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PREFACE

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TITLE 24 CREDIT FOR EFFICIENT EVAPORATIVE COOLING

- *Title 24 Credit for Efficient Evaporative Cooling,* is the final report for the project of the same name (contract number 500-10-052, conducted by the Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Energy-Related Environmental Research Program.

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ABSTRACT

The research objective of this study was to develop a new model for the EnergyPlus building energy simulation tool that can be used to simulate a new generation of high efficiency air conditioners that combine different cooling technologies in order to leverage the strengths of each. These "hybrid" cooling systems have the potential to use substantially less energy than conventional air conditioning systems. However, there are currently no modeling tools or methods to accurately project energy savings for these systems. Accordingly, there is not currently a suitable Title-24 compliance pathway for hybrid air conditioning systems. The development of this model should provide the basis to support simulations for Title 24, or for the evaluation of programs and efforts that support the California Energy Efficiency Strategic Plan goal to advance the market transfer of "climate appropriate" cooling strategies.

The research team used field data from multiple hybrid cooling systems throughout California to inform the development of this model and to validate its functionality. As an example, to test application of the new model, the research team used field data from a Coolerado H80 to develop a set of representative performance curves and model parameters that were used as the configuration inputs for simulation within EnergyPlus. With sufficient system performance data, users of this model will be able to simulate the operation of alternative hybrid cooling systems that can not presently be modeled in EnergyPlus.

The research team demonstrated that the model functions correctly in EnergyPlus and compared the modeled system performance against measured system performance from field data. Results showed that the simulation results compared acceptably well with field data. The team is currently working with industry partners to configure model inputs for additional hybrid air conditioner systems and to validate that the modeling framework appropriately accommodates a variety of hybrid system types.

Keywords: low energy cooling, hybrid cooling, indirect evaporative, Coolerado, EnergyPlus, Title-24

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EXECUTIVE SUMMARY

Introduction

The commercial buildings sector has an important role to play in helping to reduce California's energy use and associated carbon footprint. A new generation of high efficiency cooling systems has the potential to transform the commercial HVAC industry, and to result in dramatic gains in efficiency. However there are currently no building simulation tools capable of modeling these new systems. Consequently there is not a Title-24 compliance pathway to give appropriate credit to the variety of indirect evaporative and hybrid system architectures. Further, potential customers, engineers, and utility programs are not currently able to project the value of these systems with confidence.

Project Purpose

This project seeks to develop a flexible and re-configurable modeling framework for EnergyPlus that will allow EnergyPlus users to simulate performance of these new systems in a straightforward way.

Project Results

A flexible model framework has been developed and tested to function correctly in EnergyPlus. The model developed in the project performed well when compared to observations from various field trials. The model is now undergoing beta testing with early adopters and will be released to the public before the end of December 2014.

Project Benefits

The anticipated benefits of the project are that this model will facilitate broader adoption of this technology and as a result lead to significant state-wide energy savings. Widespread adoption could reduce California electricity consumption by up to 300 GWh annually.

The model framework developed offers a standard and flexible tool that can both accommodate simulation of a wide array of hybrid systems and enable a Title-24 compliance pathway for hybrid air conditioning systems. Additionally, in direct support of the California Energy Efficiency Strategic Plan, the model offers an opportunity for California utilities and regulators to accurately assess the extended energy and demand benefits offered by these energy efficiency measures, in different applications and climate zones, when adopted at broad scale.

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CHAPTER 1: Introduction

In California, commercial buildings account for a significant proportion of the state's electricity use; of that energy a significant proportion, almost 30%, is used for cooling and ventilating buildings. National surveys have shown that energy use in the commercial building sector is growing faster than transportation, industry or any other building sector (CEC 2006). In order to meet California's commitments to reduce carbon emissions by 25% by 2020 and 80% by 2050 (AB32 2006), newly built buildings will need to dramatically reduce HVAC energy consumption and a significant proportion of the existing commercial building stock will need to be retrofitted to adopt low carbon HVAC strategies.

A new generation of energy efficient cooling systems is emerging that has the potential to dramatically lower cooling energy use in California buildings. This new category, termed "hybrid" cooling systems, integrates the operation of multiple cooling components in order to leverage the strengths of different cooling strategies at different times, or to enhance the capacity and efficiency of vapor compression cooling. The hybrid systems addressed in this study utilize indirect evaporative cooling in combination with vapor compression cooling. Indirect evaporative is used as the primary cooling system and the secondary vapor compression system is used only to provide supplemental cooling during periods of peak cooling demand.

Several HVAC system manufacturers, including Coolerado, Trane, Munters and Seeley, are actively marketing (or piloting) systems that have potential to capture a significant share in the market for cooling in commercial buildings. The California Energy Efficiency Strategic Plan sets a goal to advance quick market introduction of 'climate appropriate' commercial air conditioning equipment (such as these hybrid air conditioners), targeting 15% share of new sales by 2015.

In 2008, the University of California, Davis introduced the Western Cooling Challenge, a publicly funded program that has worked with a variety of manufacturers to advance the development, commercialization, and market introduction of cooling equipment designed to capture substantial energy and demand savings in California climates. The challenge sets a target for 40% demand reduction compared to conventional rooftop air conditioners, a level of performance that has now been demonstrated by a number of manufacturers. The Challenge has laboratory tested a number of advanced cooling systems to establish the clear savings opportunity, and has piloted more than 30 systems in the field to demonstrate real world performance opportunities, system integration strategies, and persistent equipment reliability.

The strategies introduced by manufacturers in this category are diverse. Some systems are packaged rooftop air conditioners (e.g. Coolerado H80) that can be used as direct replacement for conventional rooftop units. Other systems function as Dedicated Outside Air Supply (DOAS) air handlers, or as standalone indirect evaporative precooler, that can be installed to operate in sequence with separate vapor compression equipment.

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 exchanger (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. Savings are expected to increase to a further 1.5E+08 kWh annually until they reach 3.0E+09 kWh savings once peak market penetration is realized. A breakdown of potential energy saving is available in Appendix A.

California Building Energy Efficiency Standards (CEC 2013a) allow compliance either by adherence to prescriptive requirements, or via a modeled performance method that allows designers and engineers some flexibility in design by allowing for trade off between efficiency measures while maintaining an overall energy budget. One key barrier to broader adoption of hybrid air conditioners in California is that there is not currently an accurate methodology within Title-24 Alternative Calculation Method to account for the energy savings from these systems, compared to conventional air conditioners. In addition, utility incentive programs that intend to foster and encourage the introduction of new efficient technologies currently have no method with which to estimate the annual energy savings of this category of systems. 2013 Title-24 ACM (CEC 2013b) does include a compliance pathway for hybrid air conditioners that "meet efficiency and water use requirements of the Western Cooling Challenge"; however, the method does not fully capture performance of these complex and varied systems. The EnergyPlus modeling tool developed here focuses on advancing a more thorough method for simulation of these systems that could be incorporated into future versions of Title-24 ACM.

Other research bodies are currently pursuing related modeling efforts that could accommodate performance modeling of hybrid air conditioners, including NREL, which has been developing a similar approach using Open Studio and EnergyPlus for the Technology Performance Exchange (NREL 2014).

The goal of this task is therefore 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.

1.1 Structure of the report

Chapter 2 of this report outlines the methods used to develop the flexible model, Chapter 3 gives the outcome of test performed on the model, Chapter 4 provides discussion, and Chapter 5 a conclusion. Appendix A provides estimates of potential statewide energy saving; Appendix B is an engineering reference guide that explores the numerical methods in more detail; Appendix C provides a model user guide; Appendix D gives example tables useful to engineers wishing to develop their own system specific models using the flexible EnergyPlus model; Appendix E gives tables related to the Coolerado H80 model developed as part of this work.

CHAPTER 2: Method

2.1 Method summary

The research team developed the new flexible model in three parts. Firstly, field data was collected from several hybrid evaporative cooling systems, installed throughout California. This enabled characterization of the functional and operational behavior of the various systems in real world settings. The team used the measured performance data from multiple installations of the Coolerado H80 to develop an empirical model of the performance for each major system component. The performance of each individual component is dependent on fewer variables than the H80 as a whole, thus the field data yields a more complete map of the inputs for each component than it does for the entire system. The team developed individual models for the indirect evaporative cooler and stage 1 and 2 of the direct expansion coils. Stage 1 and stage 2 are levels of performance of the same direct expansion coil. Since the components operate serially, the output of the one component can be used as the inputs to the next component. The team used these models to develop a partially synthetic set of performance data that covered the complete range of operating and environmental conditions the system could be required to operate in. The team then used this partially synthetic data set to develop performance curves that describe how the hybrid system will operate as a whole under a given set of conditions.

Secondly, the team developed a modeling framework (a model that does not represent any specific system but can be tailored to meet the user's requirements) that is flexible enough to allow users with sufficient system performance data to model any currently anticipated hybrid cooling systems within the EnergyPlus software. For the rest of this document, this modeling framework is referred to as the Hybrid-Black-Box model (HBBM).

Finally, the team configured the HBBM model to represent the Coolerado H80 system, and then performed a series of validation exercises to assess the performance of both the HBBM itself and the Coolerado H80 model represented within it.

2.2 Field trial method

In cooperation with and the support of the team's industry partners, including Southern California Edison, Pacific Gas & Electric, California Energy Commission, and California Institute for Energy & Environment, the research team lead by the WCEC have performed field trials of multiple hybrid cooling systems. Systems include the Coolerado H80, Coolerado M50, Integrated Comfort's DualCool (on Trane Voyager, and Lennox Strategos), Munters' Oasis, Munters' EPX 5000, and Seeley's ClimateWizard. These systems have been installed in a mix of office, retail and food service buildings, in various locations across California. Installation sites include the University of California, US Navy, Wal-Mart, 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 were performed. In addition to these field trials, the Western Cooling Challenge program is currently advancing a number of other installations which will be monitored throughout 2014-2015.

Table 1 Locations and start date for field trials

Technology	Location	Principal Activity	Data Period
Coolerado H80	Davis	Small Office	July 2012 –TD*
Coolerado H80	Ridgecrest	Small Office	July 2012 - TD
DualCool (retrofit) *x4*	Palmdale	Large Retail	August 2012 - TD
DualCool (Trane Voyager) *x2*	Ontario	Mall	July 2013 - TD
DualCool (Trane Voyager)	Ontario	Restaurant	July 2013 - TD
DualCool (Trane Voyager)	Fairfield	Mall	June 2013 - TD
Coolerado M50 *x3*	Bakersfield	Large Retail	June 2013 - TD
Seeley ClimateWizard *x3*	Bakersfield	Large Retail	June 2013 - TD
Munters Oasis	Temecula	Large Office	July 2012 - TD
Munters EPX 5000	San Ramon	Grocery	August 2014 - TD
Coolerado C60	Cudahy	Data Center	July 2014 - TD
Seeley ClimateWizard	Placentia	Data Center	July 2014 - TD

*TD- To date, data was still being collected.

Each of these pilot field evaluations have focused explicitly on mapping real world equipment performance in all operating modes over the course of time. The studies measure energy and mass flow characteristics for all inputs and outputs from the system, including temperature and humidity of each air node, differential static pressure, refrigerant temperature and pressure, air flow rate, water flow rate, electric power consumption, and other operating characteristics such as damper positions and fan speeds. These measurements provide clarity about dynamic system performance, real world behavior, systems integration requirements, the impact of control schemes, equipment longevity, interaction with external systems, and ongoing maintenance requirements.

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, installers, facility owners and utilities 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. Outside Air Temperature
2. Outside Air Humidity
3. Return Air Temperature
4. Return Air Humidity
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 electrical power. Furthermore, these field studies collect information about ancillary variables that help to describe system operation and response. The operational behavior for the 8 different system types was used to inform the development of the HBBM.

How observations from field trials guided model development:

The range of pilot field evaluations conducted by WCEC resulted in a wide array of lessons learned. Most importantly, it should be noted that there are many types of hybrid rooftop air conditioners that use some form of indirect evaporative cooling together with vapor compression cooling. There are many types of indirect evaporative heat exchangers and many approaches to air handler architecture, and to control strategy. Most of the technologies have shown substantial energy savings, especially at peak cooling loads. The significant implication is that the performance and savings are different for every technology, and can even differ for a particular technology, according to application and climate. As the industry progresses with these solutions, tools capable of accurately projecting the value of each strategy in each application must be developed. There are opportunities for great success in terms of energy savings, but guiding the industry strategically will require sophisticated understanding of the specific opportunities and differences.

