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LBNL EF87EE

Task 2.3: Title 24 Credit for Efficient Evaporative Cooling

Deliverable: Interim Report

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1 Background:

The goal of this task is to reduce the energy consumption of US commercial buildings through broader adoption of hybrid indirect evaporative cooling technology. The objective is to implement a flexible hybrid evaporative cooling system model in EnergyPlus to allow Title-24 credit to be awarded for use of this novel low-energy cooling technology.

We will use field data from hybrid evaporative cooling systems, installed in various locations across California, to develop and test the new user-configurable EnergyPlus model feature.

Future energy savings are anticipated to come from the incremental direct replacement of existing conventional packaged DX cooling units with hybrid units that provide a significant improvement in efficiency. Laboratory and field studies of the Coolerado Heat and Mass eXchange (HMX) have demonstrated dramatic cooling energy savings with a sensible space cooling COP more than twice that of standard rooftop units under typical Western climate conditions. Given an assumed market penetration of 35% of any newly installed RTUs, projected energy savings (reductions in energy use compared to baseline conventional RTUs) in the first year are estimated to be 1.45E+08 kWh. Projected savings increase by a further 1.5E+08 kWh annually, reaching 2.99E+09 kWh savings per year once peak market penetration is realized. Energy savings calculation details are available in the appendix section 6.1.

2 Method:

We plan to complete the development, implementation and testing of the model in three parts. Firstly, we will collect field data from several hybrid evaporative cooling systems, which include Coolerado H80, Coolerado M50, Trane’s Voyager DC, Munters’ Oasis, Munters’ EPX 5000, and Seeley’s ClimateWizard. These systems will be installed in a mix of office, retail and food service buildings, in various locations across California, under agreements with several of our commercial and industrial partners. We will use the analysis of the field data from multiple system types to ensure our model framework is compatible with any type of hybrid rooftop unit. We will use data from two Coolerado H80s to develop regression curves that are representative of that manufacturer’s system performance over a range of operating conditions. We will add a new generic Hybrid Evaporative model to EnergyPlus that will be sufficiently configurable to allow users to describe new and existing hybrid evaporative systems. We will use the generic Hybrid Evaporative model together with Coolerado-specific performance curves to produce a Coolerado specific EnergyPlus model. We will use a limited set of the measured system performance data to validate this model.

2.1.1 Field Study method

In coordination with other California Energy Commission funded projects, and in collaboration with various equipment manufacturers, California Investor Owned Utilities, and commercial energy consumers, UC Davis Western Cooling Efficiency Center has facilitated the installation and pilot field demonstration of several hybrid rooftop packaged air conditioners. The technologies installed each utilize some form of indirect evaporative cooling in conjunction with vapor compression cooling.

For each field demonstration, a package of instrumentation was deployed to measure key performance variables. Rather than focusing on a case study determination of the energy savings for the specific scenarios installed, field study efforts have aimed at carefully characterizing equipment performance as a function of independent variables such as environmental conditions, instantaneous cooling loads, and system operating modes.

Monitoring of these systems takes place over several months in order to observe system behavior and performance over a broad range of operating conditions and to assess performance variation over time. These projects have been executed as part of the Western Cooling Challenge program which provides technical and non-technical assistance and interpretive efforts related to the technologies, so monitoring has also been utilized to provide ongoing system commissioning and feedback to manufacturers and installers about opportunities and needs for improvement.

The technologies studied include packaged hybrid rooftop units and indirect evaporative cooling retrofits for existing conventional rooftop air conditioners. The field study methods deployed characterize performance of the various technologies and system types according to similar independent variables with the specific intent to feed the modeling efforts in development here. Key independent variables include:

1. Temperature Outside Air Dry Bulb
2. Temperature Outside Air Wet Bulb
3. Temperature Return Air Dry Bulb
4. Temperature Return Air Wet Bulb
5. Outside Air Fraction
6. Supply Airflow

A range of parameters are measured to determine system operating mode, sensible cooling capacity, sensible heat ratio, and electric power. Further, these field studies collect information about ancillary variables that help to describe system operation and response.

