Single speed  CW Pump Control – Single speed |
| **Units** | Per Horsepower (HP) |
| **Energy Savings** | Refer to Excel Calculation Attachment 1 |
| **Full Measure Cost ($/unit)** | Refer to Excel Calculation Attachment 1 and 6 |
| **Incremental Measure Cost ($/unit)** | Refer to Excel Calculation Attachment 1 and 6 |
| **Effective Useful Life** | NEW: 15 years (DEER EUL ID: HVAC-VSDSupFan, HVAC-VSD-pump)  REA: 6.67 years (DEER EUL ID: HVAC-VSDSupFan, HVAC-VSD-pump) in accordance with Draft Resolution E-4807 [510] |
| **Measure Installation Type** | Retrofit Add-on (REA) – All measures  New Construction (NEW) - CT Fan Control – Single speed/two-speed depending on vintage  New Construction (NEW) - CW Pump Control – Single speed |
| **Net-to-Gross Ratio** | 0.6 (DEER NTGR ID: Com-Default>2yrs) |
| **Important Comments** | This work paper has a complementary Ex Ante Database data set that will be provided in a separate submission to the California Public Utilities Commission (CPUC). |

# Revision History

|  |  |  |  |
| --- | --- | --- | --- |
| **Rev** | **Date** | **Author** | **Summary of Changes** |
| 0 | 12/13/2016 | Arvind Subramanya/TRC | - This work paper is an update of SCE13HC039.4  - New calculation template update for 2017 program year  - Work paper is updated with 2016 Title-24 code requirement language.  - Cost update from latest 2016 RSMeans Cost Database  - New construction (New) program type added. Measure impacts estimated and adjusted from corresponding REA measure  - Three calculation templates have been developed in this revision, one per each solution code.  - For REA measures, updated the EUL value in accordance with Draft Resolution E-4807 [510]  - New Solution Codes added for New Construction |

# Commission Staff and Cal TF Comments

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Rev** | **Party** | **Submittal Date** | **Comment Date** | **Comments** | **WP Developer Response** |
|  |  |  |  |  |  |

Cal TF website: <http://www.caltf.org/>

# Section 1. General Measure & Baseline Data

## 1.1 Measure Description & Background

This work paper details the energy savings achieved from installing variable frequency drives (VFD) in central plant applications with constant speed chillers.

This measure applies to equipment with constant speed cooling tower fans, condenser water pumps, and chilled water pumps not already equipped with VFD/VSDs. VFDs reduce fan or pump motor energy by adjusting motor speeds to meet actual load conditions. Estimated demand and energy savings for this work paper are based on DOE-2/eQUEST modeling results.

**Base, Standard, and Measure Cases**

|  |  |
| --- | --- |
| **Case** | **Description of Typical Scenario** |
| Measure | Variable Speed Drive on Cooling Tower (CT) Fan Control  Variable Speed Drive on Chilled Water (CHW) Pump Control  Variable Speed Drive on Condenser Water (CW) Pump Control |
| Existing Condition | N/A |
| Code/Standard | Source: Existing Custom Equipment/Title 24  CT Fan Control – Single speed/two-speed depending on vintage  CHW Pump Control – Single speed for REA Program Type  CHW Pump Control – Variable speed for NEW Program Type  CW Pump Control – Single speed |
| Industry Standard Practice | N/A |

Measures and Codes

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Measure Codes** | | | | **Measure Name** |
| SCG | SDG&E | SCE | PG&E |
|  |  | AC-14365 |  | Variable Speed Drive on Cooling Tower Fan Control |
|  |  | AC-18931 |  | Variable Speed Drive on Cooling Tower Fan Control (New Construction) |
|  |  | AC-91987 |  | Variable Speed Drive on Chilled Water Pump Control |
|  |  | AC-55411 |  | Variable Speed Drive on Condenser Water Pump Control (REA) |
|  |  | AC-18932 |  | Variable Speed Drive on Condenser Water Pump Control (New Construction) |

Throughout this paper, the terms variable frequency drive (or VFD) and variable speed drive (or VSD) are used synonymously.

This measure applies to non-residential buildings in all SCE climate zones that use a central chiller plant system with constant speed cooling tower fans, condenser water pump, and chilled water pumps not already equipped with VFDs. This measure should be accompanied by the installation of 2-way chilled water valves for the VFD addition to the chilled water pump measure. Savings are therefore greatest at low-flow conditions.

Successful implementation of this measure will depend greatly on the characteristics of the installed system. For the VFD addition to the condenser water pump special attention should be given to the condenser water flow turndown capabilities of the existing cooling tower(s) and chiller(s). It is imperative that chiller manufacturer selection data and cooling tower manufacturer retrofit information be carefully reviewed to ensure that the existing cooling tower(s) and chiller(s) are rated to operate at the selected minimum condenser water flow, and that the control strategy includes capability to increase the flow as needed to keep the leaving condenser temperature from exceeding an upper limit dependent on the existing chiller. Refer to the Attachment #3 Measure Limitations Memo in the Attachments Section for more information.

