TWO DOE-2 FUNCTIONS

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ABSTRACT

This paper presents two DOE-2 functions to expand the modeling capability of DOE-2.1E, a popular calculation engine for building energy simulations. The first function models sensible and total heat recovery between outside air and exhaust air, with optional evaporative precooling of exhaust air before the heat recovery. The existing heat recovery of DOE-2 only allows preheating outside air when exhaust air is more than 10°F warmer than outside air. The second function models distributed energy storage for direct expansion air conditioners which cannot be modeled by any existing system type of DOE-2.1E.

INTRODUCTION

As a powerful and popular simulation engine of building energy performance, DOE-2.1E has been widely used for the last several decades. With the advancement of building and HVACR technology, some new HVAC systems or components cannot be modeled by DOE-2.1E adequately or directly. Two examples are –

- The DOE-2.1E heat recovery only allows preheating outside air with exhaust air if exhaust air is more than 10°F warmer than outside air. No precooling of outside air is considered. The heat recovery is also limited to sensible heat exchange, no latent heat exchange is counted.
- The Ice Bear from Ice Energy is a distributed energy storage for direct expansion air conditioners (DES/DXAC). A DES/DXAC system is similar to a standard direct expansion (DX) cooling system in the way that refrigerant goes through the AHU cooling coil and provides cooling by direct expansion. But the returning warmer refrigerant is cooled by ice in a storage tank instead of a condenser either air-cooled or water-cooled. A DES/DXAC system is also different from chilled water based thermal energy storage system which pumps chilled water through the AHU cooling coil to provide cooling. No existing DOE-2.1E system types can model a DES/DXAC system.

With the capability of calling user written external Fortran routines (i.e., functions) in the LOADS and SYSTEMS modules of DOE-2.1E, there is opportunity of writing functions to improve and expand DOE-2.1E's modeling capabilities. Several functions are provided as examples in DOE-2 Reference Manual.

This paper describes functions written to expand the capabilities of DOE2.1E in modeling heat recovery and DES/DXAC systems. Both functions have been verified by an hourly spreadsheet, but no testing have been done against actual systems.

THE HEAT RECOVERY FUNCTION

Background

Sensible heat recovery is calculated in the subroutine ECONO of the SYSTEMS module of DOE-2.1E. The ECONO subroutine models economizer for outside air and heat recovery

Features of the Function

A function is written to expand the heat recovery feature of DOE-2.1E. The function has the following features:

- Allows a user-entered temperature difference to control the sensible heat recovery

The user can specify a minimum temperature difference between outside air and exhaust air (MinDT) to control the operation of the heat recovery device. Existing DOE-2 code hard-wires MinDT to 10°F. When the temperature difference between outside air and exhaust is less than the user-entered MinDT, the heat recovery device would be bypassed or not operating.

- Allows precooling of outside air with exhaust air

During summer months for hot climates like Las Vegas the outside air can be higher than 110°F while exhaust air is around 75°F. The delta-T of 35°F provides a good opportunity for precooling outside air with exhaust air to save cooling energy.

- Allows total/enthalpy heat recovery

Besides the sensible heat exchange, the function can calculate the latent heat exchange between outside air and exhaust air that can be provided by, for example, a desiccant heat recovery wheel. For simplicity, the function assumes the effectiveness of the latent exchange is the same as that of the sensible exchange, although it can be easily modified to take the latent exchange effectiveness as a separate input.

- Allows direct evaporative precooling of exhaust air before the heat recovery

The exahaust air can be precooled by direct evaporative cooling before entering the heat recovery device. This can lower the temperature of exhaust air and improve the potential of precooling outside air especially in sensible heat recovery mode.

Inputs of the Function

Besides reading inputs of a system like effectiveness of the heat recovery from the BDL, there are four inputs to the function that are defined as macro variables –

- HRType = HeatRecoveryType[]

This variable specifies the type of heat recovery: 1 for sensible heat only, 2 for total heat (including latent and sensible heat).