2.2 Model implementation

We considered two distinct model implementation approaches. The first, approach uses first-principles thermodynamic’s based equations to describe the physical processes in a real hybrid evaporative cooling system. Figure 1 gives a breakdown of the main physical components in the packaged Coolerado HMX system. In this modeling approach, each component in the packaged system, including the cooling coil, the outdoor air mixer and the indirect evaporative heat exchanger are represented by one or more equations. These equations are used in combination to represent the complete system.

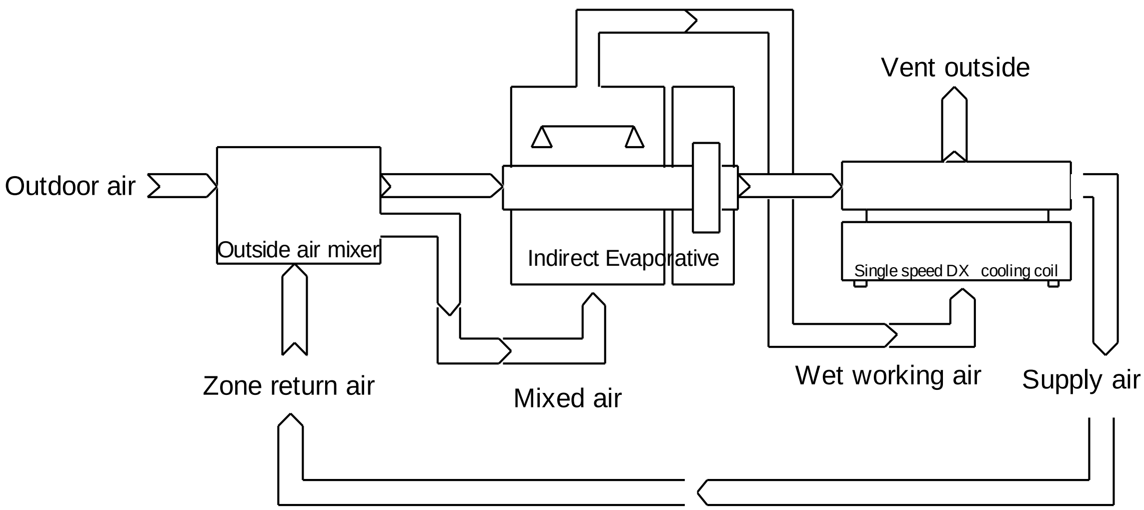

Figure 2 Coolerado HMX component model

This approach mirrors the approach used to model the other evaporative cooling models in EnergyPlus, including the *EvaporativeCooler:Indirect:ResearchSpecial*, *EvaporativeCooler:Indirect:CelDekPad*, and *EvaporativeCooler:Indirect:WetCoil models.* In these three models, users can specify several physical properties of the model, but the efficiency of the system is ultimately driven by the thermodynamic equations that form the core of each model.

The second alternative modeling approach we considered was to provide a ‘black box' component where the behavior of the model can be defined using user specified performance curves. A single set of example curves based on the Coolerado HMX would be defined and included as defaults in the model. Users wishing to use alternative hybrid evaporative cooling systems would need to obtain curves (or sufficient performance data to generate a performance curve) from the system manufacturer. Manufactures would be incentivized to provide this data because by doing so engineers would be more likely to specify the use of their product. This approach mirrors the approach used to in the DX cooling coil model in EnergyPlus.

A key consideration in selecting among these two approaches was whether or not the selected model framework would be flexible enough to model hybrid evaporative systems likely to be available to the market in the near term.

We performed an evaluation of the four current packaged hybrid indirect evaporative solutions that were identified as being either currently available or were close to market ready. These included Coolerado's HMX, Trane's EPX and Seeley's CoolingWizard. The outcome of this review was that we found fundamental differences in both the technologies and mechanical arrangements employed. Various configurations of indirect/direct evaporative cooling, variable speed fans, multiple stage compressors, evaporatively cooled condensers, water-reclamation and part-load operating modes have been adopted by these four companies. Thermodynamic models that encompass this level of variability would be complex, and models users would need to be skilled in configuring the elements of models appropriately to represent specific technologies. This challenge of applying thermodynamic models for the highly variable systems variability is compounded by the fact these hybrid technologies are in their infancy; future changes in the technologies and configurations are anticipated in the short/medium term. As a result of this analysis, we decided to develop a performance-curve-based model. This approach is also expected to be easier to implement; our current plan is to implement this as a new HVAC object using C++. EnergyPlus is expected to migrate to C++ over the next few years, and so developers are encouraged to add new features in C++. The use of Modelica language was originally proposed as a possibility will not be necessary, in part, due to the reduced complexity of implementing a performance-curve-based model.