## 1.2 Technical Description

Central plant systems provide space cooling to a building by cooling water in a chiller and circulating this chilled water either through a chilled water coil in an air handler or throughout the building zones. Chillers may be air-cooled or water-cooled, and in the case of water-cooled chillers, a separate water loop absorbs heat from the chiller which is then rejected by a cooling tower. In these systems, a significant amount of energy is consumed by the fans and pumps used to circulate air and water. Cooling tower (CT) fans circulate air to facilitate heat rejection; chilled water (CHW) pumps circulate water cooled by the chiller; condenser water (CW) pumps circulate the water that transfers heat between the chiller and the cooling tower.

These fans and pumps are designed to meet peak load conditions, when the equipment must run at 100% capacity. However, for the majority of the time the demand for cooling is less than the peak design capacity. Standard practice has been to install single-speed fan and pump controls, which causes them to run at 100% speed, even if actual demand may be much less. This presents a significant energy savings opportunity if fan and pump speed can be varied to meet actual demand conditions.

Variable frequency drives control motor speed by varying the frequency and voltage of the fan/pump motor. VFDs are programmed to reduce fan/pump speed to just meet actual load conditions, thus reducing fan/pump speed when loads drop below design conditions, resulting in significant fan/pump energy savings throughout the year.

## 1.3 Installation Types and Delivery Mechanisms

The installation type is retrofit add-on (REA) and NEW.

For NEW, the SCE Savings By Design Program offers incentives on a wide variety of energy-saving design and technologies that encourages design teams and building owners/managers to integrate a higher level of energy efficiency for their new construction and major building renovation projects. As a way to streamline incentivizing energy efficient lighting technologies, SBD offers an “express” way to participate in this opportunity using deemed lighting measures.

The process will direct the customer or their designated representative (customer) to work with an SCE New Construction Representative (NCR). The NCR will determine if the Whole Building Approach (WBA) or Deemed System Approach (DSA) will provide the most benefit to the project.

The delivery method is Financial Support - Down Stream Incentive – Deemed, with savings reported on a per horsepower basis.

**Installation Type Descriptions**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Installation Type** | **Savings** | | **Life** | |
| 1st Baseline (BL) | 2nd BL | 1st BL | 2nd BL |
| Retrofit Add-on (REA) | Above Customer Existing | N/A | EUL | N/A |
| New Construction (NEW/NC) | Above Code or Standard | N/A | EUL | N/A |

A delivery mechanism is a delivery method paired with an incentive method. Delivery mechanisms are used by programs to obtain program participation and energy savings.

**Delivery Method Descriptions**

|  |  |
| --- | --- |
| **Delivery Method** | **Description** |
| Financial Support | The program motivates customers, through financial incentives such as rebates or low interest loans, to implement energy efficient measures or projects. |

**Incentive Method Descriptions**

|  |  |
| --- | --- |
| **Incentive Method** | **Description** |
| Down-Stream Incentive - Deemed | The customer installs qualifying energy efficient equipment and submits an incentive application to the utility program. Upon application approval, the utility program pays an incentive to the customer. Such an incentive may be deemed or customized. |

**Installation Type Descriptions**

Table below lists the installation and building types for each measure based on the previous workpaper. In this revision of the work paper, separate calculation templates are developed for each solution code to cover the combinations as shown below.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Attachment #** | **Measure Codes** | **Measure Name** | **Program Type** | **Building Types** |
| SCE |
| 1 | AC-14365 | Variable Speed Drive on Cooling Tower Fan Control | REA | Asm, ESe, EUn, Hsp, Htl, MBT, MLI, OfL, OfS, Rt3, WRf |
| 1 | AC-18931 | Variable Speed Drive on Cooling Tower Fan Control (New Construction) | NEW | Asm, ESe, EUn, Hsp, Htl, MBT, MLI, OfL, OfS, Rt3, WRf |
| 1 | AC-91987 | Variable Speed Drive on Chilled Water Pump Control | REA | Asm, ESe, EUn, Hsp, Htl, MBT, MLI, Nrs, OfL, OfS, Rt3 |
| 1 | AC-18932 | Variable Speed Drive on Condenser Water Pump Control (New Construction) | NEW | Asm, ESe, EUn, Hsp, Htl, MBT, MLI, OfL, OfS, Rt3 |
| 1 | AC-55411 | Variable Speed Drive on Condenser Water Pump Control | REA | Asm, ESe, EUn, Hsp, Htl, MBT, MLI, OfL, OfS, Rt3 |

## 1.4 Measure Parameters

### 1.4.1 DEER Data

The 2017 Database for Energy Efficient Resources (DEER) [26, 49] does contain similar central plant/VFD measures (DEER ID D03-063: Two-Speed Cooling Tower Fans; DEER ID D03-064: VSD Cooling Tower Fans; DEER ID D03-051: VSD Supply Fan Motors; DEER ID D03-046: Variable Flow Chilled Water Loop; DEER ID D03-047: VSD Chilled Water Loop Pump). DEER does not contain a measure for installing a VSD on Condenser Water Pumps.