This big picture observation motivated the core strategy underlying the development of the Hybrid Black Box Model. The research team identified from the onset that the variety of approaches for indirect evaporative cooling and hybrid air conditioner system designs translates to a need to develop a flexible modeling strategy that could accommodate all technologies in this class. Moreover, a modeling tool was needed that could keep pace with the rapid evolution of product capabilities and performance characteristics in this market while maintaining some standard and comparable approach. There are many ways that each of these indirect evaporative and hybrid air conditioners could be modeled. The typical approach would be to describe performance characteristics of each sub-object in a component-by-component model designed to replicate the schematic form of a physical system. This approach typically uses a combination of empirical relationships and first-principal physical estimates to calculate system operation in each conceptual mode of operation. While this method can be accurate and descriptive, it requires a substantial amount of custom program development and validation to produce. For this reason, modeling tool capabilities lag behind product and technology evolution – often by several years.

2.2 Component-by-component empirical model for Coolerado H80

The research team developed a parameterized numerical model of the Coolerado H80 using empirical formulae to describe the performance of each component. This model was used to generate a comprehensive set of synthetic performance data by mode, which was subsequently used to generate polynomial curves for the HBBM.

The research team created the empirical model by separating performance data for the indirect evaporative cooler from data for the two stage vapor compression system, and then by developing separate second order polynomial formulae to describe the supply air temperature, supply air humidity and component power draw. These separate relations were then combined in a parameterized numerical model to estimate equipment performance for any desired scenario.

The research team used field data of the Coolerado H80, operating in an "Indirect Evaporative Only" cooling mode to develop the empirical model for the indirect evaporative heat exchanger. Mixed air conditions at the inlet of the heat exchanger, and supply airflow rate were used as the input variables for a polynomial formula to predict power draw for the fans, and air conditions at the heat exchanger outlet. The team developed these formulae using least squares regression.

The research team used field data from the Coolerado H80 with its compressor active to develop models of the vapor compression system in each stage of operation. Power draw and cooling performance for the vapor compression system were modeled as an independent component separate from the indirect evaporative heat exchanger, and separate from the system's fans. Independent curves were developed for first and second stage compressor operation. The empirical model for the indirect evaporative heat exchanger was used to process the mixed air conditions and to estimate the input conditions seen at the inlet of the evaporator coil. The curve predictions for the power draw of the indirect evaporative cooler were subtracted from the measured power draw for the entire system, in order to asses compressor power draw independently.

2.3 Development of second-order performance curves

The research team used the component-by-component model of the Coolerado H80 to generate performance data for the whole system, across a wide range of possible operating conditions. This comprehensive matrix of synthetic performance data was used as input to a least squares regression to generate the second order polynomial curves required for definition of the system in the HBBM.

It is common industry practice to describe air conditioner system performance in terms of total cooling capacity, sensible heat ratio, and electric power consumption. Given this, the model was initially constructed with an input format that conforms to familiar industry practices. However, during the development of second order curves, it was determined that the polynomial maps would provide a better data fit if they predicted supply air temperature and humidity ratio instead of total capacity and sensible heat ratio. Based on prior experience, models based on fundamental system characteristics (such as temperature and humidity) are generally more stable than models based on calculated metrics and ratios (such as capacity and sensible heat ratio), which can be highly sensitive to small and large input values.

Three curves that give the supply air temperature, the supply air humidity ratio and the unit power consumption were generated for each of the three cooling modes for the Coolerado H80 (resulting in 9 curves in total). In order to allow for user scaling of nominal equipment capacity, the curves for power describe system power draw relative to the supply air mass flow rate at reference conditions.

In Appendix B the Engineering Reference Guide provides a more comprehensive description of the form of the performance curves, the required curve input coefficients, the curve outputs, and the scaling method.

2.4 HBBM implementation

The research team developed the HBBM as a flexible shell that does not represent any specific system, but can be tailored by users with sufficient system performance data to model any currently anticipated hybrid cooling system, within EnergyPlus.

The development of the HBBM was guided by three core requirements:

1. The model must be flexible enough to accommodate performance characteristics for a wide range of system types. This feature required more than the capability to define nominal performance (EER) for different systems; it must also accommodate various operating modes and approximate control schemes appropriate for each unit. Hybrid systems commonly have different modes of operation with only certain components in the system active at any particular point in time. For example, the Coolerado H80 can operate in a mode that uses indirect evaporative cooling only, or another mode that uses indirect evaporative cooling plus multiple compressor stages. At the same time,

the primary and secondary fans in this system can operate at variable speed. Each of these modes must be characterized with distinct performance maps.

2. Model configuration for any particular system must be relatively easy for the user to define. It should not require the custom definition of multiple sub-components, nor should it require the definition of specific control sequences.
3. Any model that is produced by a user must be easily distributable to other users, and accessible in a common and comparable structure.

Based on these requirements, the team determined that it would be unrealistic to attempt to develop a first-principals model that mirrors the approach used to model the other evaporative cooling models in EnergyPlus. A first-principals model can serve as valuable and reliable tool for exploring and characterizing hybrid system operation, but any particular model it is not flexible enough to accommodate the wide variety of components and innovative system architectures that are emerging with these technologies.

Instead the team chose to develop an empirical modeling framework that can manage all of the input and output conditions for a wide variety of system types, regardless of their internal components. In order to model performance of a hybrid air conditioner, the user must define multiple empirical curves to describe the performance of each distinct mode of system operation. The mode of operation and the operating conditions (outside air fraction and supply airflow rate) in real world systems are determined by the control sequence for a specific system. In the model implementation, for any given operating scenario (outdoor conditions, zone conditions, sensible room cooling load, and ventilation requirement), the HBBM will choose the most energy efficient mode of operation that will satisfy all load and ventilation requirements for the time step. This approach should provide a framework to model any new hybrid rooftop air conditioner, as long as the certified performance maps are available or can be developed for each system mode. This model will likely not represent the performance of any system that is not controlled to minimize energy use. For example, the HBBM would not accurately predict performance for a system that is manipulated to deliver a constant supply air temperature regardless of the load.

Through consultation with manufacturing partners, the research team established that it was reasonable that manufacturers would be able and willing to publish certified performance maps for new hybrid equipment in order to support specification, design, and application of their technology. This manufacturer-specific, system-specific performance data would be made available much in the same way that many manufacturers currently publish performance data for conventional systems, design drawings, 3D models, or sample design specifications. Furthermore, manufacturers, if they chose to do so, could publish results of their own EnergyPlus simulations for a system based on the HBBM model, using certified performance maps, standard building types (as available from PNNL), and standard climates (as guided by ASHRAE and AHRI).

The approach developed mirrors some of the methods used in the current DX cooling coil model in EnergyPlus. The performance curves used for the new model have more terms than those typically used to describe a DX cooling coil. However, the basic approach is similar. The

HBBM currently does not incorporate the type of part load runtime fraction calculations that are employed for the DX cooling coil model because the physics to describe transient characteristics associated with system cycling have not been well explored.

2.5 Validation against field measurements

The research team used the performance curves developed in section 2.3 and an appropriate nominal capacity to define a model configuration for the HBBM. Then they compared model predicted sensible cooling capacity against measured cooling capacity for 300 hours worth of 1 hour averaged increment measurements from a field evaluation in Ridgecrest California. The period of data used for validation was separate from the periods of data used to train the regression models. To cancel out any disparities in performance caused by a difference in cooling demand between the simulated zone, and the cooling demand in the field study building, measured cooling capacity from each hour was used as the requested load input to the model.

2.6 Model to model validation

The research team then used the model to simulate cooling to a single zone in EnergyPlus to verify that the model selects an appropriate mode of operation for the cooling load conditions, and that cooling set points are met. High internal loads and ventilation rates were modeled based on California Title-24, using climate zone 15 weather file. To demonstrate a full range of mode transitions throughout the day this simulation addressed a day with comparatively low outdoor temperatures for climate zone 15.

The team performed a comparison of simulated HVAC energy use and average indoor temperatures, again for a single zone building model using the Coolerado H80 model and then a reference packaged air conditioning system (PAC), using the EnergyPlus object *HVACTemplate:System:PackagedVAV*. A limited set of simulations compared the performance of these two system models when operating during the summer design day. The summer design day represents the worst case cooling load conditions and is commonly used to size HVAC equipment.

CHAPTER 3: Results

3.1 Field trials

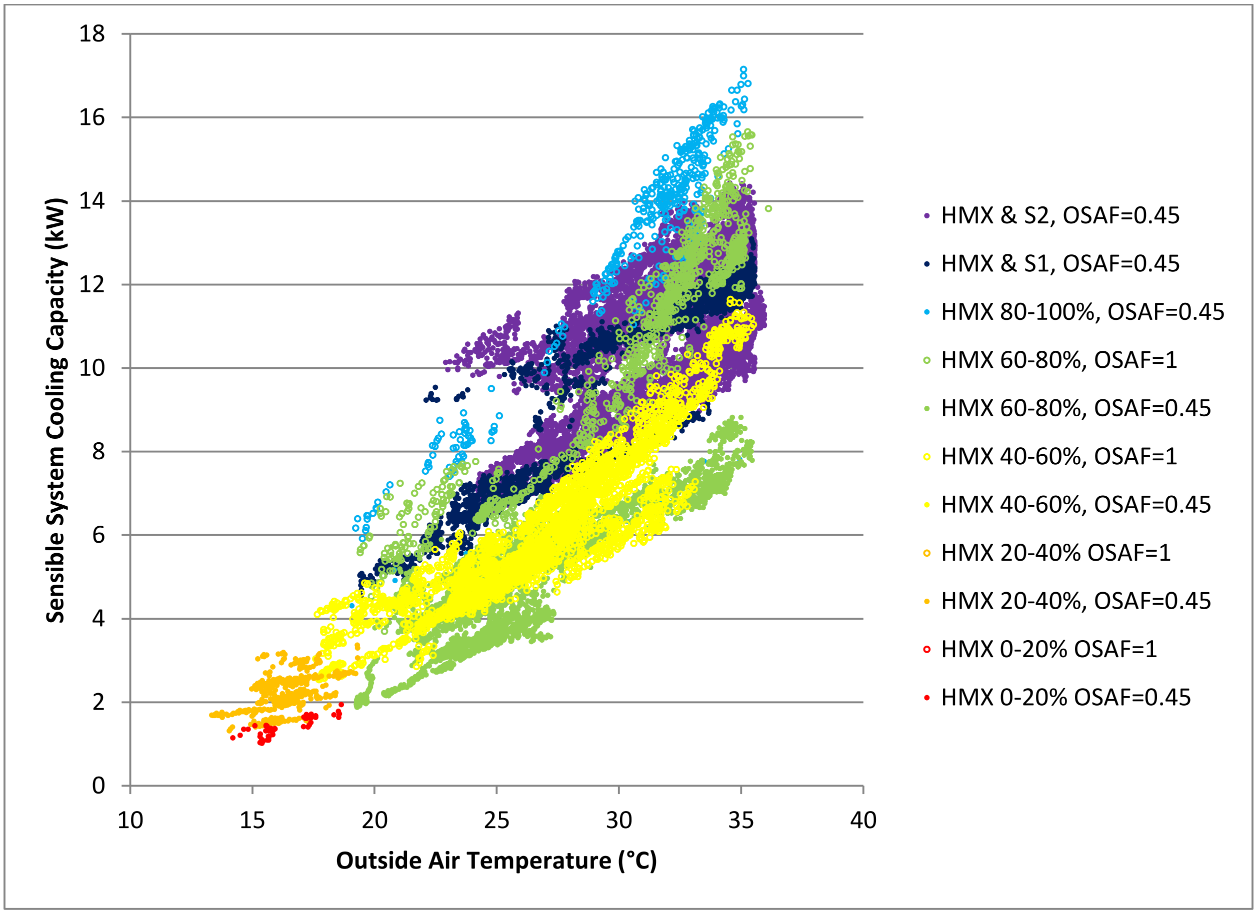
Without sophisticated modeling tools to evaluate the annual performance potential for these technologies, and since most of the evaluations were not designed to capture a full year of baseline data prior to retrofit, it has been difficult to accurately assess the annual impacts from each project. However, the studies have developed great clarity about the specific performance characteristics for each technology in order to quantify performance at particular conditions in comparison to standard equipment. For example, measurements for the DualCool system in Palmdale indicate COP improvement of 15-20% at 25-30 °C and 20-25% at 30-35 °C. A rough empirical projection of savings for the Coolerado H80 in Davis and Ridgecrest predict cooling season savings of approximately 20%. Even more promising, a recent study of the Coolerado and Climate Wizard equipment in Bakersfield has recently measured full load sensible efficiency for cooling outside air at Energy Efficiency Ratio (EER)>50; part load efficiency for the same systems was observed to exceed EER=85. The Western Cooling Challenge has also conducted several laboratory evaluations which have projected savings at peak conditions, compared to a conventional rooftop unit, that range from 20%-65%.