3 Progress

3.1.1 Field study

A field study of several hybrid systems has progressed in cooperation with a range of partners including Southern California Edison, Pacific Gas & Electric, California Energy Commission, and California Institute for Energy & Environment. We have installed test equipment to service several commercial end users including: University of California, US Navy, WalMart, Target, Simon Property Group, Starwood Property Group, City of Temecula, and two independently owned restaurants.

Table 1 summarizes the technologies, locations, and building types where field monitoring efforts are currently underway. The Western Cooling Challenge program is currently advancing a number of other installations which will be monitored in 2014. The installed systems listed in Table 1 will be collecting data that will be available to support the development and validation of our EnergyPlus module. Given the appropriate performance curves the configurable model will be capable of representing all of the listed system types, however the detailed regression curves required to specify the system performance will only be generated for the Coolerado H80 model within the scope of this project.

Technology	*Location*	*Principal Activity*	*Data Period*
Coolerado H80	Davis	Small Office	July 2012 -
Coolerado H80	Ridgecrest	Small Office	July 2012 -
DualCool (retrofit) *x4*	Palmdale	Large Retail	August 2012 -
Trane Voyager DC *x2*	Ontario	Mall	July 2013 -
Trane Voyager DC	Ontario	Restaurant	July 2013 -
Trane Voyager DC	Fairfield	Mall	June 2013 -
Coolerado M50 (retrofit) *x3*	Bakersfield	Large Retail	June 2013 -
Seeley ClimateWizard *x3*	Bakersfield	Large Retail	June 2013 -

Munters Oasis	Temecula	Large Office	July 2012 -

Recent analysis efforts for these datasets has focused on developing clear regression models that describe sensible cooling capacity and energy efficiency as a function of operating mode and environmental conditions. Current work is focused on 2012 data for the Coolerado H80 installed at UC Davis, and at NAWS China Lake. Observation so far indicates that equipment performance can be described very accurately by linear regression in each operating mode, and that biquadratic regression models used elsewhere in Energy Plus may not afford improved model accuracy. However, the data analyzed so far only covers a limited range of environmental conditions, so alternative regression forms are under consideration. We will quantify how well each alternative regression method fits with measured data in order to make a final determination about the most appropriate format. Many of the equipment types include variable speed fans, in these cases, supply airflow or compressor speed must be included as independent variables used to describe the system cooling capacity. Equipment performance, cooling capacity and power consumption was found to be significantly impacted by the fraction of outside air utilized at any particular time. Therefore this factor was also included as an independent variable in our regression analysis.

Figure 1 plots sensible cooling capacity for the Coolerado H80 as a function of outside air temperature, and operation mode. The modes of operation do not always translate to physical discrete modes of operation, but were based on both quantized ranges of observed air-flow percentage of maxium, and whether or not the coiling coil is used (indicated by stage one (S1) and stage two (S2)). This visualization demonstrates the broad range of part load capacity operation for the equipment, and that performance is most significantly related to mode, airflow, and environmental conditions. It is most notable that cooling capacity for the system varies so significantly compared to standard constant volume single speed vapor compression equipment which can be characterized quite accurately by a linear regression as a function of outside air temperature alone.