For the VSD measure for Chilled Water Loop pumps, DEER reports only a limited number of building types. Additionally, the DEER measure descriptions do not match the measure in this work paper; D03-046 has three-way valves and a single-speed pump in the base case, and two-way valves and a single-speed pump in the measure case; D03-047 has two-way valves and a single-speed pump in the base case, and two-way valves and a variable-speed pump in the measure case. The measure in this work paper has three-way valves and a single-speed pump in the base case, and two-way valves and a variable-speed pump in the measure case.

For the VSD measure for Cooling Tower Fans, DEER also only reports a limited number of building types, and the DEER measure descriptions do not match the measure in this work paper; D03-063 has single-speed fans in the base case, and two-speed fans in the measure case; D03-064 has two-speed fans in the base case, and variable-speed fans in the measure case. The measure in this work paper has a weighted average of single-speed and two-speed fans in the base (based on the code requirements for each vintage), and variable-speed fans in the measure case. Additionally, the savings in DEER for VSD Cooling Tower Fans are reported as savings per cooling ton, instead of the required kWh savings per horsepower (hp).

Due to the differences between the DEER measures and the measures contained in this work paper, modeling was performed to determine savings for all measures and building types – all results reported in this work paper were modeled.

DEER Difference Summary

|  |  |
| --- | --- |
| **DEER Item** | **Used for Workpaper?** |
| Modified DEER methodology | No |
| Scaled DEER measure | No |
| DEER Base Case | No |
| DEER Measure Case | No |
| DEER Building Types | Yes |
| DEER Operating Hours | Yes |
| DEER eQUEST Prototypes | Yes |
| DEER Version | N/A |
| Reason for Deviation from DEER | * DEER 2017 does include similar measures, but for a limited number of buildings. Additionally, the DEER measure descriptions do not exactly match the measures in this work paper * This work paper expands the applicable building types, assumes different baseline cases, and uses different per unit savings (kWh/hp vs. kWh/ton) |
| DEER Measure IDs Used | N/A |

**Net-to-Gross Ratio**

The NTG values were obtained using the DEER READI tool. The relevant NTG values for the measures in this work paper are in the table below.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **NTGR ID** | **Description** | **Sector** | **BldgType** | **Measure Delivery** | **NTGR** |
| Com-Default>2yrs | All other EEMs with no evaluated NTGR; existing EEM in programs with same delivery mechanism for more than 2 years | Com | Any | Any | 0.6 |

**Spillage Rate**

Spillage rates are not tracked in work papers; they are tracked in an external document which will be supplied to the Commission Staff.

**Installation Rate**

The IR values were obtained using the DEER READI tool version 2.4.7. The relevant IR values for the measures in this work paper are in the table below.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **GSIA ID** | **Description** | **Sector** | **BldgType** | **ProgDelivID** | **GSIAValue** |
| Def-GSIA | Default GSIA values | Any | Any | Any | 1 |

**Effective and Remaining Useful Life**

The EUL and RUL values were obtained using the DEER READI tool version 2.4.7. DEER defines the RUL as 1/3 of the EUL value. The RUL value is only applicable to the first baseline period for an RET measure with an applicable code baseline. The relevant EUL and RUL values for the measures in this work paper are in the table below. For REA measures, the EUL and RUL values were obtained in accordance with Draft Resolution E-4807 [510]

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **EUL ID** | **Description** | **Sector** | **UseCategory** | **EUL (Years)** | **RUL (Years)** |
| HVAC-VSDSupFan (**REA**) | VSD Supply Fan Motors  (used for the VFD on Cooling Tower Fan) | Com | HVAC | 6.67 | 0 |
| HVAC-VSDSupFan  (**NEW**) | VSD Supply Fan Motors  (used for the VFD on Cooling Tower Fan) | Com | HVAC | 15 | 5 |
| HVAC-VSD-pump  (**REA**) | Variable Flow Water Loop, VSD Pump (used for the VFD on Chilled Water Pump and VFD on Condenser Water Pump) | Com | HVAC | 6.67 | 0 |
| HVAC-VSD-pump  (**NEW**) | Variable Flow Water Loop, VSD Pump (used for the VFD on Condenser Water Pump) | Com | HVAC | 15 | 5 |

### 1.4.2 Codes and Standards Analysis

Current requirements for heat rejection fan speed controls in non-residential applications are contained in Title 24 2016 [496], Section 140.4(h), page 192. Each fan powered by a motor of 7.5 hp (5.6 kW) or larger shall have the capability to operate that fan at 2/3 of full speed or less, and shall have controls that automatically change the fan speed to control the leaving fluid temperature or condensing temperature or pressure of the heat rejection device.

Current requirements for variable flow hydronic loops in non-residential applications are contained in Title 24 2016, Section 140.4(k)5 Water-Cooled Air Conditioner and Hydronic Heat Pump Systems; Section 140.4(k)6A Variable Flow Controls - Variable Speed Drives, page 193. For chilled water pumps 5 hp or greater, Title 24 requires variable speed drives on hydronic loops with variable flow capability. “Individual pumps serving variable flow systems and having a motor horsepower exceeding 5 hp shall have controls or devices (such as variable speed control) that will result in pump motor demand of no more than 30 percent of design wattage at 50 percent of design water flow. The pumps shall be controlled as a function of required differential pressure.” Condenser water systems serving only water-cooled chillers are exempt from the requirements in this section.