Generally, the potential for savings from these systems is higher for buildings that have high ventilation rates. This is partly because high ventilation rates result in high cooling loads but also because the indirect evaporative systems are most efficient at cooling hot air because it has a higher potential for evaporation. The sensible room cooling generated by indirect evaporative equipment is substantial, and generally generated at a higher efficiency than cooling from vapor compression equipment, but the difference in efficiency is smaller for room cooling applications

3.2 Coolerado field data.

Figure 1 plots sensible system cooling capacity for the Coolerado H80 as a function of outside air temperature, and operation mode. Sampled data included periods when the Coolerado was operating in one of three modes of operation: using indirect evaporative cooling only (HMX); the indirect evaporative system plus the first stage of DX cooling (HMX S1); or the indirect evaporative system plus the second stage (HMX S1). Data for the HMX-only mode was first binned over a range of fan speeds (0-20%, 20-40%, 40-60%, 60-80% and 80-100%), and by outside air fraction (OSAF). 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 significantly, compared to standard constant volume single speed vapor compression equipment. Conventional AC equipment can be characterized quite accurately by a linear regression as a function of outside air temperature alone.

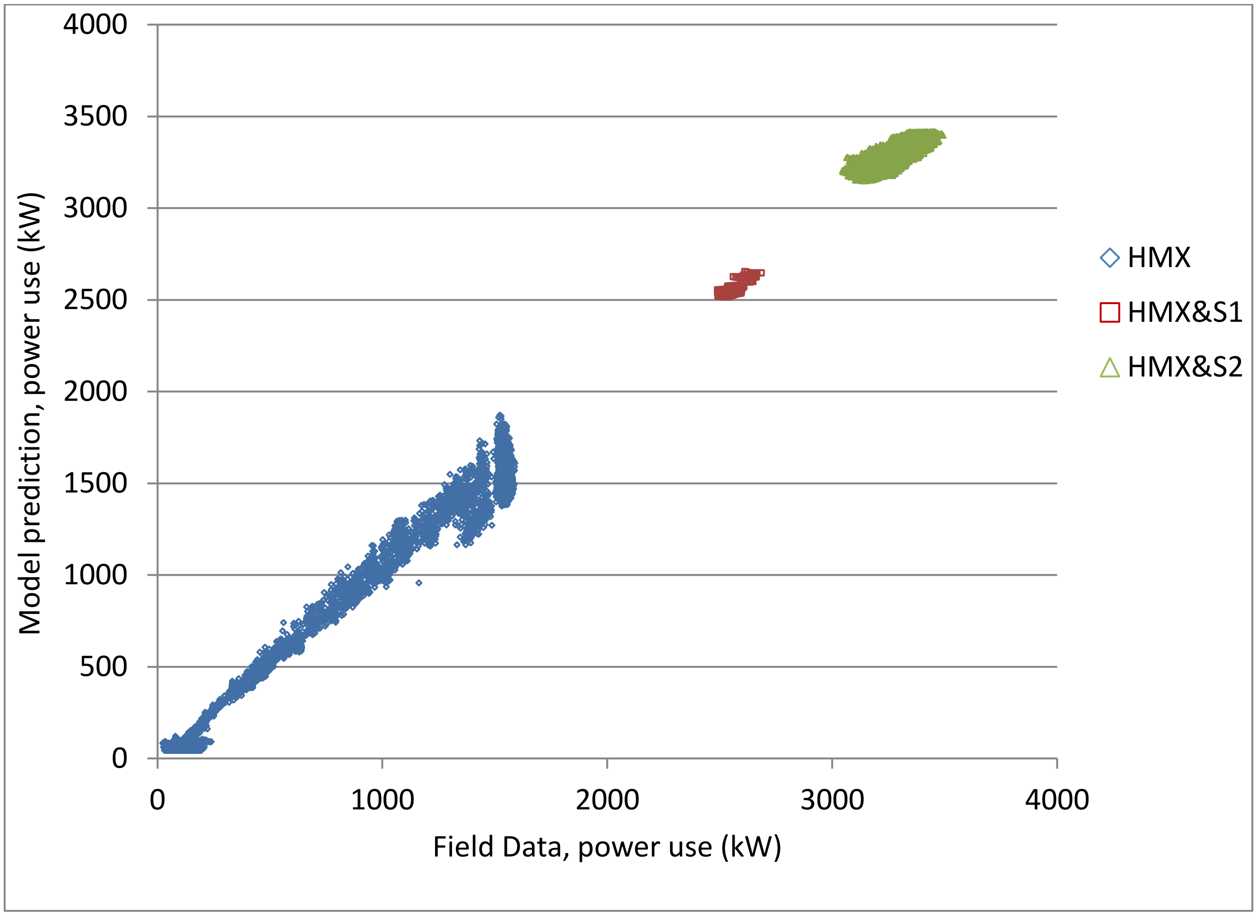
Figure 1 Sensible system cooling capacity as a function of outside air temperature, operating mode, & outside air fraction



3.3 Coolerado H80 component empirical model

Figure 2 through Figure 3 plot the results of the model fitting of the component-by-component empirical model against the recorded field data at identical input conditions. Points that lie on the line passing through the origin with a slope of 1 indicate points where the error in the model when compared to the observed system performance is low. Points that lie far from this line indicate that some system performance characteristic(s) for the real system are not accurately captured by the model.

Figure 2 Power consumption predicted by the component level model versus power consumption observed in the field



As shown in Figure 2 the component level model accurately predicts the system power consumption in all three modes.

Figure 3 Supply air temperature predicted by the component level model versus Supply air temperature observed in the field

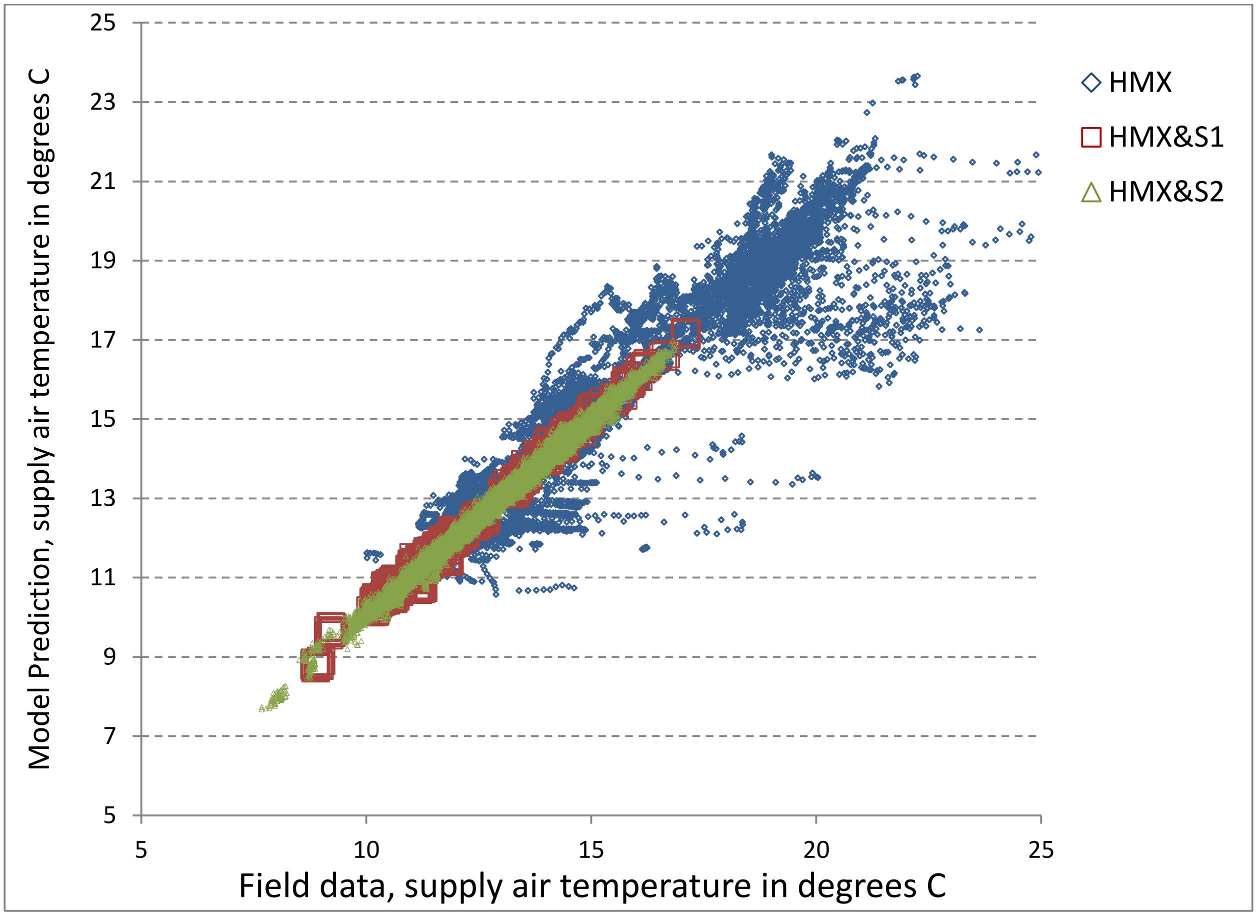


Figure 3 shows that the empirical component-by-component model predicts the supply air temperature with a high degree of accuracy in HMX&S1 and HMX&S2 operating modes. However, there is some deviation between prediction and data for operation in the "Indirect Evaporative Only" mode. This was unexpected, because the component level approach uses the output of the indirect evaporative heat exchanger as input for the model to predict the input conditions to the Stage 1 and Stage 2 compressor models. Thus, any error inherent in the HMX model should propagate through to the stage 1 and stage 2 compressor models. Further analysis found that these instances are associated with the transient temperature behavior that occurs during mode shifting events. The current version of the HBBM is not intended to capture these transient events; the performance predictions are made according to steady state operating characteristics in each mode. Fortunately, in this instance, these transient periods only account for a very small fraction of the minute-by-minute observations.

3.3.1 Error analysis

The research team performed error analysis to determine how well the component model agreed with the measured field data. This analysis was repeated for each of the three curves and three operation modes, with the results given in Table 2.

Table 2 Field data means and root mean square errors,

	Average supply air temp. (°C)	Average supply air HR (g/g)	Average power (kW)	Supply air temp. error (°C-%)	Supply air HR error (g/g-%)	Power error (kW-%)
HMX	15.5	0.0079	697	1.0-6%	0.0006-8%	62-9%
HMX&S1	11.9	0.0070	2556	0.2-2%	0.0006-9%	19-1%
HMX&S2	13.0	0.0074	3285	0.1-1%	0.0007-9%	41-1%