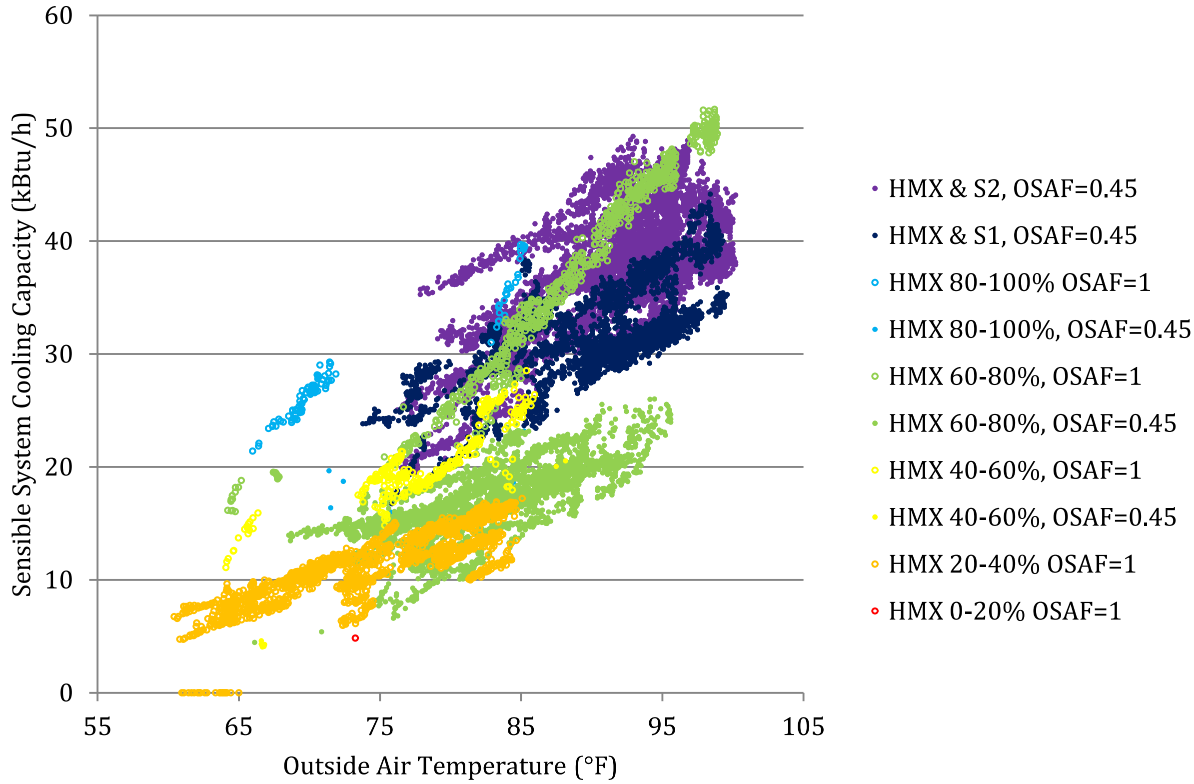

Figure 1: Sensible System Cooling Capacity as a function of Outside Air Temperature, Operating Mode, & Outside Air Fraction (OSAF)

Data from the Coolerado H80 at NAWS China Lake for August 2012 was used to test an initial approach to model formulation. The following formula was used as the structure to model sensible cooling capacity for each mode of operation.

$$Q_{Sens,Sys} = \beta_0 + \beta_1 T_{db,OSA} + \beta_2\, \omega_{OSA} + \beta_3 T_{db,RA} + \beta_4\, \omega_{RA} + \beta_5 V_{SA}$$

In this case, since the Coolerado H80 predominately operates with two distinct levels of outside air, outside air fraction was used to characterize separate operating modes, similar to levels of compressor operation. This approach appears to work well for the Coolerado H80, but we presume that it will be less appropriate for equipment that operates with a continuously varying outside air fraction, or even for modeling equipment that might be applied in various scenarios with different ventilation requirements. For these other systems, we anticipate outside air fraction or some derivative factor will be used as an independent variable to predict system performance.

Current results of the linear regression of this data are recorded in Table 2. A multivariable linear model for capacity in each mode achieves very good fit (R^2=92%-99%). It should be noted that the regressions were developed for only two weeks' worth of operating data and that the range of conditions encountered was therefore limited. While the regression achieves very good fit to the data, it is no guarantee for the predictive value of these regression coefficients across all possible operating conditions.