**Hydronic System Measures**

Code requirements for hydronic system flow controls are only for new chilled water systems (e.g., chilled water pump) and apply to this work paper. The 2016 version of the Code does not include flow modulation control requirements for new condensing water pumps.

**Heat Rejection System Measures**

Code requirements for cooling tower fan requires fan control to 2/3 of full speed as a function of fluid temperature. However, the code does not require variable speed control and/or fan control modulation beyond ½ of full speed of the cooling tower fan.

Code Summary

|  |  |  |
| --- | --- | --- |
| **Code** | **Reference** | **Effective Dates** |
| Title 24 (2016) | 2016 Building Energy Efficiency Standards for Residential and Nonresidential Buildings,  Section 140.4(h)2 Heat Rejection Systems - Fan Speed Control, pg. 192  Section 140.4(k)5 Water-Cooled Air Conditioner and Hydronic Heat Pump Systems; Section  Section 140.4(k)6A Variable Flow Controls - Variable Speed Drives, pg. 193 | January 1, 2017 |

## 1.5 EM&V, Market Potential, and Other Studies – Base Case and Measure Case Information

N/A

## 1.6 Data Quality and Future Data Needs

N/A

# Section 2. Calculation Methodology

Estimated demand and energy savings for this work paper are based on simulated variable frequency drives (VFD) in central plant cooling tower fans, chilled water pumps, and condenser water pumps. Simulations were conducted using the DOE-2/eQUEST v.3.64 modeling tool (for the Refrigerated Warehouse building type, the refrigeration version of eQuest was used). Model development and savings analyses are discussed in detail in this section.

## 2.1 DEER Prototypes

Non-residential buildings that can use a central chiller plant system were included in the simulation analysis. A list of the 12 selected building types is reported in table below. The selection of the building types was based on potential program targets. Building models were generated using the eQUEST DEER batch processing tool. The DEER batch processing tool creates eQUEST building models based on existing DEER prototypes for both residential and non-residential market sectors. These building prototypes contain the building characteristics (such as HVAC equipment, construction materials, and occupancy schedules) that are used to calculate DEER measure savings. In addition, the DEER batch tool allows prototypes to be generated by desired vintages, and climate zones.

The DEER non-residential prototypes are generated in the batch processor with the HVAC configuration typical for each building type. For example, Education­ - University prototypes are automatically generated with a central chiller plant system, as this is the expected system in the majority of university settings. Some building types considered for program participation do not typically have a central chiller plant configuration in DEER. In these cases, the building prototype was generated in the DEER batch processor with its typical packaged roof-top unit (RTU) configuration. This configuration was then modified in the eQUEST detailed data edit mode to allow a central plant configuration. The table shown below reports which building prototypes include a central chiller plant configuration, and which required modification to allow this type of configuration.

Non-Residential DEER Prototype Models

|  |  |
| --- | --- |
| **DEER Building Type** | **DEER Prototype HVAC Configuration** |
| Assembly | Package RTU |
| Education - Secondary School | Package RTU |
| Education – University | Chiller Plant |
| Health/Medical – Hospital | Chiller Plant |
| Health/Medical - Nursing Home | Chiller Plant |
| Lodging – Hotel | Chiller Plant |
| Manufacturing - Bio/Tech | Package RTU |
| Office – Large | Chiller Plant |
| Office – Small | Chiller Plant |
| Retail - Multistory Large | Chiller Plant |
| Manufacturing-Light Industrial | Package RTU |
| Warehouse-Refrigerated | Package RTU |

Once each building type was modified to allow a central plant configuration, each baseline model was then modified per the keyword changes listed in the table shown below (eQUEST Keyword Modifications) to simulate each measure.

## 2.2 Energy Savings

### 2.2.1 eQUEST Energy Simulations

Over 2000 energy simulations were performed to account for the baseline, three measures, 13 building types, eight climate zones (CZ) in SCE service territory, and seven DEER building vintages. The DEER vintages (with their single-reference year in parentheses) are included in the table shown below.

1. Before 1978 (1975 – shown in the table below as 75)
2. 1978 – 1992 (1985 – shown in the table below as 85)
3. 1993 – 2001 (1996 – shown in the table below as 96)
4. 2001 – 2005 (2003 – shown in the table below as 03)
5. 2005 – 2009 (2007 – shown in the table below as 07)
6. 2009 – 2013 (2011 – shown in the table below as 11)
7. 2013 – 2014 (2014 – shown in the table below as 14)

The simulated prototype building with chiller plant for each vintage and CZ was considered the baseline model. The energy and demand consumption from these simulated models represents the base case consumption. Each measure was then modeled using individual model runs. VFDs on chilled water loop pumps were not modeled for 2007 or later vintage buildings. Since they are required by code, the prototype models for these vintages have VFDs already installed in the base case. The table shown below reports the eQUEST keywords used for the model runs, including the input values for both the base case and the measure conditions. The resulting energy and demand consumption from the measure simulations represent the measure case consumption.