- MinDT = HeatRecMinDT[]

This variable is the minimum temperature difference between outside air and exhaust air for the heat recovery to operate.

- EvapClEA = EvapClAddOn[]

This variable determines whether there is a direct evaporative precooling of exhaust air before heat recovery: 1 means Yes, 0 means No.

- EvapClEff = EvapClEff[]

This variable is the effectiveness of the direct evaporative precooler for exhaust air.

These four macro variables should be assigned values before the function is called. These four inputs are shared by all systems with heat recovery. Therefore, only one type of heat recovery can be modeled for all systems in one simulation run.

The function also has a variable PrintHlyRpt to control the output of hourly calculation results. Set PrintHlyRpt = 1 to save hourly calculations in file fort.50 so that users can double check the calculation results.

Outputs of the Function

For each system with heat recovery, the function produces a LOADS summary report LS-Z which lists:

- Function inputs for each system
- Annual number of hours heat recovery is on
- Annual thermal loads recovered in kBtu
- Annual number of hours in cooling recovery mode
- Annual cooling loads recovered in kBtu
- Annual number of hours in heating recovery mode
- Annual heating loads recovered in kBtu
- Annual moisture recovered in pounds if any

If PrintHlyRpt is set to 1, hourly calculation results are printed in file fort.50.

Calling the Function

The heat recovery function is called at the entry point of ECONO-3 in the subroutine ECONO. In a DOE-2 input file, the function is called using the SUBR-FUNCTIONS command after the INPUT SYSTEMS command:

```
$ SYSTEMS INPUT starts here
INPUT SYSTEMS ..
 SUBR-FUNCTIONS
  ECONO-3 =*HeatRecovery* ..
$ SYSTEMS INPUT continues …
END ..
 ##INCLUDE HeatRecovery.func
 COMPUTE SYSTEMS  ..
$ SYSTEMS INPUT ends here
```

The name of the function is HeatRecovery indicated in the line "ECONO-3 =*HeatRecovery* ..". The function source code is stored in an external file HeatRecovery.func indicated by keyword "##INCLUDE". The HeatRecovery.func file must be located in the DOE-2 executable files folder

Source Code of the Function

The Fortran source code of the heat recovery function is available at http://www.archenergy.com/products/visualdoe/heatrecovery.func.

Case Studies

A sample one-story office building is used in the case studies to demonstrate energy savings of heat recovery using the function for climate of San Francisco (very mild summer) and Las Vegas (very hot and dry summer). The building has a floor area of 10,000 ft² with a space height of 9 ft and a 3 ft plenum. The building is served by a packaged single zone system with furnace heating and 100% outside air. The minimum supply air temperature of the system is set to 55℉. There is no preheat for the system. VisualDOE 4.0, using DOE-2.1E version 119 as the calculation engine, is used to calculate the annual energy use of the building. Design alternatives with variations of heat recovery are listed in Table 1 together with their whole building cooling and heating energy savings compared with the Base Case.

Table 1 - Design Alternatives of Heat Recovery for San Francisco Climate

ALTERNATIVES	ANNUAL COOLING KWH	ANNUAL HEATING THERM	COOLING; HEATING SAVINGS
SF Base Case, no heat recovery	3407	5723	n.a.; n.a.
SF with DOE-2 existing heat recovery	3407	2702	0.0%; 52.8%
SF with sensible HR, 10°F MinDT	3334	2702	2.1%; 52.8%
SF with sensible HR, 5°F MinDT	3274	2614	3.9%; 54.3%
SF with total HR, 5°F MinDT	3254	2614	4.5%; 54.3%
SF with sensible HR, 5°F MinDT, and evap-precooling of exhaust air	3028	2614	11.1%; 54.3%
SF with total HR, 5°F MinDT, and evap-precooling of exhaust air	3017	2614	11.4%; 54.3%