Table 1: Coefficients and R^2 Fit of Regression Models for Each Mode

MODE	OSAF	Variable Coefficient						Model Fit
		β_0	β_1	β_2	β_3	β_4	β_5	Adj. R^2
HMX only	100%	-4.39E+01	7.28E-01	-4.72E+02	6.41E-02	-2.07E+03	1.69E-02	0.977
HMX only	45%	-2.55E+01	4.13E-01	-3.73E+02	1.59E-01	-1.26E+03	7.39E-03	0.925
HMX & S1	100%	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HMX & S1	45%	-3.81E+01	4.57E-01	-3.67E+02	3.55E-01	-2.35E+03	1.93E-02	0.986
HMX & S2	100%	N/A	N/A	N/A	N/A	N/A	N/A	N/A
HMX & S2	45%	-5.39E+01	4.18E-01	-5.10E+01	5.60E-01	-3.08E+03	2.67E-02	0.984

Figure 2 charts sensible system cooling capacity for operation in HMX only mode with 45% outside air. This chart illustrates the strongly linear quality of for capacity in three dimensions as a function of airflow and outside air temperature. At low airflow and low outside air conditions the system cooling capacity is small, while for high outside air temperatures and at high supply air flow rates sensible system cooling capacity may be as high as 50 *kbtuh.*

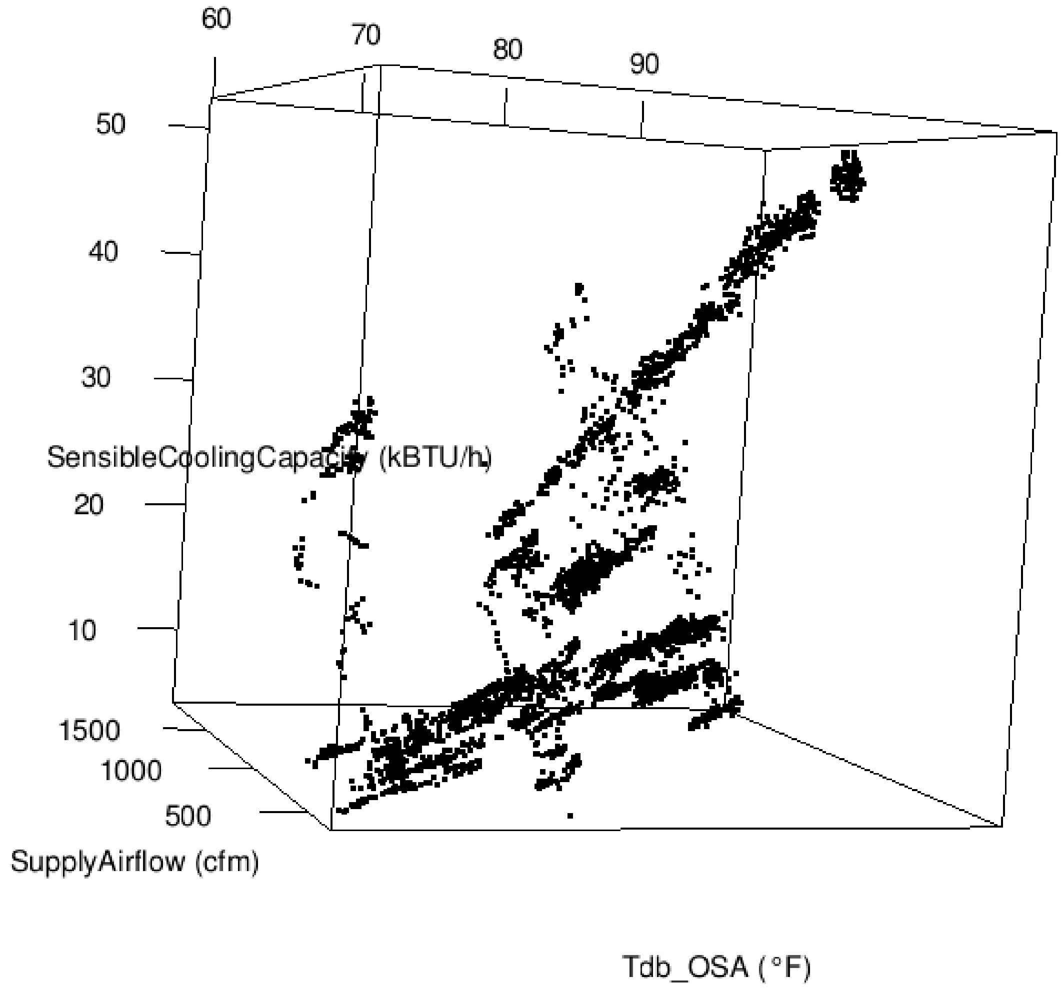

Figure 2: Sensible System Cooling Capacity for HMX 45% OSAF as a function of Outside Air Temperature, and Supply Airflow Rate