* HR= Humidity ratio

3.4 Coolerado second-order curves and constraints

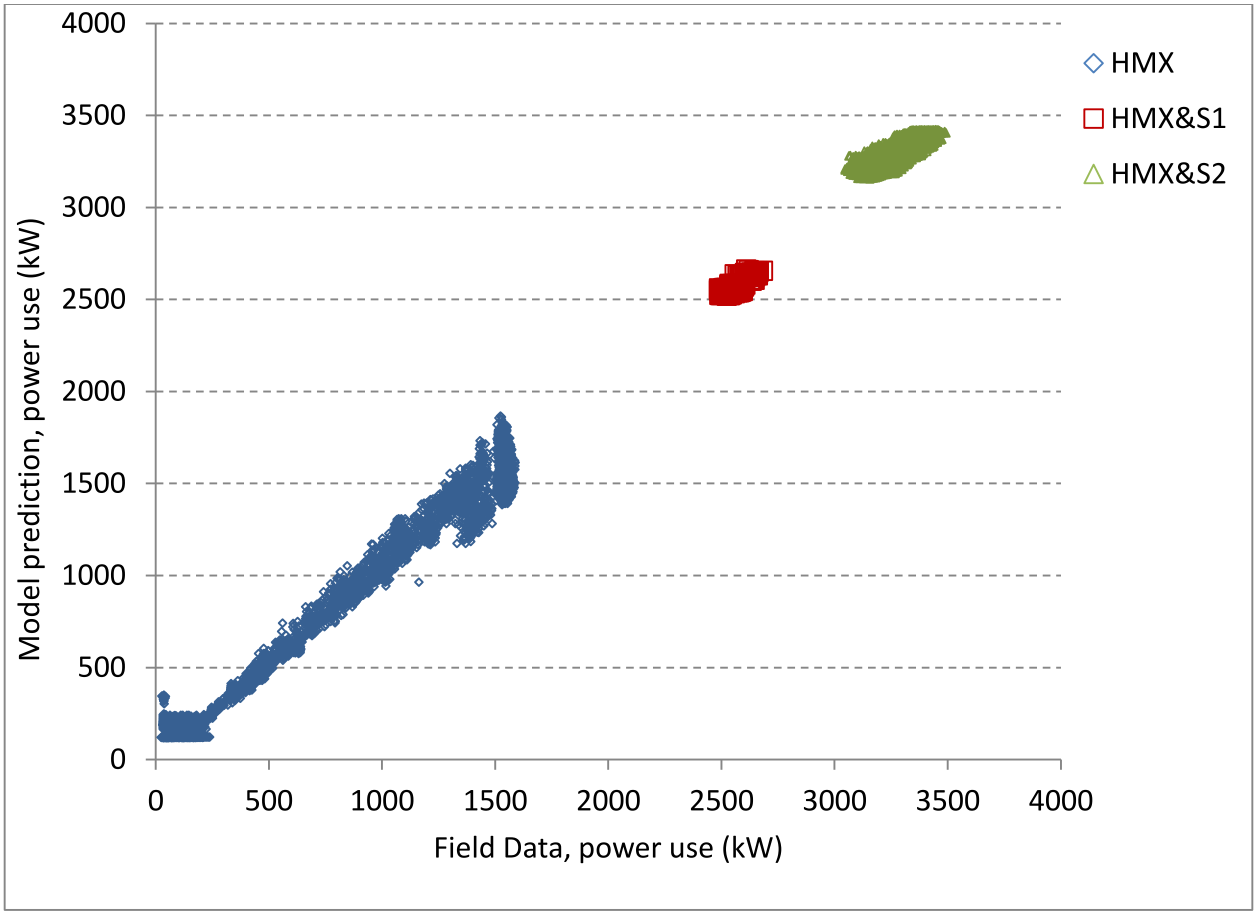
The Coolerado H80 model developed for this project is comprised of a set of second order curves, and a set of environmental and operating conditions across which the model can be applied with confidence. Appendix C User guide, provides more details on the application of these constraints. Table 6 in Appendix F gives the second order curve coefficients for the model and Table 7 and Table 8 give the operational and environmental constraints for each mode.

The second order curves developed during this process represent the performance of the H80 for three of the Coolerado's main cooling modes of operation, HMX only, HMX with single stage compressor, and finally HMX with stage 2 compressor. The Coolerado system can also operate in at least three additional modes not modeled in this work, including a ventilation only mode and two different heating modes. While definition of all possible modes of operation is important for an annual evaluation of equipment performance, demonstration of model function for the three active cooling modes is sufficient to test functionality of the HBBM.

3.5 Second-order performance curve validation

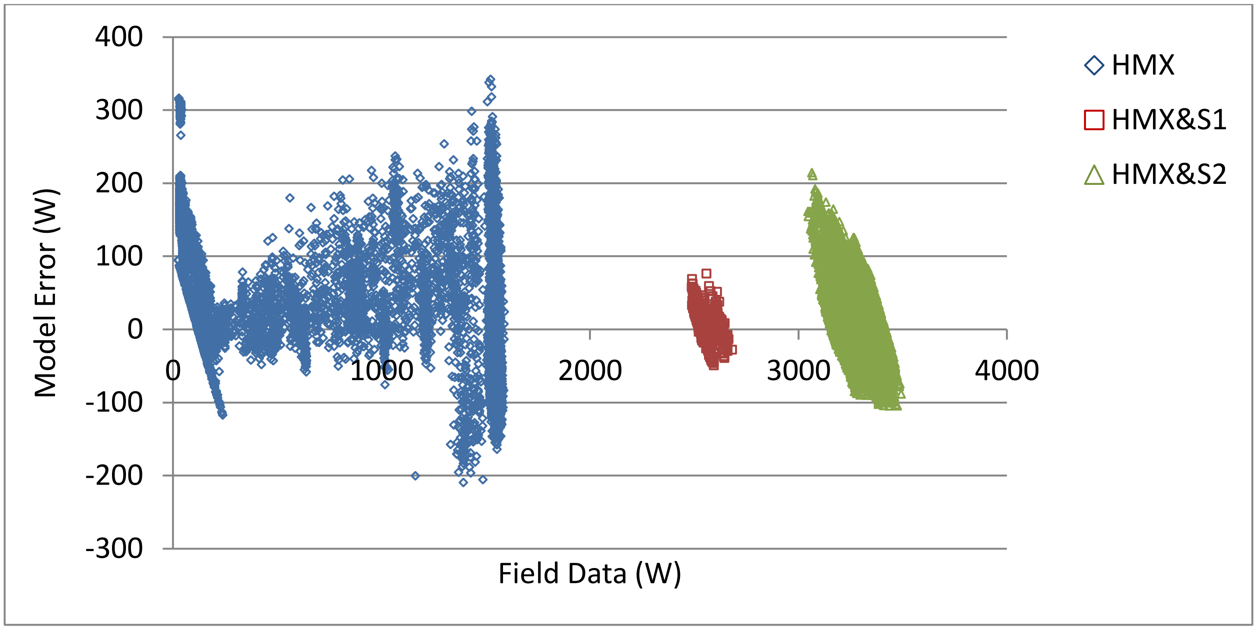
Figure 4 compares the electricity demand in each operating mode predicted by the second-order performance curves to the measured observations at the same input conditions.

Figure 4 Comparison of second order polynomial model and field data



That the modeled data and predictions generally align indicates that the model is broadly behaving as expected. A more detailed look at the difference between the modeled and measured results is presented in Figure 5. The most significant differences between modeled and measured data emerge from transient system performance associated with mode switching events. Also, initial analysis suggests that the model does not capture the effect of changes in the humidity ratio as well as would be desired. Post completion of this project further analysis is planned to improve the second order curves with a view to using the improved model in future studies.

Figure 5 Difference between second order polynomial model electricity use and field data



3.5.1 Error analysis

The research team performed error analysis to determine how well the model based on the second order curves agreed with the measured field data, with the results given in Table 3.

Table 3 Root mean square errors, and field data means

	Supply air temp. (°C)	Supply air HR (g/g)	Power (kW)	Supply air temp. error (°C-%)	Supply air HR error (g/g-%)	Power error (kW-%)
HMX	15.5	0.0079	697	1.0-6%	0.0008-10%	128-18%
HMX&S1	11.9	0.0070	2556	1.9-16%	0.0035-50%	21-1%
HMX&S2	13.0	0.0074	3285	0.6-5%	0.0017-23%	42-1%

3.6 Implementation

The HBBM makes use of EnergyPlus's native ability to interface with external models or simulation programs which implement the Functional Mockup Interface (FMI) standard version 1.0 (Nouidui 2013). FMI is an independent and nonproprietary standard to support both model exchange and co-simulation of dynamic models using a combination of XML-file, C-header files, and C-code in source or binary form (MODELISAR-Consortium, 2008-2012). A model or a simulation program which implements the FMI standard is called a Functional Mock-up Unit (FMU).

The FMU based HBBM is configured to represent a model of a hybrid cooling system using a text based configuration file. The FMU file is in essence a .zip file containing the model and any resources the model needs, including the configuration file. To run the HBBM model it must be referenced in an .idf building model definition file, along with supporting EnergyPlus objects, including the ZoneHVAC:ForcedAir:UserDefined object. A more detailed description of the EnergyPlus objects used to enable the FMU is given in the Appendix C: Input-Output reference Guide. An example of the method used, and the HBBM model, can be downloaded as a package from the project website (LBNL 2014). A more detailed description of the download model package, its contents and the methods used to develop a new model are provided in the User Guide, Appendix D.

Figure 6 provides a visual representation of the relationship between EnergyPlus the idf model file, the FMU and the model configuration file. EnergyPlus reads the idf file that references the FMU based model, this model then reads in the text based configuration file.

Figure 6 Model component description

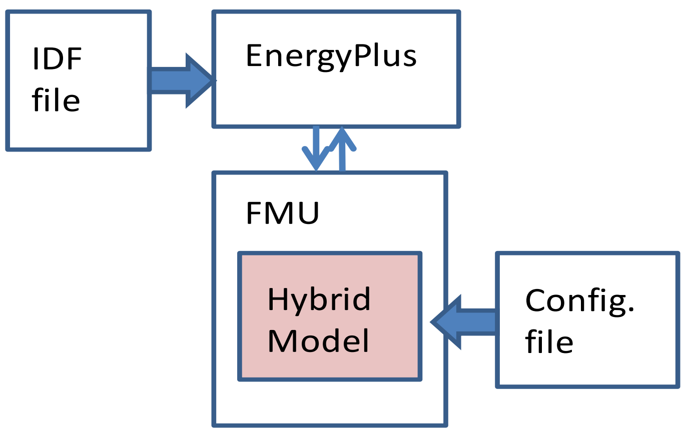
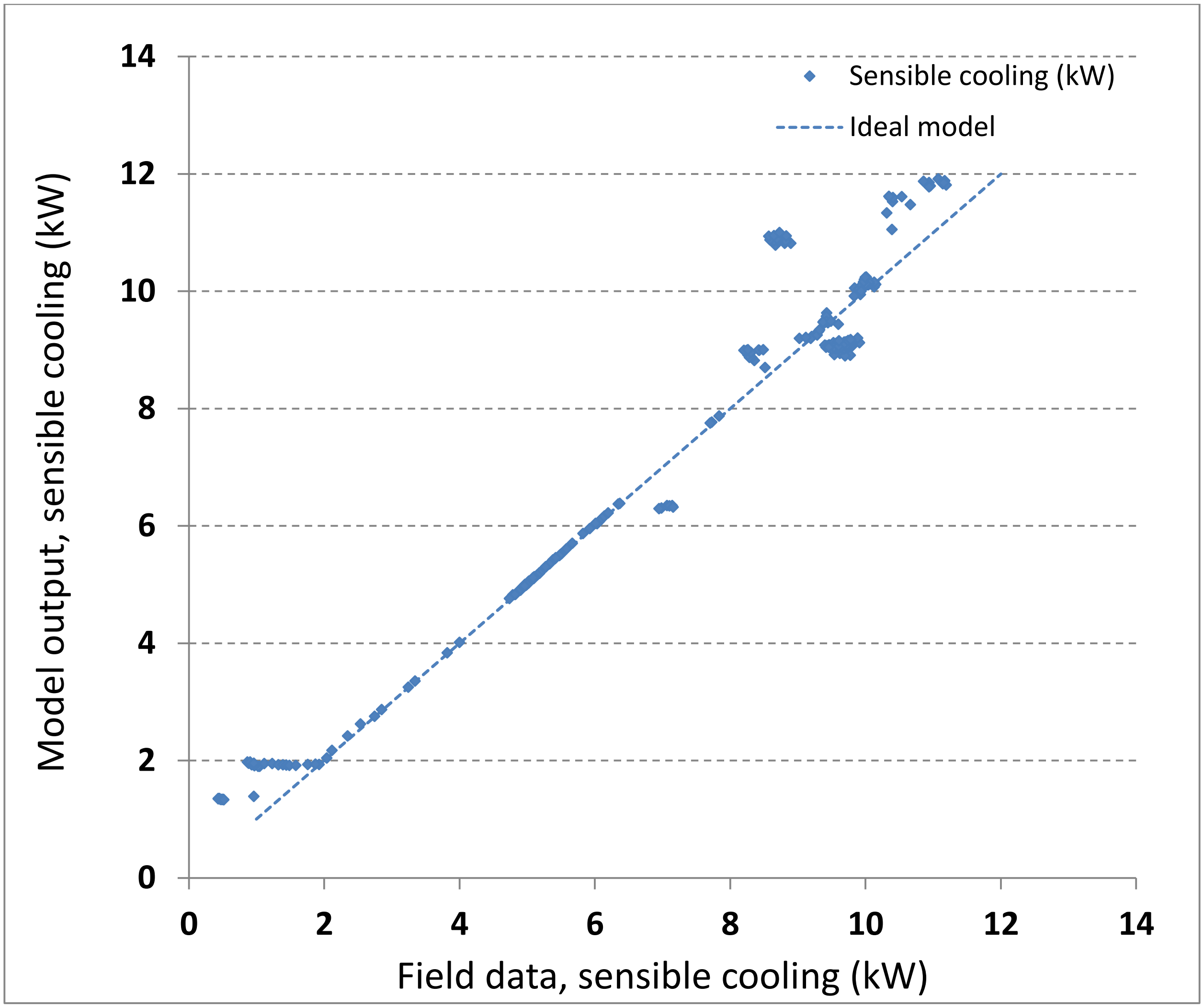


Figure 7 shows the predicted and measured sensible cooling capacity for 300 sample data points. Points that lie closer to the ideal model line represent more accurate predictions.