Table 2 - Design Alternatives of Heat Recovery for Las Vegas Climate

ALTERNATIVES	ANNUAL COOLING KWH	ANNUAL HEATING THERM	COOLING; HEATING SAVINGS
LV Base Case, no heat recovery	63990	3843	n.a.; n.a.
LV with DOE-2 existing heat recovery	63990	1932	0.0%; 49.7%
LV with sensible HR, 10°F MinDT	53247	1932	16.8%; 49.7%
LV with sensible HR, 5°F MinDT	52218	1869	18.4%; 51.4%
LV with total HR, 5°F MinDT	51495	1869	19.5%; 51.4%
LV with sensible HR, 5°F MinDT, and evap-precooling of exhaust air	41340	1869	35.4%; 51.4%
LV with total HR, 5°F MinDT, and evap-precooling of exhaust air	40825	1869	36.2%; 51.4%

Results Discussions

For San Francisco's mild climate, simulation results listed in Table 1 show no cooling savings using the existing DOE-2 heat recovery code compared with 2.1% cooling savings using the function with sensible heat recovery and a MinDT of 10°F. If MinDT is reduced to 5°F, the cooling savings increases to 3.9%. With a total heat recovery and 5°F MinDT settings, the cooling savings is 4.5%. If equipped with direct evaporative precooling (assumed 80% effectiveness) of exhaust air, the cooling savings can be 11.1% for sensible heat recovery and 11.4% for total heat recovery. The existing DOE-2 heat recovery shows heating savings of 52.8%. The function gives same savings with sensible heat recovery and MinDT of 10°F. When MinDT is reduced to 5°F, the heating savings is increased to 54.3%.

For the Las Vegas hot-dry climate, the simulation results listed in Table 2 show no cooling savings using the existing DOE-2 heat recovery code compared with 16.8% cooling savings using the function with sensible heat recovery and a MinDT of 10°F. If MinDT is reduced to 5°F, the cooling savings increases to 18.4%. With a total heat recovery and 5°F MinDT settings, the cooling savings is 19.5%. If equipped with direct evaporative precooling (assumed 80% effectiveness) of exhaust air, the cooling savings can be significantly increased to 35.4% for sensible heat recovery and 36.2% for total heat recovery. The existing DOE-2 heat recovery shows heating savings of 49.7%. With the function, the heating savings can be up to 51.4%.

In general, the heat recovery function calculates significant cooling energy savings especially with evaporative precooling of exhaust air for hot-dry climates like Las Vegas. Also demonstrated is there can be more than 50% heating savings with heat recovery for 100% outside air systems either in San Francisco or Las Vegas.

THE DES/DXAC FUNCTION

Background

A DES/DXAC system uses off-the-shelf components including a conventional condensing unit (outdoor unit), evaporator coil (indoor unit) and packaged ice storage unit (insulated tank, refrigerant management system, controls). DES/DXAC can be added to new or existing direct-expansion air conditioning systems (packaged rooftop or split residential style system). It is referred to as distributed energy storage because it can be deployed in tens to hundreds of thousands of installations, thereby establishing a noteworthy utility resource. This distinguishes the DES/DXAC from relatively large central plant thermal energy storage (TES) systems that use chilled water for cooling.