Further, the relatedness of variables was considered in order assess what factors might be dropped from the regression model while still achieving good fit. Figure 3 plots one such analysis of factor relatedness using a pairs plot developed from data for operation in HMX only mode with 45% OSAF. Each plot in the figure charts every individual record in the data set. A different pair of factors is used in each plot to illustrate the correlation between independent variables. The vertical axis of each plot is defined by the title located to the left of each corresponding row. The horizontal axis of each plot is defined by the title located at the bottom of each corresponding column. For example, the plot in the first row of the second column charts outside air dry bulb temperature as a function of return air dry bulb temperature. If two independent variables are tightly correlated, a trend will develop in the plot. If the two variables are truly independent from one another the plot should result in a cloud of random points. This analysis indicates when there is some physical relationship between variables, and offers an opportunity to reduce the number of regression factors used as inputs for a model. For example, there is a very strong correlation between outside air absolute humidity and return air absolute humidity. Including both of these as variables in a linear regression model for the data analyzed is redundant because the value of these characteristics remain proportional to one another throughout the period of study. Indeed, dropping either outside air humidity or return air humidity from the regression model has almost no impact on the R^2 value. For the time being, however, we believe it is important to maintain both of these variables as inputs since the physical operation of other technologies should cause indoor humidity to behave more independent from outside humidity. This would certainly occur when a system provides active humidity control, or when direct evaporative cooling is utilized. In such scenarios, physical performance will hinge on the behavior of each factor independently. We believe this will be especially relevant for modeling hybrid air conditioning systems such as the Munters Oasis which regularly switches from a direct evaporative cooling mode that adds humidity to a vapor compression mode that provides latent cooling. *Tdb OSA* is the outdoor supply air dry bulb temperature, Tdb RA is the return air dry bulb temperature, w OSA is the outdoor air absolute humidity, w RA is the return air absolute humidity.