Figure 7 Comparison of modeled and predicted sensible capacity



For 77% of the time HBBM predicted the same mode of operation that was observed for equipment operation in the field. The modeled sensible cooling and power consumption are highly dependent on which mode of operation the model chooses. On average, the model predicted a 0.3% higher delivered sensible cooling capacity, and 10% higher electricity use than the real system. On average, mass flow rates were predicted to be 0.4% higher than observed. These disparities occurred under three conditions described below.

First, at low cooling demands ($\dot{L}_{Sensible\ Room}$<2 kW) the model consistently predicted a higher than necessary mass flow rate. Analysis of the performance curves found this is the result of a global minimum in the polynomial curve for electric power consumption for the "HMX Only" mode of operation which occurs at a supply air mass flow rate of approximately 0.3 kg/s. The synthetic data table used to generate the second order performance curves did not contain data for flow rates below 0.4 kg/s, which limited the accuracy of the curve below those points. For accurate functioning of the HBBM, it is very important that the performance curves input accurately predict system performance across the full range of system operation.

Second, the model was found to select the wrong mode approximately 23% of the time. In the vast majority of these cases, this was again found to be the result of insufficient field data under certain environmental conditions resulting in a poorly defined performance curves. Under some conditions the polynomial curves for “HMX+S2” predicts a lower cooling capacity than “HMX+S1”, and lower than is required. In this case the model chooses the “HMX+S1” mode when in reality the system would operate in “HMX+S2”.

Finally, the model was found to occasionally over cool when the cooling demand exceeded the peak capacity of the HMX only model, but was below the minimum delivered cooling capacity of the next highest mode satisfied by “HMX+S1” or “HMX+S2”. This resulted in large fixed steps in capacity, and so necessarily generated more cooling than is required in that time step. This behavior is consistent with the real H80 system.

The assessment demonstrates that the HBBM functions as intended to select the optimal mode and operating conditions, given the performance curves used. The differences between modeled and predicted data occur as a result of inaccuracy in the empirical equations under certain operating conditions. For cases where the test points coincided with actual field conditions the model outputs aligned very well with field observations, resulting in highly accurate predictions of mode, power use and sensible cooling capacity. This can be observed in Figure 7 over the measured sensible cooling capacity ranging from approximately 2kW to 6.2kW.

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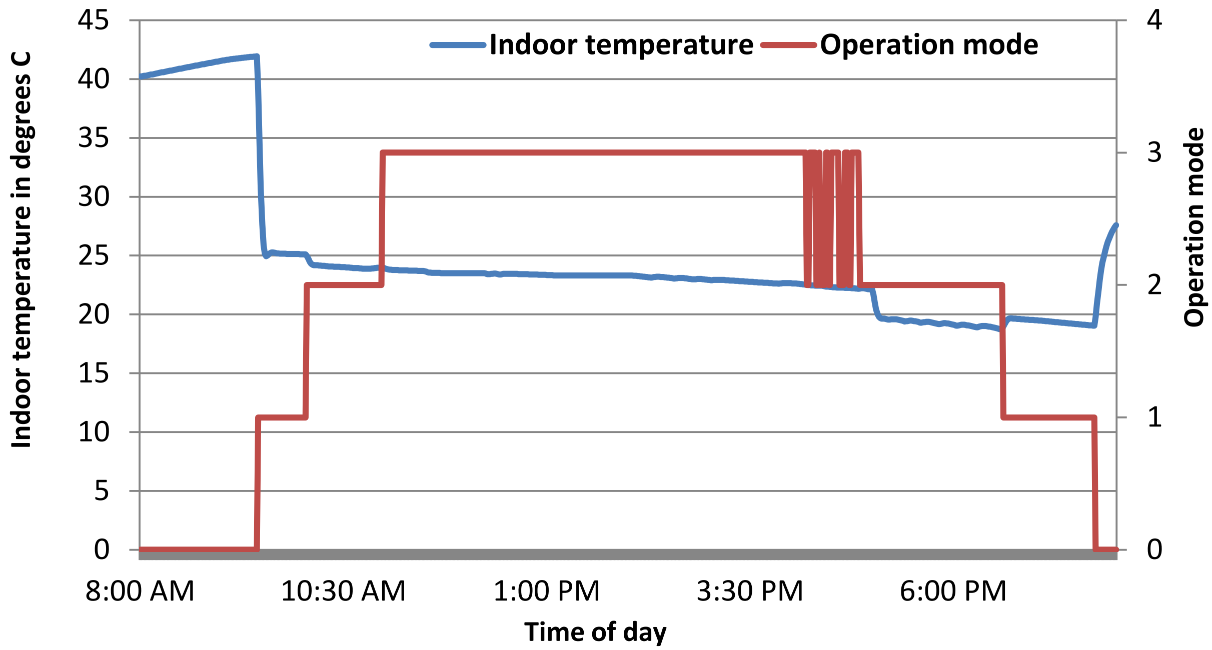
3.7 Validation of EnergyPlus Simulation

3.7.1 Set point test

Figure 8 shows the indoor temperature of the test-case single zone model rising when the cooling system is turned off up to 9 am. When the cooling model activates, indoor temperatures are shown to fall to below the cooling set point of 25 degrees C. As the daytime outdoor temperatures rise to a peak, cooling loads increase, and the cooling model is shown to step up from mode 1(HMX only) up to mode 2 (HMX with single stage cooling), and then finally up to mode 3 (HMX with stage 2 cooling).

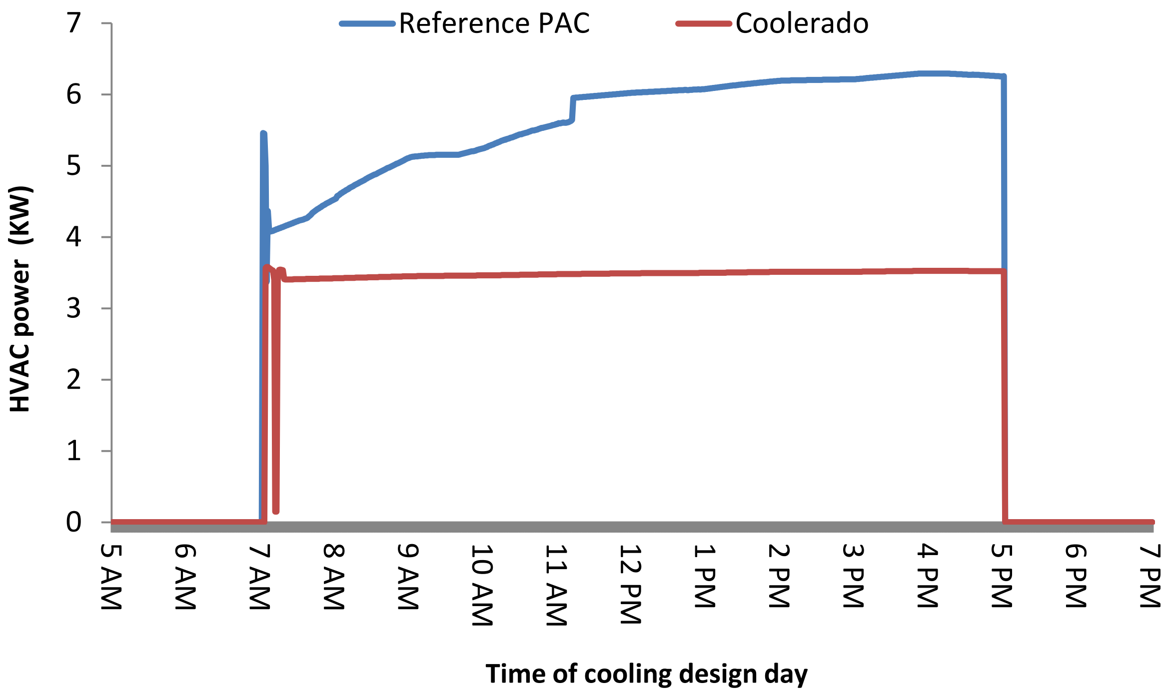
Figure 8 Indoor temperature and operation mode of the Coolerado H80 model



This initial testing has highlighted some control issues that will need to be addressed. Towards the end of the day the model was shown to switch rapidly between modes. This was considered a likely issue during the design of the model. Future improvements to the model could introduce a delayed transition from mode to mode that would limit this effect. This would also align well with the control for the H80, at least, which gradually transitions between modes as the system seeks to meet the cooling demand.

Figure 9 shows HVAC electrical power for a Coolerado and a conventional packaged air conditioner (PAC) being used to condition the simple 1 zone test building. The total energy used to condition the zone was 39% lower for the Coolerado-based model.

Figure 9 Comparison of HVAC energy, Coolerado and a conventional PAC



These initial validation exercises represent the first stage of testing of the HBBM. The results presented here are cannot be generalized to alternative building models or different climates.

CHAPTER 4: Discussion

The research team has developed a new flexible modeling tool that can be used in EnergyPlus to model multi-mode zone HVAC systems that previously could not be accurately represented in EnergyPlus. The approach used is novel, and utilizes several features of EnergyPlus that are not commonly used together. The tool was developed as an EnergyPlus “plug-in” called a Fuctional Mockup Unit. This approach had several advantages over the conventional approach to model development and testing, not least of these being that the model can be trialed by external partners using the current version of EnergyPlus, without requiring the model to be fully integrated into a formal EnergyPlus release.

The team also developed an empirical model of the Coolerado H80 that compared well with the field data. This model was used to populate a 60,000 point table of synthetic performance data, which in turn was used to develop the second order polynomial equations that are used by the HBBM to choose mode and operating conditions and to output performance characteristics to EnergyPlus. This approach to developing performance curves was used out of necessity rather than design. Ideally, a performance data table would be developed by a manufacturer of a cooling system under controlled conditions. Consequently, the performance maps that were derived from our field data are somewhat limited by the operating and environmental conditions observed in the field.

Despite the limitation of this approach, the second order performance curves developed for the Coolerado H80 compared sufficiently well with the field data to proceed with testing of the HBBM. This was based on an acceptability criteria of <20% RMS error in both delivered cooling capacity and electrical power use. A comparison of the predicted and measured performance characteristics found percentage RMS error in the power consumption of 18%, 1% and 1% for the HMX only, HMX plus stage 1 cooling, and HMX plus stage 2 cooling respectively. These figures verify that the second order curves used to define the Coolerado H80 model are sufficiently accurate (<20% RMS error). However, it should be reiterated that the purpose of developing the Coolerado model was for the purpose of testing the HBBM framework, and that the accuracy of this Coolerado model is only significant in that it provides a realistic test model to verify that the HBBM functions as intended.

When these curves are used within the HBBM framework and tested using input data from the field study, the model predicted mode selection and delivery of sensible cooling to an acceptable level of accuracy. Comparing 300 test points of field data to model predictions, the average predicted sensible cooling aligned with field data with a difference of less than 1%, average electricity use differed by less than 10%. The research team believes that future improvements can be made in the HBBM by tuning variables such as timing within the logic and minimum runtime for each mode. The use of the Fuctional Mockup Unit was, in general, a benefit to the HBBM; however, it did introduce several issues. One issue relates to the synchronization between the EnergyPlus thermal model and the FMU HVAC system running as a co-simulation model. The current implementation of the FMU in EnergyPlus uses a "loose coupling" architecture for co-simulation, with values being passed at the beginning of each timestep and returned via the Ptolemy II "middle-ware". The data exchange is based on synchronous dataflow, described by Wetter (2011a), that results in a two timestep delay between an observed cooling demand in the EnergyPlus model and the response from the HVAC model. Section 4.6 of the report by Wetter (2011b) further explains why this delay is unavoidable. For this reason, at this point, the research team recommends that users of the HBBM only use short timesteps, ideally one minute. Limiting the simulation timestep to very short timesteps is also necessary because, at this stage, the model remains in a fixed state for a complete timestep. The model does not account for any transient behavior, system modulation or mode changes within a timestep. Future development of the model could introduce these concepts, potentially allowing longer timesteps and therefore shorter simulation runtimes.