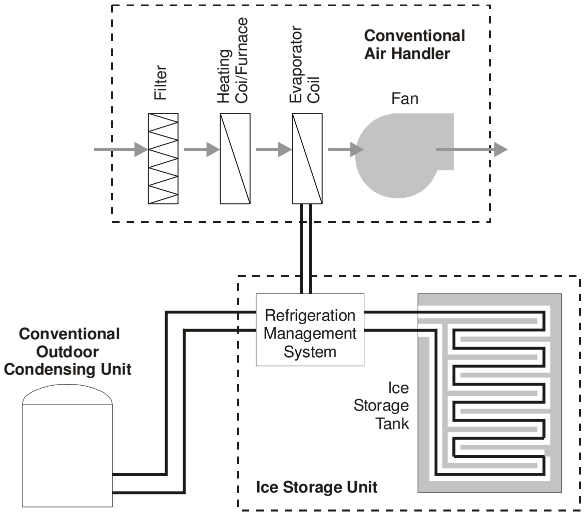

Figure 1 - DES/DXAC System Components

During nighttime, the condensing unit charges the storage tank until it has full solid ice; during daytime, DES/DXAC uses ice to cool the refrigerant which is circulated by a pump to the AHU cooling coil to provide cooling while the condensing unit is off. If the tank runs out of ice and the system calls for cooling, the condensing unit can operate to provide cooling as a standard DX system. As most electricity use is shifted from daytime peak hours to nighttime off-peak hours, DES/DXAC system significantly reduces peak electricity use on hot days. Figure 2 compares hourly cooling electricity use for a conventional DX system and one with DES/DXAC.

A DES/DXAC system is similar to a DX system in the way refrigerant goes through the AHU cooling coil and provides cooling by direct expansion. But the returning warmer refrigerant is cooled by ice in a storage tank instead of a condenser. A DES/DXAC system is also different from chilled water based thermal energy storage system which pumps chilled water through the AHU cooling coil to provide cooling. No existing DOE-2.1E system types can model the performance of a DES/DXAC system.

To model a DES/DXAC system with DOE-2.1E, a DOE-2 function ISACFunc is written for packaged DX system types PSZ, PVAVS, PMZS, and PVVT.

Features of the Function

The ISACFunc function calculates hourly cooling energy use for a DES/DXAC system of type PSZ, PVAVS, PMZS, or PVVT. Other energy use like fan energy is not changed by the function.

The proposed control algorithm tries to optimize time dependent value (TDV) energy by making ice during nighttime hours when outside air temperature is low, delaying ice melting for cooling during summer until say 11:00 am, and using the condensing unit for direct cooling before 11:00 am.

The function allows multiple DES/DXAC units to serve a single AHU with multiple cooling coils. Each DES/DXAC serves a cooling coil.

Inputs of the Function

Besides reading inputs of a system like DX cooling EIR (Energy Input Ratio = 1 / COP) from the BDL and hourly outside air temperature and cooling loads, there are several other inputs to the function:

- NumIB

Number of DES/DXAC units serving the system, usually set to 1.

- IBMaxCl

Maximum cooling load Btu/h to be served by a DES/DXAC unit. It should not be more than the rated cooling capacity of the storage tank.

- DES/DXAC equipment specification

IBClCAP – storage tank cooling capacity in ton-hours, TANKUA – tank heat loss coefficient, ParaCool – Parasitic electrical losses in kW during discharging (mostly pump energy), ParaStore – Parasitic electrical losses in kW during charging, ParaIdle - Parasitic electrical losses in kW during idle.

- DES/DXAC performance data

There are two performance curves for the DES/DXAC. One performance curve is condensing unit capacity as a bi-quadratic equation (represented by six coefficients sngCap0 to sngCap5) of outside air temperature and charging completion ratio. Another performance curve is condensing unit EER as a bi-quadratic equation (represented by six coefficients sngEER0 to sngEER5) of outside air temperature and charging completion ratio.

- DES/DXAC control parameters

There are 10 user entered variables that control the charging and discharging operation of the DES/DXAC system.

The function also has two variables OrgDXHrp and ISACHrp to control the output of hourly calculation results. Setting them to 1 will produce hourly calculation results in two files fort.50 and fort.51.