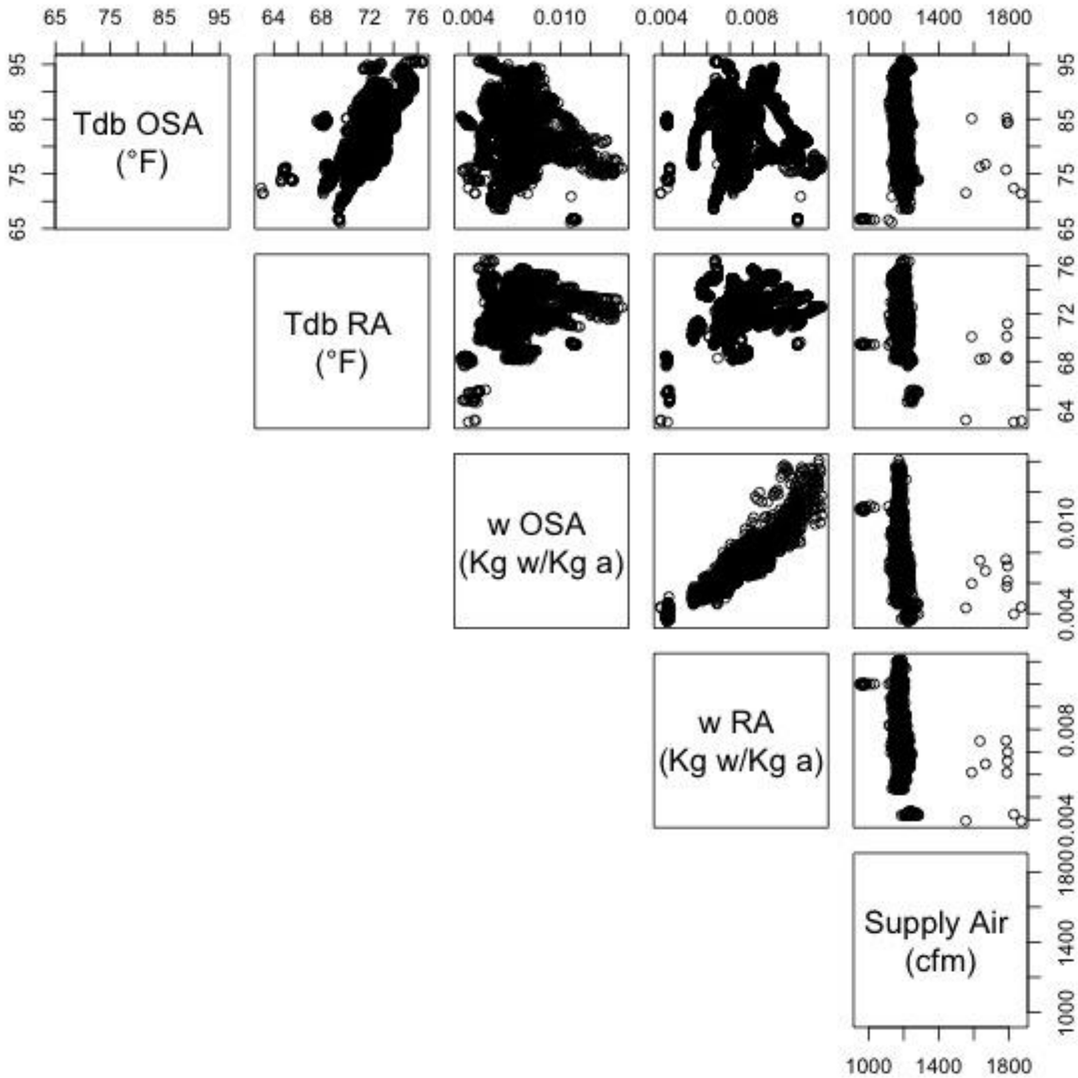

Figure 3: Pairs chart for all independent parameters in the linear regression model

3.1.2 Model implementation

To date, we have setup an EnergyPlus development build and begun the initial stages of new model framework development using the DX cooling coil model as a reference starting point.

Each significant addition to EnergyPlus must first undergo a "new feature proposal" procedure. Firstly, a new feature proposal must be submitted to the advisory board. The proposed feature is reviewed, and must be defended in front of a panel of technical experts. The deadline for submission of new features for the next October release of EnergyPlus is July 10th 2013, we will be submitting the proposed addition of the new Hybrid Indirect Evaporative cooling model. This new feature proposal is expected to be a joint effort with Brent Griffith from NREL, who is also interested in adding a similar model.

3.1.3 Overall task progress

Table 1 gives a breakdown of the tasks and subtasks, with corresponding percentage complete.

Table 1 Project task break down

Tasks	*Sub task*	*Principle Provider*	*Percent complete*
Assess the current state of advanced evaporative systems research and products.	Review of current research systems and published performance data.	LBNL + WCEC	90%
	Survey of manufacturers and developers of hybrid evaporative systems	LBNL + WCEC	90%
	Build limited database of operational modes and published system performance.	LBNL + WCEC	90%
Field and laboratory studies of system performance	Collation and analysis of measured performance data	WCEC	60%
	Explore alternative conceptual approaches to formulation of a model that would be flexible enough to accommodate simulation of a variety of systems	WCEC	50%
	Collect additional field data to broaden the range for which regression models may be appropriately are applied	WCEC	5%
	Develop performance curves specifically for the Coolerado H80 system	WCEC	20%
Gain project input from stakeholders	Identify, contact and engage relevant stakeholders	LBNL	5%
Develop and test an EnergyPlus Indirect evaporative model	Write and submit EnergyPlus new feature proposal	LBNL	10%
	Develop generic hybrid indirect evaporative model framework in EnergyPlus	LBNL	5%
	Validate the EnergyPlus Coolerado model using field data from a Coolerado unit.	LBNL	0%
Write final report		LBNL + WCEC	0%

4 Discussion and conclusion

We have made significant progress in the collection of field data, and the analysis of that data. We currently have five different types (a total of seventeen), Hybrid Indirect evaporative cooling systems, installed in various locations throughout California. Installed systems include the Coolerado H80, Trane's Voyager DC, Munters' Oasis, Munters' EPX 5000, and Seeley's ClimateWizard.