The research team stress-tested the model in the EnergyPlus implementation. For a simple single zone EnergyPlus building model, the Coolerado H80 model delivered sufficient cooling to meet the cooling load requirements of the space. An initial comparison of HVAC energy consumption for the Coolerado and a conventional PAC system found energy use savings of 39%, and the average occupied zone temperatures were effectively identical. These preliminary tests were intended to demonstrate the HBBM functioning within EnergyPlus; however, the results cannot be generalized to indicate typical or potential energy savings.

The systems field tested in this study all made use of a hybrid combination of indirect evaporative and vapor compression cooling systems. Consequently, all of the assessed systems consume both water and electricity under typical operating conditions. At this stage, the HBBM does not calculate water consumption. The primary objective of this work was to develop a model framework that could accommodate the performance definition and simulation of hybrid cooling systems within the EnergyPlus environment. Future model revisions could easily allow for water consumption as an output, as long as adequate water use information for a system can be defined as a function of environmental conditions and system operating parameters. However, given that not all hybrid air conditioner configurations use water it is unclear whether water use should be added to the HBBM. Future studies should utilize the HBBM to assess the potential for energy savings and water use in a variety of applications.

Further testing and validation of the HBBM and the Coolerado model are to continue past the delivery of this report. The model will be released initially for beta testing by industry partners, and then released to the EnergyPlus user community before the end of December 2014.

CHAPTER 5: Conclusions

- The research team have developed and tested new plug in model (the Hybrid Black Box Model) for EnergyPlus that allows the modeling of multi-mode hybrid cooling systems using empirical performance curves.
- The team used field data from a Coolerado H80 to develop one set of performance curves that, when used in EnergyPlus via the HBBM, were found to accurately capture the performance of the H80 under three discrete modes of operation.
- The research team developed a detailed user guide to enable manufactures of novel high efficiency cooling systems to develop the performance curves needed to model their systems using this tool.
- The model is currently undergoing stability testing, and trials with an industry partner, before public released before the end of FY 2014.

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APPENDIX A: 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 the evaporative cooling units installed in buildings throughout California will provide system performance data that will lower the uncertainty in the 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 grow 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 3.0+09 kWh per year.

Table 4 Calculation inputs

Input	Value	Detail
Installed cooling tonnage (ICT)	8.3E+08 kW	Equals the total commercial floor area (A=5E+09 meters) (CEC 2006 (CEC-400-2006-005, March 2006), divide by, the average cooling capacity per square meter that are serviced by RTUs (8.6 m^2 per kW), CEUS 2006 multiplied by fraction of commercial area serviced by RTUs 70%, (CEC 2006) ICT=A/(8.6 *0.7)
Cooling Load Factor (CLF)	20%	CLF for RTU's currently in service, (CEC 2006)
Conventional RTU Energy Efficiency Ratio (EER)	10	EER for RTU's currently in service, (CEC 2013)
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.

APPENDIX B: Engineering Reference

B.1 Performance Curves

At the core of the HBBM model are one or more sets of performance curves that describe the model outputs of interest of supply air temperature, supply air humidity and power draw in each mode of operation. These dependent performance outputs are a function of four environmental conditions (indoor and outdoor temperature and humidity) and two operating conditions (outside air fraction and supply air mass flow rate).

Each curve is defined as a second order polynomial function, and describes a single dependent performance output of interest (Y_i) as a function of the multiple independent environmental and system variables(X_i). Each equation will be of the form:

$$
\begin{aligned}
Y_i^{mode} &= \beta_{0\,(Y_i^{mode})} \cdot X_0 \cdot X_0 + \cdots \\
&\left(\beta_{1\,(Y_i^{mode})} \cdot X_0 \cdot X_1\right) + \left(\beta_{2\,(Y_i^{mode})} \cdot X_0 \cdot X_2\right) + \left(\beta_{3\,(Y_i^{mode})} \cdot X_0 \cdot X_3\right) + \left(\beta_{4\,(Y_i^{mode})} \cdot X_0 \cdot X_4\right) + \cdots \\
&\left(\beta_{5\,(Y_i^{mode})} \cdot X_0 \cdot X_5\right) + \left(\beta_{6\,(Y_i^{mode})} \cdot X_0 \cdot X_6\right) + \cdots \\
&\left(\beta_{7\,(Y_i^{mode})} \cdot X_1 \cdot X_1\right) + \left(\beta_{8\,(Y_i^{mode})} \cdot X_1 \cdot X_2\right) + \left(\beta_{9\,(Y_i^{mode})} \cdot X_1 \cdot X_3\right) + \left(\beta_{10\,(Y_i^{mode})} \cdot X_1 \cdot X_4\right) + \cdots \\
&\left(\beta_{11\,(Y_i^{mode})} \cdot X_1 \cdot X_5\right) + \left(\beta_{12\,(Y_i^{mode})} \cdot X_1 \cdot X_6\right) + \cdots \\
&\left(\beta_{13\,(Y_i^{mode})} \cdot X_2 \cdot X_2\right) + \left(\beta_{14\,(Y_i^{mode})} \cdot X_2 \cdot X_3\right) + \left(\beta_{15\,(Y_i^{mode})} \cdot X_2 \cdot X_4\right) + \left(\beta_{16\,(Y_i^{mode})} \cdot X_2 \cdot X_5\right) + \cdots \\
&\left(\beta_{17\,(Y_i^{mode})} \cdot X_2 \cdot X_6\right) + \left(\beta_{18\,(Y_i^{mode})} \cdot X_3 \cdot X_3\right) + \left(\beta_{19\,(Y_i^{mode})} \cdot X_3 \cdot X_4\right) + \left(\beta_{20\,(Y_i^{mode})} \cdot X_3 \cdot X_5\right) + \cdots \\
&\left(\beta_{21\,(Y_i^{mode})} \cdot X_3 \cdot X_6\right) + \left(\beta_{22\,(Y_i^{mode})} \cdot X_4 \cdot X_4\right) + \left(\beta_{23\,(Y_i^{mode})} \cdot X_4 \cdot X_5\right) + \left(\beta_{24\,(Y_i^{mode})} \cdot X_4 \cdot X_6\right) + \cdots \\
&\left(\beta_{25\,(Y_i^{mode})} \cdot X_5 \cdot X_5\right) + \left(\beta_{26\,(Y_i^{mode})} \cdot X_5 \cdot X_6\right) + \left(\beta_{27\,(Y_i^{mode})} \cdot X_6 \cdot X_6\right)
\end{aligned}
$$

where:

$X_0 = 1$ a constant.

$X_1 = T_{db,OSA}$ the outdoor air temperature (dry bulb) {°C}.

$X_2 = \omega_{OSA}$ the outdoor humidity ratio { g/g }.

$X_3 = T_{db,RA}$ the return air temperature (dry bulb) {°C}.

$X_4 = \omega_{RA}$ the return air humidity ratio { g/g }.

$X_5 = \frac{\dot{m}_{SA}}{\dot{m}_{SA}^{REF}}$ the normalized mass flow rate {–}.

$X_6 = OSAF$ the outside air fraction {–}.

β_j = coefficients used to describe the sensitivity to each independent variable.

The second order polynomial is sensitive to each independent variable, the square of each independent variable, and the combination of any two independent variables. When it is determined that a simpler equation is adequate to describe performance of the specific equipment, the coefficients for higher order elements in the function can be defined as zero. For each operating mode, separate polynomials must be defined for each of the following dependent performance outputs:

$Y_1^{mode} = T_{db,SA}$ {°C}

$Y_2^{mode} = \omega_{SA}$ {%}

$Y_3^{mode} = \frac{Power}{\dot{m}_{SA}^{REF}} \left\{\frac{kW}{kg/s}\right\}$

Note that the power draw of the unit is normalized by supply air mass flow rate at reference conditions. Reference conditions are defined in section: *Reference Conditions*.

B.2 Modes of Operation

HBBM function requires a complete set of performance curves for each "mode" of operation. These modes of operation discrete system operation categorically. Each mode represents a distinct and unique combination of component operations that is not captured by environmental conditions, or by the two independent operational variables (supply air mass flow rate, and outside air fraction). For example, "DX1", and "DX2" would be distinct modes, but "ventilation", and "economizer" would not be distinct modes because they only differ in mass flow rate and outside air fraction. Similarly, "DX1" and "economizer+DX1" should not be considered separate modes because they only differ by outside air fraction, which is accounted for as an independent variable.

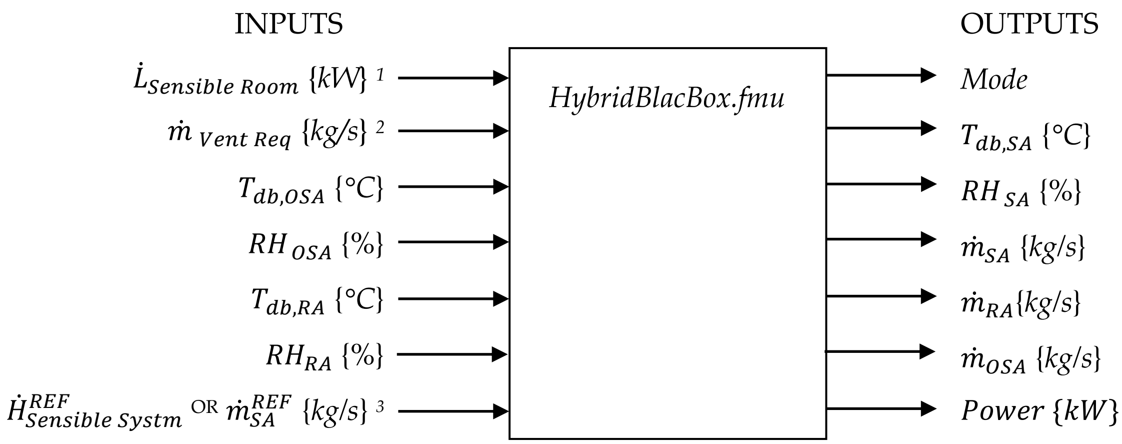
Each mode of operation represents a separate discrete physical state for a machine, and should not be confused with other means of categorization that make conceptual separations according to external variables or controls sequences. For example, "occupied cooling" and "unoccupied cooling" would probably not be separate modes of operation. They may be separate states in a real sequence of operations, and would control systems to deliver a different volume of outside air, but since the HBBM uses the ventilation requested at each time step as an input to choose the mode, supply airflow rate, and outside air fraction, "occupied cooling" and "unoccupied cooling" do not result in discrete physical states for the machine. In this case, the controls concept "unoccupied cooling" would be addressed by the EnergyPlus schedule for occupancy and the associated ventilation requirements. This would result in a more fundamental cooling mode, and supply airflow and outside air fraction that is adequate to satisfy the ventilation requirement at each time step.

However, if a system can only operate with distinct fan flows or outside air fraction settings, and the associated components are not physically capable of operating across a continuous field, these separate airflow states could be described as discrete modes of operation. In this case, system modes might include "High Speed Cooling", "Low Speed Cooling", and "Economizer", or "ventilation only".

B.3 HBBM Model Inputs & Outputs

The inputs passed from EnergyPlus to the HBBM FMU at each time step, and the outputs returned include:

Figure 10 Model inputs and outputs



where:

$\dot{L}_{Sensible\ Room}$ = remaining sensible room load to reach the temperature setpoint, for each time step, in kilo Watts.

$\dot{m}_{Vent\ Req}$ = the requested ventilation flow rate for each time step in kilograms per second.

$T_{db,OSA}$= the outside air dry temperature (dry bulb) in degrees centigrade.

RH_{OSA} = the outside air relative humidity (%).

$T_{db,RA}$= the return air dry temperature (dry bulb) in degrees centigrade.

RH_{RA} = the return air relative humidity (%).

$\dot{H}^{REF}_{Sensible\ Systm}$ = system sensible cooling capacity at reference conditions
$\dot{m}^{REF}_{SA}$ =mass flow rate of supply air at reference conditions
Mode = the name of the operating mode as defined in model configuration

$T_{db,SA}$= the supply air dry temperature (dry bulb) in degrees centigrade.

RH_{SA} = the supply air relative humidity (%).

$\dot{m}_{SA}$ = the supply air ventilation flow rate for each time step in kilograms per second.

$\dot{m}_{RA}$ = the requested ventilation flow rate for each time step in kilograms per second.

Power = the electrical power use in kilo Watts.