Outputs of the Function

For each DES/DXAC system, the function produces a SYSTEMS summary report SS-Z which lists:

- System ID corresponding to the order of the system in the BDL
- Number of DES/DXAC units serving the system, usually set to 1.
- System cooling capacity Btu/h from BDL
- System cooling EIR from BDL
- System peak cooling load Btu/h from DOE-2 output
- Annual cooling kWh if the system is served by a standard DX unit

- Annual cooling kWh of the DES/DXAC system with breakdowns for the ice storage kWh and the standard DX cooling kWh for direct cooling
- Annual cooling kWh savings of the DES/DXAC compared with a standard DX system

If OrgDXHrp is set to 1, hourly calculation results of the standard DX system are printed in file fort.50. If ISACHrp is set to 1, hourly calculation results of the DES/DXAC system are printed in file fort.51.

Calling the Function

The function is called after a system completes an hourly calculation but before looping for the next system. In a DOE-2 input file, the function is called using the FUNCTION keyword after the SYSTEM-TYPE keyword for each DES/DXAC system:

```
$ Description of System_101

"System_101" = SYSTEM

SYSTEM-TYPE = PSZ

$ CALL SYSTEM AFTER FUNCTION

FUNCTION = (*NONE*,*ISACFunc*)

$ System_101 inputs continue …

$ Other systems inputs …

END ..

##INCLUDE ISAC.func

COMPUTE SYSTEMS ..

$ SYSTEMS INPUT ends here
```

The ISACFunc function should be inserted between the system "END .." line and the "COMPUTE SYSTEMS .." line. This can also be done by inserting an include statement "##INCLUDE ISAC.func", and put the actual DOE-2 function file ISAC.func at the DOE-2 executable files folder.

If there are multiple DES/DXAC systems in a DOE-2 input file, each function should have a unique name to be called by each system.

Source Code of the Function

The Fortran source code of the DES/DXAC function is available at http://www.archenergy.com/products/visualdoe/isac.func.

Time Dependent Valuation (TDV) Energy

TDV energy is used in the 2005 California building energy efficiency standards to account for the relative value of energy use at different hours of a year. At a specific hour, the TDV energy (kBtu) equals a multiplier times the actual kWh consumed at that hour. The hourly TDV multipliers are derived from life cycle cost analysis of generating and delivering electricity at each hour by California's electric utilities. TDV multipliers vary each hour of the year based on resource types (electricity, natural gas, propane), building types (residential and nonresidential), and climate zones (California has 16 climate zones). The electricity TDV multipliers are much higher in summer peak hours than winter or summer off-peak hours as shown in Figure 3. The hourly TDV energy multipliers can be converted to hourly TDV cost multipliers representing the life cycle cost of each kWh of electricity.

Case Studies

A sample one-story office building measuring 30 ft by 60 ft and 10 ft high is used in the case studies. Windows are distributed evenly on four facades with a window-wall-ratio of 20%. The building has a single thermal zone occupied during the day time. Five of the sixteen California climate zones are used in the case studies. These are chosen to represent distinctly different climate types.

Table 3 – California Climate Zone Example Cities

CLIMATE ZONE	REPRESENTING AREA AND CITY
3	North Coast. Oakland
6	South Coast. Long Beach
12	Central Valley. Sacramento
14	Desert. China Lake
16	Mountains. Mount Shasta

A design using a split DX system for each climate zone is created so that it minimally complies with the prescriptive requirements of Title 24-2005 standard, then the Proposed Design is created by changing the HVAC system from an air-cooled condenser to a DES/DXAC system which has a peak cooling rate of 7.5 tons and a storage capacity of 45 ton-hours.

Five simulation runs are performed with EnergyPro 4.0, a California certified compliance tool for nonresidential buildings, to demonstrate the TDV (Time Dependent Value) energy savings of Ice Bear DES/DXAC Proposed Designs for the five climate zones (results listed in Table 4).