For the VFD on condenser water pump measure, it is important to define a minimum condenser water flow rate and a maximum allowable leaving condenser temperature. For the minimum flow rate, the determinants are the minimum flow required by the chiller and the minimum flow required by the tower. Based on research a conservative estimate of 70% [A – D] achievable flow turndown was chosen for the measure case. For the maximum leaving condenser temperature the limit was set to be the condenser temperature at the rated conditions for the baseline model (keyword CHILLER:RATED-COND-T).

Note that eQuest Keyword Modifications indicated below are specific for measure impact estimates for REA measures. Methodology for estimating NEW VFD for cooling tower fan control measure impact, which is similar to this, is detailed later in the workpaper in Section 2.2.5.

eQUEST Keyword Modifications

|  |  |  |  |
| --- | --- | --- | --- |
| **Measure** | | | |
| **Vintage(s)** | **Keyword** | **Baseline Design Value** | **Measure Design Value** |
| **CHW\*  Loop Pump EEM\*\*** | | | |
| 75,85,96,03 | PUMP:CAP-CTRL | N/A | VAR-SPEED-PUMP |
| 75,86,96,03 | SYSTEM:CHW-VALVE-TYPE | N/A | TWO-WAY |
| **Chiller Plant Tower Fan EEM** | | | |
| 75,85,96 | HEAT-REJECTION:CAPACITY-CTRL | ONE-SPEED-FAN | VARIABLE-SPEED-FAN |
| 03,07,11,14 | HEAT-REJECTION:CAPACITY-CTRL | TWO-SPEED-FAN | VARIABLE-SPEED-FAN |
| **CW\*\*\* Loop Pump EEM** | | | |
| 75,85,96,03,07,11,14 | PUMP:CAP-CTRL | N/A | VAR-SPEED-PUMP |
| 75,85,96,03,07,11,14 | CHILLER:CW-FLOW-CTRL | CONSTANT-FLOW | VARIABLE-FLOW |
| 75,85,96,03,07,11,14 | CHILLER:CW-MIN-FLOW | N/A | 0.70 (ratio) |
| 75,85,96,03,07,11,14 | CHILLER:MAX-COND-T | N/A | 85.0 (degF) |

\*Chilled Water (CHW)

\*\* Energy Efficiency Measure (EEM)

\*\*\*Condenser Water (CW)

While the Health/Medical - Nursing Home prototype included a chiller plant, it utilized an air-cooled condenser instead of a cooling tower. Thus, the VFD on Cooling Tower Fan and VFD on Condenser Water Pump measures were not modeled for this building type. The Warehouse-Refrigerated model does not include a chiller plant, as space cooling is provided by a refrigeration system. Thus, the VFD on Chilled Water Pump and VFD on Condenser Water Pump measures were not modeled for this building type.

The difference in energy consumption between the baseline simulation run and the measure runs represents the energy savings.

### 2.2.2 Multiple Chillers and VFD Towers

The prototypes in the DEER model included only single chiller plants and cooling towers. Since many buildings have multiple chillers and cooling towers, some of the buildings were modeled to include multiple chiller plants and cooling towers. Additional models in three separate climate zones were created for the following building types listed in the table shown below. The three climate zones were selected as a comparison to ensure that energy savings amounts found were consistent with savings from models with single chiller plants taking into account a wide range of climates.

Buildings Modeled with Multiple Chillers and Cooling Towers

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **DEER Building Type** | **Cooling Tons** | **Vintage** | **CZ** | **Number of Modeled Chillers/Towers** |
| Education - University | 2500 | 85 | 6, 8, 13 | 3 |
| Health/Medical - Hospital | 625 | 85 | 6, 8, 13 | 2 |
| Lodging - Hotel | 500 | 85 | 6, 8, 13 | 2 |
| Retail – Multistory Large | 300 | 85 | 6, 8, 13 | 2 |

To add the multiple systems, a second tower identical to the existing DEER one was added to the condenser water loop. Variable speed control was added to both towers. As required by the equipment configuration one or two chillers and the associated pumps were created based on the baseline chiller and pumps. The only variable that was modified was the capacity ratio, such that the chillers were equally sized and with a total capacity equal to the baseline chiller. This resulted in modeling chillers that would not normally be found in practice. For example, the DEER prototype for the hospital building type had 625 cooling tons of capacity and was modeled with 2 chillers of 312.5 tons. For the chilled water pump, the chilled water loop can only have one pump assigned. This pump, however, may consist of a single pump or multiple pumps (set by keyword “NUMBER”).

For the VFD on the chilled water pump measure the savings are on average 11% greater (with a minimum of 7% and a maximum of 15%) for the multiple chiller models and for the VFD on the cooling tower fans measure the savings are on average 25% less (with a minimum of 5% and a maximum of 49%) for the multiple chiller models; these differences are explained further in the eQUEST Simulation Issues section that follows. The savings difference for the VFD on the chilled water pump is within an acceptable range, and so no adjustment was made to the modeled savings for this measure. To account for the relatively high difference in savings for the cooling tower fan measure, the modeled savings for this measure were decreased by 25%.

Costs for installing multiple VFDs in these applications will not increase as the costs are calculated on a per horsepower basis as discussed in Section 4.