1. EnergyPlus object *ZoneHVAC:ForcedAir:UserDefined* makes available internal EnergyPlus variables that represents the estimated $\dot{L}_{Sensible\ Room}$, called *"remaining load to cooling setpoint"* and *"remaining load to heating setpoint"*. The *"remaining load to dehumidification*

set point" and "*remaining load to humidification set point*", are also available however, while the HBBM does calculate latent cooling, it is currently only configured to respond to sensible loads.

2. The requested ventilation flow rate for each time step is determined from a combination of the EnergyPlus design ventilation rate and a fractional schedule that can be used to vary minimum VR throughout the day.
3. The EnergyPlus user will edit the *.idf* in a text editor to input either the desired system sensible cooling capacity at reference conditions ($\dot{H}^{REF}_{Sensible\ Systm}$ $\{kW\}$), or the mass flow rate of supply air at reference conditions ($\dot{m}^{REF}_{SA}$ $\{kg/s\}$). This allows the EnergyPlus user to scale the model performance to a desired nominal capacity, at least to the degree allowed by a particular system model configuration. The method by which this scaling is accomplished is described in section: *Unit Scaling*.

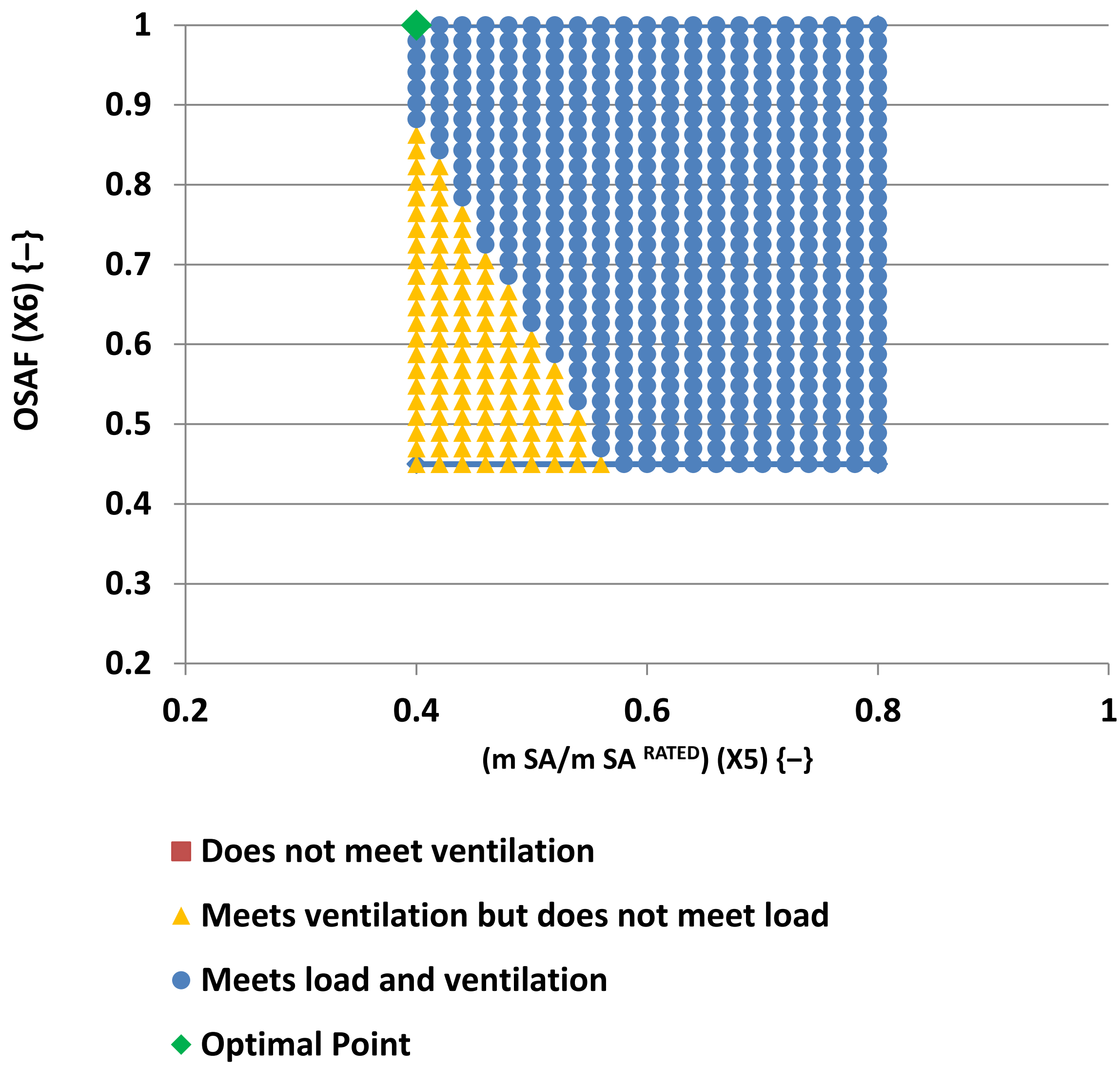
B.4 How the HBBM chooses a mode, mass flow, and OSAF.

The HBBM assumes that for any given environmental condition, the system being modeled is able to vary the OSAF, the supply air mass flow rate (($\dot{m}_{SA}$ $\{kg/s\}$)) or both in order to meet the required cooling load, while ideally using the least amount of electrical energy. The OSAF and $\dot{m}_{SA}$ are both dependent variables of the performance curves; therefore changes in each of these operating conditions have a direct impact on the delivered cooling capacity and electrical energy use of the modeled system.

In order to determine which mode of operation to use, and which operating conditions within that mode, the HBBM identifies the mode and operating conditions that meet the required minimum ventilation and load requirements, for the lowest electrical energy consumption.

Figure 11 shows an example of operating condition limits that define the bounds of a range of viable operating conditions. Operating conditions within these bounds could all in theory be selected by the real systems control logic. A proportion of these conditions will meet the minimum ventilation requirements specified by the EnergyPlus model, and a proportion of those may meet the required heating or cooling load. The HBBM iterates though each option, using the specific performance curve for the mode of operation; it identifies the viable conditions that use the least amount of electricity.

Figure 11 Operating conditions, solution space map



B.5 Unit Scaling

Performance curves for a particular model configuration are defined in a way that is independent of system size. Therefore, the EnergyPlus user is able to easily scale the nominal size of a system for simulation by defining either a desired sensible system cooling capacity at reference conditions ($\dot{H}^{REF}_{Sensible\ System}$ {kW}), or a desired mass flow rate of supply air at reference conditions ($\dot{m}^{REF}_{SA}$ {kg/s}). The latter option accommodates simulation of equipment designed on the basis of flow rate, such as Dedicated Outside Air Supply (DOAS) systems.

As described in section *"How the HBBM chooses a mode, mass flow, and OSAF"*, the model uses the Sensible Room Energy Intensity Ratio ($EIR_{Sensible\ Room}$) to choose the mode, supply air mass flow rate ($\dot{m}_{SA}$), and outside air fraction that will satisfy both the sensible room load ($\dot{L}_{Sensible\ Room}$) and ventilation requirement ($\dot{m}_{\ Vent\ Req}$) for each time step. All of these variables are calculated from the characteristic performance curves, and scaled according to the mass flow rate of supply air at reference conditions ($\dot{m}^{REF}_{SA}$). For example:

$$Power\ = Y_3^{mode} \cdot \dot{m}^{REF}_{SA}$$

and

$$\dot{m}_{SA} = X_5 \cdot \dot{m}^{REF}_{SA}$$

therefore

$$\dot{H}_{Sensible\ System} = \dot{m}_{SA} \cdot c_p \cdot \left(T_{db,MA} - T_{db,SA}\right)$$

$$\dot{H}_{Sensible\ Room} = \dot{m}_{SA} \cdot c_p \cdot \left(T_{db,RA} - T_{db,SA}\right)$$

and

$$EIR_{Sensible\ Room} = \frac{Power}{\dot{H}_{Sensible\ Room}}$$

In the case that the Energy Plus user defines a desired sensible system cooling capacity at reference conditions ($\dot{H}^{REF}_{Sensible\ System}$ (kW)), instead of desired mass flow rate of supply air at reference conditions ($\dot{m}^{REF}_{SA}$ (kg/s)), the later is calculated internally as:

$$\dot{m}^{REF}_{SA} = \frac{\dot{H}^{REF}_{Sensible\ System}}{c_p \cdot \left(T^{REF}_{db,MA} - T^{REF}_{db,SA}\right)}$$

where

$$T^{REF}_{db,MA} = T^{REF}_{db,RA} + OSAF^{REF} \cdot \left(T^{REF}_{db,OSA} - T^{REF}_{db,RA}\right)$$

$T^{REF}_{db,SA} = Y_1^{mode}$, calculated from performance curve at reference conditions

$\dot{H}^{REF}_{Sensible\ System}$, as defined by EnergyPlus user

The outside air fraction, outside air temperature, and return air conditions at reference conditions are described in Users' Guide section: *Reference Conditions*.

The example model described in the User Guide demonstrates how the EnergyPlus variable "Final Zone Design Cooling Load" can be used to scale the unit's performance using EnergyPlus's auto-sizing capabilities.

B.6 Reference Conditions

Since the model is designed to be scaled according to EnergyPlus user inputs for the nominal equipment size, it is important that the definition of performance curves in the model configuration be scaled relative to performance at a particular set of fixed reference conditions and operating constraints. All new hybrid model configurations for any hybrid system must be developed according to and scaled against these reference conditions.

B.6.1 Temperature Conditions

Temperature and humidity for reference conditions are:

$T_{db,OSA}^{REF} = 105°F\ (40.5°C)$ $\quad$ $T_{db,RA}^{REF} = 78°F(25.6°C)$

$T_{wb,OSA}^{REF} = 73°F(22.8°C)$ $\quad$ $T_{wb,RA}^{REF} = 64°F(17.8°C)$

B.6.2 Outside Air Fraction

Performance at reference conditions is also sensitive to outside air fraction:

$$OSAF^{REF} = \frac{\dot{m}_{vent}^{REF}}{\dot{m}_{SA}^{REF}}$$

This may be any number, but must be defined in the model configuration, and should correspond to the scenario that an EnergyPlus user would expect for input of nominal capacity. For example, if $OSAF^{REF}$ is defined as 1.0 in the model configuration, and an EnergyPlus user inputs $\dot{H}_{Sensible\ System}^{REF} = 10\ kW$, the HBBM will scale all performance metrics such that $T_{db,SA}$ from the highest capacity mode at reference conditions $\left(T_{db,OSA}^{REF}, T_{wb,OSA}^{REF}, T_{db,RA}^{REF}, T_{wb,RA,}^{REF} \dot{m}_{SA}^{REF}, OSAF^{REF}\right)$ results in a sensible system cooling capacity of 10 kW according to:

$$\dot{H}_{Sensible\ System} = \dot{m}_{SA} \cdot c_p \cdot \left(T_{db,MA} - T_{db,SA}\right)$$

B.6.3 External Static Pressure Conditions

In the current model structure, system performance is not sensitive to changes in airflow resistance for different duct systems or other dynamic flow conditions. Therefore, the model configuration need not describe fan characteristics separate from thermal characteristics. However, definition of the performance curves for a specific system should adhere to following reference airflow resistance conditions:

$$ESP\{InWC\} = \left(\frac{V_{SA}\left\{\frac{cfm}{ton_{H^{REF}_{Sensible\ System}}}\right\}}{350\left\{\frac{cfm}{ton_{H^{REF}_{Sensible\ System}}}\right\}} \right)^2 \cdot 0.7\ \{InWC\}$$

For example, the performance curve definition for $Y_1^{mode} = T_{db,SA}$ should be given for operation on the system curve defined above. Therefore, performance at part airflow is given with lower external static pressure than performance at full airflow.