Table 4 – Annual Cooling TDV Energy and kWh Savings of DES/DXAC Proposed Design vs Title 24-2005 Standard Design

	COOLING ENERGY (kWh/ft^2)			COOLING TDV ENERGY ($kBtu/ft^2$)		
Climate Zone	T24-2005	DES/DXAC	Savings	T24-2005	DES/DXAC	Savings
3	2.0	2.3	-17%	61.6	44.8	27%
6	2.9	3.4	-20%	96.1	75.9	21%
12	3.3	3.0	11%	120	67.1	44%
14	4.4	4.1	6%	184	122	34%
16	2.0	1.9	3%	73.5	42.3	42%

Results Discussions

Compared with the Title 24-2005 Standard Designs, the Ice Bear DES/DXAC Proposed Designs show annual cooling TDV energy savings of 21% to 44% for the five California climate zones. The cooling TDV energy savings is greatest for climate zones 12

(44%) and 16 (42%), the Central Valley and Mountain areas, while it is least for climate zone 6 (21%), the South Coast area. Climate zones 3 and 14 also show cooling TDV savings of 27% and 34% respectively. All five climate zones show cooling TDV energy savings of more than 20%, while climate zones 12, 14, and 16 show savings of more than 30%.

In terms of annual cooling electricity use kWh, climate zones 3 and 6 show DES/DXAC consumes up to 20% more cooling kWh, while climate zones 12, 14, and 16 show cooling kWh savings of up to 11%.

In summary, DES/DXAC shows significant TDV energy savings for the five California climate zones. Greater TDV savings with DES/DXAC are for climate zones with greater daily variation in outdoor air temperature, for example, climate zone 12, 14, and 16 have much higher outdoor air temperature during daytime than nighttime. On the other hand, DES/DXAC may consume more cooling kWh for some climate zones while can save some for others.

Further details of DES/DXAC system is described in the report (Architectural Energy Corporation et al., 2005).

The TDV energy listed in Table 4 can be converted to present value of TDV energy cost by a constant factor. Therefore, the reported TDV energy savings percentages also represent the life cycle energy cost savings.

CONCLUSION

This paper introduces two DOE-2 functions to improve and expand the modeling capabilities of DOE-2.1E. The heat recovery function allows total heat recovery between outside air and exhaust air with the option of direct evaporative precooling of exhaust air before the heat recovery. The DES/DXAC function enables DOE-2.1E to model a DES/DXAC system. Case studies demonstrate the use of the two functions to evaluate energy savings of heat recovery and DES/DXAC for different climates.

Potential improvements to these functions include calculation of the energy use by the heat recovery device, for example, the kWh use by the motor for wheel-type equipment, as well as calculation of increased fan energy due to air pressure drop across the heat recovery device.

ACKNOWLEDGMENT

Joe Huang encouraged authors to add the total heat recovery to the function and also provided valuable inputs. Ice Energy funded the development of the DES/DXAC DOE-2 function.

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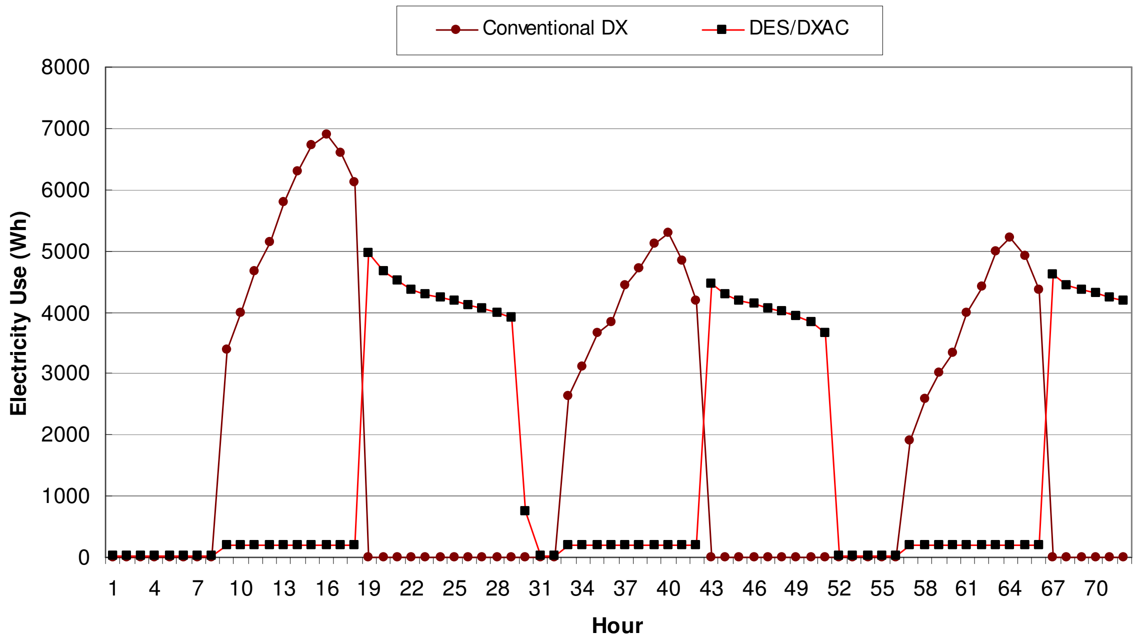