### 2.2.3 eQUEST Simulation Issues

After performing simulations on the “normal operation” buildings, discrepancies were observed in the resulting fan sizes for all buildings. The cooling loads and the resulting equipment sizing were determined by eQUEST without any modifications of the original defaulted DEER and BDL inputs. For example, results on the part load ranges generated by eQUEST for the cooling tower fans and chilled water pumps are not consistent with expectations.

In the models used for this analysis, the cooling towers are significantly oversized (see the table below; for University, CZ 6, V85, the tower is sized at 226.4 kW, while the actual peak load is only 148.9 kW). As a result, the towers are operating at between 40 and 50% load for 99% of hours in the baseline case. This over-sizing is greater in the single tower case (baseline peak load is 65.8% of tower size in the single tower model as opposed to 83.6% in the multiple tower scenario). Thus, the savings potential for adding a variable speed drive on the fan is slightly higher in the single tower case. Reducing the tower capacity in the model increases the ratio between peak load and equipment size but results in warnings that the capacity is less than demand.

**Equipment Sizing Results for University Building Type**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Model: University, CZ6, v85** | | | | |
|  | **Equipment Sizing**  **(PV-A)\***  **(kW)** | **Equipment Peak**  **(PS-C)\*\***  **(kW)** | **Equipment Sizing**  **(PV-A)**  **(kW)** | **Equipment Peak**  **(PS-C)**  **(kW)** |
|  | **Tower Fan** | | **Chilled Water Pump** | |
| **Single Chilled Water Pump/Cooling Tower Fan** | | | | |
| Baseline | 226.4 | 148.9 | 187.4 | 187.4 |
| Tower Fan VSD | 226.4 | 47.0 | - | - |
| Chilled Water Pump VSD | - | - | 187.4 | 77.4 |
| **Multiple Chilled Water Pumps/Cooling Towers** | | | | |
| Baseline | 79.69 | 66.6, 62.9, 53.9 | 202 | 202 |
| Tower Fan VSD | 79.69 | 40.7, 62.9, 53.9 | - | - |
| Chilled Water Pump VSD | - | - | 202 | 74.7 |

\*PV-A is the Plant Design Parameters report available in the eQUEST SIM (simulation) file

\*\*PS-C is the Equipment Loads and Energy Use report available in the eQUEST SIM file

For the chilled water pumps, the baseline pumps have a peak load consistent with the equipment sizing, and they operate at 100% loading for all operating hours. The modeled pumps with variable speed drives are operating for a significant number of hours in the 0 to 10% load range, particularly when the specified turndown ratio is set at 0.40. This is due to the methodology used in eQUEST for sizing. This sizing issue results in significantly higher savings for installing a VFD on the chilled water pump than installing a VFD on the cooling tower fans. In the baseline model, the cooling tower fan operates at less than 60% load for most hours while the chilled water pump operates at 100%. Savings potential is, therefore, greater for the chilled water pump. The lower savings potential of the cooling tower fan is then divided by a larger motor HP due to over sizing, thereby further increasing the difference in savings on a per HP basis. Engineering review of the energy and demand savings values determined that the energy savings reported by the model are reasonable.

The part load operating hours for the variable speed pumping options are the same in both the single and multiple pump options. What does change is the number of hours in the part load bins for the electrical consumption. For the multiple pump option, only one of the three pumps is required for low load operation. For the single pump option, the majority of hours (80%) are in the 20-30% load range, as the single pump cannot turn down as far. Hence the slightly increased savings potential for the multiple pump model.

### 2.2.4 Weighted Average Methodology

To create a single value for each building type and climate zone, the Attachment #2 DEER2014 Energy Impact Weights Tables were used to create a weighted average of each vintage represented in the climate zone. The weighted average was applied to the combined base cases to create a single savings amount for each measure and climate zone. The weighted average baseline for the CHW measure was calculated separately from the weighted average baseline for the CT and CW measures, as it did not include the 07 or later vintages (as VFDs on CHW loop pumps are required for these vintages).

### 2.2.5 Energy Savings Results

Energy savings are calculated as the difference between the baseline model energy use and the energy use as modeled with the VFD installed. To convert savings to kWh/HP, the HP is first calculated by taking the demand (kW) as reported in the Plant Design Parameters (PV-A) Report available in the SIM file. This is then converted by dividing by the constant 0.746 kW/HP. Energy values from the model output are then divided by HP, resulting in kWh/HP. The table shown below shows the energy savings for the Hospital building type.

**Energy Savings for Hospital**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Energy Savings (kWh/HP)** | | |
| **Climate Zone** | **CHW Loop Pump VSD** | **CT Fan VSD** | **CW Loop Pump VSD** |
| CZ06 | 5,432 | 454 | 2,214 |
| CZ08 | 5,552 | 498 | 2,256 |
| CZ09 | 5,504 | 473 | 2,202 |
| CZ10 | 5,110 | 459 | 2,090 |
| CZ13 | 4,897 | 489 | 2,000 |
| CZ14 | 4,727 | 388 | 1,930 |
| CZ15 | 5,101 | 709 | 2,066 |
| CZ16 | 4,502 | 171 | 1,779 |

As Energy Savings for Hospital table shows, energy savings for the VFD on Chilled Water Pump measure are the most significant as the savings include reductions in space cooling energy (including the constant volume chiller) and heat rejection energy in addition to the reduced pumping energy. For example, for the 2003 vintage Hospital building type in climate zone 6, the VFD on Chilled water pump measure results in a 20% reduction in pump energy, 4% reduction in heat rejection energy, and 3% reduction in space cooling energy. Pumping savings account for 83.2% of total measure savings, space cooling savings account for 16.7%, and heat rejection savings account for 0.3% (there is a slight energy penalty for ventilation fan energy).