Preliminary regression analysis of the data is underway and we are exploring various combinations of input regression factors used to build our proposed model. Progress has been made towards the development of the configurable EnergyPlus model framework; a detailed implementation plan has now been established and the process of submitting an EnergyPlus new feature proposal is underway.

Finances for the project are healthy given the balance of our objectives met and still to be completed, with a significant proportion of the original budget (with the exception of the lien for WCEC UC Davis) is still available to be spent this year. We plan to significantly increase the LBNL effort over the next few months and are on schedule for our next major deliverable in November.

5 Financial Support

The research reported here was supported by the California Energy Commission Public Interest Energy Research Program, Energy-Related Environmental Research Program, award number 500-10-052.

6 Appendix

6.1 Estimates of potential savings

Future energy savings from adoption of hybrid evaporative cooling are dependent on a number of factors, including how well these systems perform in practice, the performance of the conventional systems they replace, and how broadly these systems are adopted in the market. Estimates of projected annual energy saving benefits are based on input data detailed in **Error! Reference source not found.** below. Estimates of each of these factors include a significant degree of uncertainty. Field test data from our evaporative cooling units installed in buildings throughout California will provide system performance data that will lower the uncertainty in our estimates. Until these data are available, conservative estimates of hybrid system performance were used. Currently installed HVAC Rooftop Units (RTUs), use an estimated 2E+10 kWh per year of electricity, approximately 5% of these units are replaced each year. In addition, the total number of RTU's in use was estimated to be growing at 1.4% each year. Given an assumed market penetration of 35% of any newly installed RTUs, projected energy savings (reductions in energy use compared to baseline conventional RTUs) in the first year are estimated to be 1.45E+08 kWh. Each successive year that obsolete RTU are replaced, the number of hybrid systems in use is expected to increase, leading to increased energy savings over time (annual savings increasing approximately 1.5E+8 kWh each year following their introduction). After a period of 20 years, (the assumed typical lifespan of a conventional RTUs), savings are projected to have increased to 2.99E+09 kWh per year.

Table 2 Calculation inputs

Input	Value	Detail
Installed cooling tonnage (ICT)	1.08E+07 tons	Equals the total commercial floor area (A=5E+09) (CEUS 2006 (CEC-400-2006-005, March 2006)), divide by, the average tonnage per square foot that are serviced by RTUs (325 ft2 per ton, CEUS 2006 multiplied by fraction of commercial area serviced by RTUs 70%, (CEUS 2006) ICT=A/(325*0.7)
Cooling Load Factor (CLF)	20%	CLF for RTU's currently in service, (CEUS 2006)
Conventional RTU Energy Efficiency Ratio (EER)	10	EER for RTU's currently in service, (Title 24)
Installed RTU energy use	2.26E+10 kWh per year	Equals the ICT, multiplied by the CLF, multiplied by 12 (months in a year), divided by the sum of the EER and 8760 (the number of hours in a year) RTU_Energy=ICT*CLF*12/(EER*8760)
Conventional RTU life-span	20 years	The typical (conservative estimate) lifespan of conventional RTU's currently in use. Estimate based on Mark Modera's industry experience.
Hybrid system efficiency gain	40%	Conservative figure of efficiency improvement possible with hybrid systems compared to conventional RTU's. Based on minimum performance specifications for the Western Cooling Challenge (http://wcec.ucdavis.edu/programs/western-cooling-challenge/)
New RTU installs	1.4%	Annual increase in RTU tonnage. Calculated by multiplying annual percentage growth in newly constructed commercial buildings (2%, a broadly used rule of thumb) area by the fraction serviced by RTU's (70%, derived from CEUS 2006 source data)
Hybrid system fraction of new RTU installations	35%	Estimated uptake of Hybrid systems based on exceeding California's energy efficiency strategic plan (15% of HVAC unit sales shall be optimized for climate appropriate technologies by 2015) by at least a factor of two
Annual energy savings	≈1.5E+8 kWh increase in savings each year	Each year 5% (1/20 year life span) of the total installed RTU tonnage is replaced, in addition to the 1.4% of new installs, totaling 6.4%. 35% of those newly installed systems are estimated will be hybrid systems with a 40% efficiency improvement.