Figure 2 – Electricity Use for a Three-Day Period (the first day is the peak cooling day)

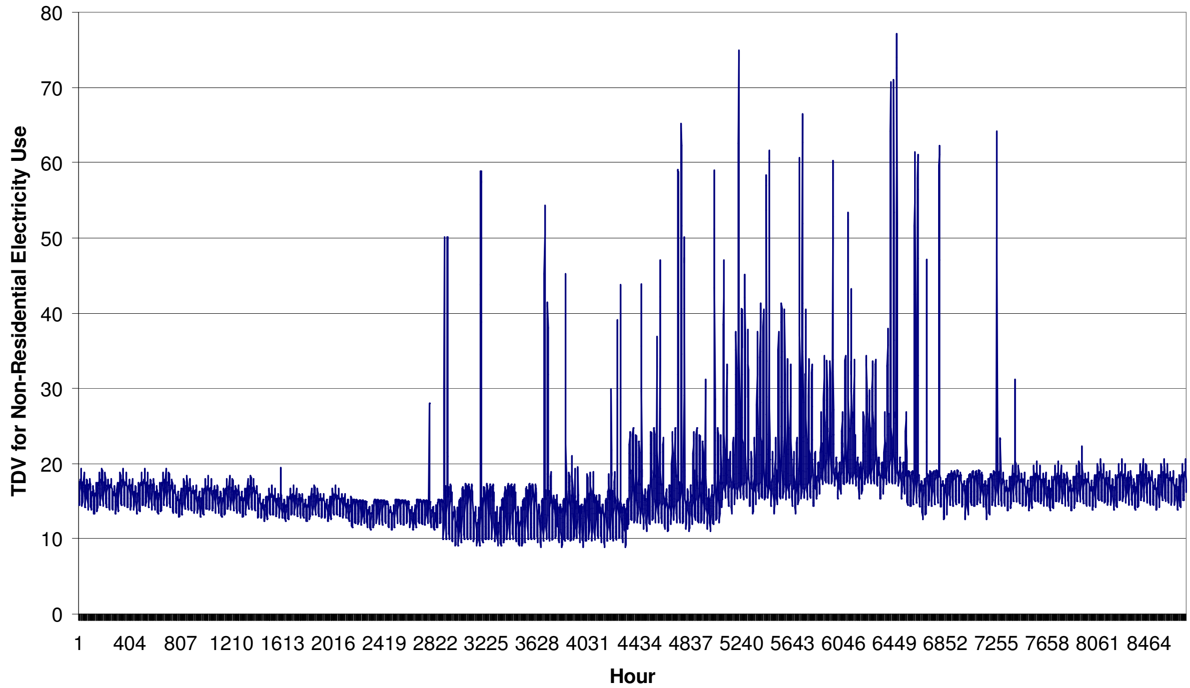

Figure 3 – TDV Multipliers for Nonresidential Electricity Use for Climate Zone 3 of California