The addition of a VFD on the cooling tower only results in reduced fan power. The addition of a VFD on the condenser water pump results in reduced pumping power during part-load conditions, but there is an increase in space cooling energy (due to higher chiller consumption); however, the reduction in pumping energy is great enough to provide energy savings overall.

**Scaling Savings for the NEW delivery method - Variable Speed Drive on Cooling Tower (CT) Fan Control**

Scaling for the NEW delivery method is being applied to adjust measure impacts due to changes on T24 Energy Standards affecting cooling tower fan control - refer to T24 Energy Standards section for details. The NEW impacts, which requires for energy and demand savings to be evaluated from “Code-to-Measure,” were estimated by reducing energy and demand savings estimated in original version of the workpaper for the REA delivery method, evaluated from “Customer-Average-to-Measure.”

The scaling was determined by evaluating energy and demand impacts from single-speed, two-speed, and VFD cooling tower fan control technologies via building modeling of Office-Large DEER prototype; 2011 vintage; CZ2010 weather, and most representative Climate Zones (e.g., largest building population - about 94% of total) and weighted per DEER weights – “DEER2014-EnergyImpact-Weights-Tables-v2.xlsx.”

The CAPACITY-CTRL heat rejection keyword was used to evaluate the fan power consumption and control options in the parametric runs.

Scaling for NEW were estimated at 25% on energy and 5% on demand; hence, only 25% and 5% of the energy and demand from corresponding REA measures respectively can be claimed for NEW. Contributions on measure impacts are limited to that beyond code – e.g., from two-speed fan control (as the baseline) to variable speed fan control (the measure).

In Attachments #1, energy saving impacts for NEW program type have been scaled down based on the above percentages.

Refer to Attachment #5 for Scaling calculation.

## 2.3 Demand Savings

The peak demand results from eQUEST do not conform to the DEER methodology for determining demand across a three-day peak heat wave. To ensure the DEER methodology was applied to determine peak demand savings, the hourly reports included in the eQUEST simulation runs

eQUEST simulation runs include hourly consumption reports. These reports were utilized to extract the demand from the 2-5pm peak period for the DEER-defined three-day peak heat waves. DEER reports the beginning date of the expected three-day heat wave for each climate zone, as follows:

**Peak Demand Period used for DEER 2014**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Start of 3 Day Period** | | |
| **Climate Zone** | **Month** | **Day** | **Week Day** |
| CZ06 | Sept | 1 | Tue |
| CZ08 | Sept | 1 | Tue |
| CZ09 | Sept | 1 | Tue |
| CZ10 | Sept | 1 | Tue |
| CZ13 | July | 8 | Wed |
| CZ14 | Aug | 26 | Wed |
| CZ15 | Aug | 25 | Tue |
| CZ16 | Jul | 8 | Wed |

Once the data was extracted for the three-days selected, the hourly results from 2-5pm on the three consecutive days (9 data points) were averaged to provide peak demand estimates. The difference between the baseline and measure peak demand estimates results in the peak demand savings. To create a single demand savings value for each building type in each climate zone, the same methodology as was used for energy savings was applied. The table below shows the demand savings for the Hospital building type.

**(REA) Demand Savings for Hospital**

|  |  |  |  |
| --- | --- | --- | --- |
|  | **Energy Savings (kW/HP)** | | |
| **Climate Zone** | **CHW Loop Pump VSD** | **CT Fan VSD** | **CW Loop Pump VSD** |
| CZ06 | 0.52 | 0.23 | 0.20 |
| CZ08 | 0.51 | 0.23 | 0.18 |
| CZ09 | 0.48 | 0.29 | 0.09 |
| CZ10 | 0.45 | 0.28 | 0.09 |
| CZ13 | 0.45 | 0.28 | 0.12 |
| CZ14 | 0.48 | 0.23 | 0.16 |
| CZ15 | 0.46 | 0.26 | 0.11 |
| CZ16 | 0.52 | 0.16 | 0.23 |

As is explained in Section 2.2.5, savings are most significant for the VFD on Chilled Water Pump measure, as it results in savings for pump energy, space cooling energy, and heat rejection energy.

# Section 3. Load Shapes

The ideal load shape for net benefits estimates would represent the difference between the base case and measure case. The closest load shapes that are applicable to the measures in this work paper are listed in the table below.

Building Types and Load Shapes

|  |  |  |
| --- | --- | --- |
| **Building Type** | **Load Shape** | **E3 Alternate Building Type** |
| Assembly | DEER:HVAC\_Chillers | NON\_RES |
| Education - Secondary School | DEER:HVAC\_Chillers | NON\_RES |
| Education - University | DEER:HVAC\_Chillers | NON\_RES |
| Health/Medical - Hospital | DEER:HVAC\_Chillers | NON\_RES |
| Health/Medical - Nursing Home | DEER:HVAC\_Chillers | NON\_RES |
| Lodging – Hotel | DEER:HVAC\_Chillers | NON\_RES |
| Manufacturing - Bio/Tech | DEER:HVAC\_Chillers | NON\_RES |
| Office – Large | DEER:HVAC\_Chillers | NON\_RES |
| Office – Small | DEER:HVAC\_Chillers | NON\_RES |
| Retail - Multistory Large | DEER:HVAC\_Chillers | NON\_RES |
| Manufacturing-Light Industrial | DEER:HVAC\_Chillers | NON\_RES |
| Warehouse-Refrigerated | DEER:HVAC\_Chillers | NON\_RES |

# Section 4. Costs

## 4.1 Base Case Cost

**Retrofit add on**

For this measure category, the base case cost is assumed to be zero because these are discretionary modifications (retrofit) to the customers’ existing equipment. Their alternative is to make no changes to their existing system.

**Base Case Cost**

The base case cost is $0/unit for all three measures because the base case refers to the existing equipment, which does not require replacement.

Measure documentation assume that base case includes a motor that is premium efficiency (and capable to provide two speed control dependent on vintage) and/or compatible with variable speed drive applications and/or that cost of the measure case motor if required (e.g., premium efficiency and/or AC Inverter/Vector Duty motor) is not significantly higher than the base case motor - http://www.baldor.com/catalog.

Please refer to Attachment #6 Cost Calculations for details.

## 4.2 Measure Case Cost

All Measure and Labor Cost documentation for the measures was updated using 2016 RS Means Mechanical Cost Data Handbook [504]. Measure cost assumes new VFD with NEMA 1 Enclosure, 460 Volts applications, and electrical work in full compliance with latest NEC.

Cost documentation assumes that Chilled and Condensing pump control applications will generally require higher capacity drives compare to that of cooling tower fan control applications.

Measure and labor cost for Chilled Water and Condenser Water pump VFD control was estimated by averaging cost for drives from 7.5-hp through 100-hp in terms of $/hp. See Attachment 6.

Measure and labor cost for Cooling Tower Fan VFD control was estimated averaging cost for drives from 7.5-hp through 50-hp in terms of $/hp. See Attachment 6.

**VSD Chilled Water and Condenser Water Pump Control - Full Measure Cost**

Full Measure Cost ($/HP) = Measure Case Cost + Labor Cost = $248.1.0 = $210.0 + $38.1

**VSD Cooling Tower Fan Control - Full Measure Cost**

Full Measure Cost ($/HP) = Measure Case Cost + Labor Cost = $263.9 = $220.9 + $43.1

## 4.3 Full and Incremental Measure Cost

**Full and Incremental Measure Cost Equations**

|  |  |  |  |
| --- | --- | --- | --- |
| **Installation Type** | **Incremental Measure Cost** | **Full Measure Cost** | |
| **1st Baseline** | **2nd Baseline** |
| REA | MEC + MLC | MEC + MLC | N/A |
| NEW | (MEC + MLC) – (BEC + BLC) | (MEC + MLC) – (BEC + BLC) | N/A |

MEC = Measure Equipment Cost; MLC = Measure Labor Cost

BEC = Base Case Equipment Cost; BLC = Base Case Labor Cost

**Full and Incremental Costs**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Measure** | **Installation Type** | **Incremental Measure Cost** | **Full Measure Cost** | |
| **1st Baseline** | **2nd Baseline** |
| AC-14365 | REA | $263.9 | $263.9 | N/A |
| AC-18931 | NEW | $263.9 | $263.9 | N/A |
| AC-91987 | REA | $248.1 | $248.1 | N/A |
| AC-55411 | REA | $248.1 | $248.1 | N/A |
| AC-18932 | NEW | $248.1 | $248.1 | N/A |

# Attachments

1. SCE17HC039.0 A1 - Calculation Template\_Final.zip
2. SCE17HC039.0 A2 - DEER Energy Impact Weights Table.xlsx
3. SCE17HC039.0 A3 - Limitations Memo.docx
4. SCE17HC039.0 A4 - EDDispositionCentralPlantVFDs .docx
5. SCE17HC039.0 A5 - Heat RejectFanControlMeasuresParameters.xlsx
6. SCE17HC039.0 A6 - MeasureCost2016.xlsx

# References

1. References\_12122016\_100741.xlsx

[26]

[49]

[496]

[504]

[510]

[A] Taylor, Steven T. 2011. “Optimizing Design & Control of Chilled Water Plants Part 5: Optimized Control Sequences” ASHRAE Journal 54(6):56-74

[B] http://spxcooling.com/pdf/TR-014.pdf

[C] http://www.energy.ca.gov/2008publications/CEC-400-2008-017/rev1\_chapters/NRCM\_Chapter\_4\_Mechanical\_Systems.pdf#page=83

[D] http://www.energy.ca.gov/2013publications/CEC-400-2013-002/chapters/04\_mechanical\_systems.pdf#page=107