APPENDIX C: Input Output Reference

The HBBM makes use of several relatively new features to EnergyPlus including the EnergyManagement model, the ExternalInterface object and the *ZoneHVAC:ForcedAir:UserDefined* object. The ExternalInterface:FunctionalMockupUnitImport object is used to reference the FMU either as a relative location as below or as a full path.

```
ExternalInterface:FunctionalMockupUnitImport,
   HybridEvapCooling.fmu,          !- FMU File Name
   0,                     !- FMU Timeout {ms}
   0;                     !- FMU LoggingOn
```

Inputs to the model are sent from EnergyPlus to the FMU using the ExternalInterface:FunctionalMockup-UnitImport:From:Variable object.

```
ExternalInterface:FunctionalMockupUnitImport:From:Variable,
   west zone,              !- Output:Variable Index Key Name
   Zone Mean Air Temperature,  !- Output:Variable Name
   HybridEvapCooling.fmu,   !- FMU File Name
   Model1,               !- FMU Instance Name
   TRooMea;               !- FMU Variable Name
```

Data returning from the FMU is connected directly to the EMS actuators that control the inlet and outlet nodes on the *ZoneHVAC:ForcedAir:UserDefined* object.

```
ExternalInterface:FunctionalMockupUnitImport:To:Actuator,
     Zone1WinAC_Msa, !- EnergyPlus Variable Name
     Zone1WindAC, !- Actuated Component Unique Name
     Primary Air Connection, !- Actuated Component Type
     Outlet Mass Flow Rate, !- Actuated Component Control Type
     HybridEvapCooling.fmu, !- FMU File Name
     Model1, !- FMU Instance Name
     SupplyAirMassFlow, !- FMU Variable Name
     0; !- Initial Value
```

The *ZoneHVAC:ForcedAir:UserDefined* object specifies the primary inlet and outlet nodes that connect to the zone air nodes, and the secondary nodes that connect to the outside air inlet and exhaust. For more details on this object reference the EnergyPlus Application Guide for EMS.

```
ZoneHVAC:ForcedAir:UserDefined,
   Zone1WindAC,            !- Name
   Zone 1 Window AC Model Program Manager,  !- Overall Simulation Program Manager Name
   Zone 1 Window AC Init Program Manager,  !- Model Setup Program Calling Manager Name
   Zone1WindACAirInletNode, !- Primary Air Inlet Node Name
   Zone1WindACAirOutletNode,!- Primary Air Outlet Node Name
   Zone1WindACOAInNode,     !- Secondary Air Inlet Node Name
   Zone1WindACExhNode,      !- Secondary Air Outlet Node Name
   0;  !- Number of Plant Loop Connections
```

There are a few model option variables that can be changed by the user to effect how the model behaves. Firstly users can select whether they wish to provide the system capacity at rated conditions using a supply air mass flow rate at rated conditions or using a nominal cooling capacity at rated conditions. Setting the variable MsaOrHref_Flag in the idf file to 1 switches how the capacity is interpreted by the model. The idf is configured to allow users to decide if they specify their own cooling capacity or if the "Final Zone Design Cooling Load" as determined by EnergyPlus is used instead. To specify which the UserDefinedMRated can be set to false or true.

APPENDIX D: Users' Guide

D.1 Model package description

The downloadable Hybrid Black Box Model package (LBNL 2014) is comprised of:

HybridBlackBox.fmu	Hybrid Black Box Model as a Functional Mockup Unit
ExampleModel.idf	Example EnergyPlus model using *HybridBlackBox.fmu*
EMS application guide.pdf	Application guide for energy management system objects
Users' Guide.pdf	How to use the Hybrid Black Box Model with EnergyPlus
SourceCode.C	Un-compiled C source code for reference

The HBBM makes use of EnergyPlus's native ability to interface with external models or programs by way of the Functional Mockup Interface (FMI) version 1.0 (Nouidui 2013). FMI is an independent and nonproprietary standard to support both model exchange and co-simulation of dynamic models using a combination of XML-file, C-header files, and C-code in source or binary form. The Functional Mockup Unit: *HybridBlackBox.fmu* contains all features and algorithms needed to implement the Hybrid Black Box Model within EnergyPlus.

The FMU file is essentially a *.zip* file containing the model and any resources the model needs, including the configuration file. The contents of the FMU can be viewed by changing the file name extension from *.fmu* to *.zip* and extracting all files from the compressed folder. Contents of the FMU include:

```
\HybridBlackBox
    modelDescription.xml
    \binaries
        \win32
            HybridEvapCooling.dll
    \resources
        \HybridModelConfig
            Config.csv
    \sources
```

The internal file structure of the FMU is composed in accord with the FMI standard.

modelDescription.xml serves as a map for the overall function and behavior of the Hybrid Black Box Model. This file provides a standardized definition of all input and output variables that are exchanged with EnergyPlus, and identifies any events and states that must occur for the tools to interact appropriately..

HybridEvapCooling.dll is the binary form C code that defines all calculations and iterative algorithms that constitute the Hybrid Black Box Model. The binary comes in two forms for 32 bit and 64 bit systems. This is the heart of the model, where all inputs are processed and from where all outputs are reported. All of the calculations explained in the *Engineering Reference* occur within this element.

Config.csv is a text based configuration file where all performance characteristics for a particular hybrid rooftop air conditioner are defined. This configuration essentially holds all input values that are not passed from EnergyPlus on each time step and are used to initialize the FMU. The *.csv* file contains fields for:

1. Names for each mode of operation
2. Coefficients for each polynomial equation
3. Environmental operating constraints for each mode
4. Functional operating constraints for each mode
5. The outside air fraction at reference conditions $OSAF^{REF}$
6. The allowable nominal capacity range for which the model can be scaled

The configuration file is structured in a standard way to allow performance description for a variety of hybrid air conditioning systems in a common format. The approach for developing performance definition for a new system is described in section "*Developing a New Model Configuration*".

To run the HBBM it must be referenced in an *.idf* building model input data file. *ExampleModel.idf* is a slimmed-down but functional Energy Plus model that includes all of the elements necessary to support operation of the Hybrid Black Box Model. When this *.idf* is run, EnergyPlus will link to the FMU, initialize it and perform co-simulation with the HBBM. The relative location of the *.fmu* and *.idf* files is important – the two should be located in the same folder at all times.

ExampleModel.idf is arranged and commented in a way that clearly highlights all of the features that are essential for application of the Hybrid Black Box Model, including:

1. *The ZoneHVAC:ForcedAir:UserDefined* object is used to provide HVAC system nodes. The mass flow, temperature and humidity of the air flow at these nodes is controlled by the HBBM, allowing the HBBM to interact with the thermal and airflow networks.
2. Us of the *ZoneHVAC:ForcedAir:UserDefined* object necessitates the use of EneryPlus's *Energy Management System* model that helps manage data input and output exchanged with the HBBM.
3. An *External Interface* object that makes the link to the Functional Mockup Unit.

A more thorough explanation of the essential requirements for using the HBBM within EnergyPlus is included in section: "Input Output Reference".

D.2 Developing a new model configuration

The HBBM is intended as a shell that can be used by others to simulate annual performance of a variety of indirect evaporative or hybrid air conditioners. The tool is flexible enough to accommodate the complex nature of multi-component, multi-modal, variable speed hybrid systems, and considers the sensitivity to an array of independent environmental and system variables. Consequently, the definition of performance characteristics for a particular system can be more laboursome than user definition of the inputs for a conventional vapor compression system.

The definition of all performance characteristics for a particular system is done in the text based configuration file: *Config.csv*. The file is structured in a standard way to interact with the *HybridEvapCooling.dll*. A new model developer should use the sample configuration file as a template, and must input values for all fields therein to fully describe a new system.

To use a new configuration file for the HBBM, the model developer must first unzip *HybridBlackBox.fmu* and replace the existing *Config.csv* file with the alternative *Config.csv* file. The FMU must then be rezipped and the *.zip* file extension replaced with a *.fmu* extension.

Once the characteristics of a particular machine are established, the HBBM can be utilized for annual building energy simulations by an EnergyPlus user. However, definition of a new model is not trivial. The research team envisions that models for particular systems would be developed by manufacturers, third party evaluators, or research organizations and made available to end-users who intend to simulate equipment performance in a variety of applications.

The EnergyPlus user that desires to simulate performance of a hybrid air conditioner is supplied with the complete model developed for this project. In application, the only parameter that an EnergyPlus user must define to characterize the HBBM is a desired nominal system capacity at reference conditions. This HBBM internally scales all appropriate performance characteristics according to this single user supplied input.

The performance characteristics for a system may be developed in a number of ways including regression from laboratory and field measurements, or by numerical multiphysics or thermal systems models that simulate theoretical performance of a machine under a variety of conditions. It will be the responsibility of the developer to produce external documentation that validates the system performance used as the basis for the inputs to the model. If adopted as a pathway for code compliance, governing bodies or policy could require that this model use only "certified performance maps".

D.2.1 Developing Performance Curves

The HBBM uses a set of polynomial equations to describe equipment performance characteristics. These curves form the empirical basis of the model. The *Engineering Reference* describes the specific form for the second order polynomial functions.

The performance characteristics of a machine in a particular mode of operation is defined by three polynomial equations, one to describe supply air temperature, one to describe supply air humidity, and one to describe specific power consumption. The three equations must be defined for each mode of operation, so a machine with three distinct modes of operation would require nine input equations.

There are a number of ways that one could develop these equations. One of the more direct methods could use the following process:

1. Laboratory test equipment in each mode of operation across a complete range environmental conditions, and system operating variables.
2. Record laboratory measurements of each output variable in a matrix table for each mode of operation. The matrix table should record values across the complete range of ambient conditions, return conditions, supply airflow rates, and outside air fractions.[1]
3. Utilize a software tool such as Minitab, Matlab, R, or Excel to conduct a multivariate least squares regression for each dependent variable (the model inputs). These regressions must consider first order and second order independent effects of each variable in order to develop the model.

D.2.1 Defining Model Constraints

In addition to the polynomial coefficients, definition of a model configuration requires the developer to define the range of operating conditions within which the model for each mode of operation will be constrained, and the range of environmental conditions across which the model can be applied with confidence,

Operational constraints are bounds that define the range of normalized supply air mass flow ($X_5 = \dot{m}_{SA}/\dot{m}_{SA}^{REF}$) and outside air fraction ($X_6 = OSAF$) values for which a particular mode of operation is able function. The range of values specified should correspond to the range of operational conditions within which the real system is physically capable of functioning; it should also reflect the range of operating conditions that were actually tested. For example, many indirect evaporative air conditioners are physically constrained to operate with 100% outside air. Model definition for this type of system would constrain the functional operating range to OSAF=1.0.

Environmental constraints specify the range of outdoor and indoor dry bulb temperature and humidity ratio conditions within which the performance map for each operating mode predicts real performance with confidence. These constraints should set the range for which model performance has been validated, and could be used to set environmental limits for the operation of particular modes. For example, if a system performance were only measured for hot-dry conditions, the environmental constraints could restrict operation of the system to within these boundaries.

Further, the HBBM allows the EnergyPlus user to input the desired sensible system cooling capacity at reference conditions, or the nominal supply air mass flow rate, which is used to scale the equipment performance characteristics. In order to accommodate this feature, the model configuration must specify the appropriate range of nominal capacity ($\dot{H}_{Sensible\ System}^{REF}$) for which the model can scale accurately. It must also define the outside air fraction at reference conditions ($OSAF^{REF}$).

[1] Appendix E: Table 5 provides a partial example matrix table to record performance for one mode of operation across a range for one independent variable. This example table would be replicated for each independent variable.

Appendix E: Example Matrix Table

Table 5 Example mapping table

Lab based test conditions						Measured system performance (HMX only)		
Outside air temp. (C)	Outside air humidity ratio (-)	Return air dry bulb temp.(C)	Return air humidity ratio (-)	Supply air mass flow rate (kg/s)	Outside air fraction	$T_{db,SA}$ (°C)	ω_{SA}(%)	Elec. Power (W)
15	0.002	18	0.004	0.4	0.45	9.3	0.0021	141.15
15	0.002	18	0.004	0.4	0.54	9.0	0.0018	141.15
15	0.002	18	0.004	0.4	0.63	8.7	0.0015	141.15
15	0.002	18	0.004	0.4	0.73	8.4	0.0013	141.15
15	0.002	18	0.004	0.4	0.82	8.2	0.0010	141.15
15	0.002	18	0.004	0.4	0.91	7.9	0.0007	141.15
15	0.002	18	0.004	0.4	1.00	7.6	0.0004	141.15
15	0.002	18	0.004	0.52	0.45	9.4	0.0021	263.76
15	0.002	18	0.004	0.52	0.54	9.1	0.0018	263.76
15	0.002	18	0.004	0.52	0.63	8.9	0.0015	263.76
15	0.002	18	0.004	0.52	0.73	8.6	0.0013	263.76
15	0.002	18	0.004	0.52	0.82	8.3	0.0010	263.76
15	0.002	18	0.004	0.52	0.91	8.0	0.0007	263.76
15	0.002	18	0.004	0.52	1.00	7.8	0.0004	263.76

Appendix F: Model Configuration for Coolerado 80

Table 6 Coolerado H80 coefficients

Mode	HMX Only			HMX & S1			HMX & S2		
Yi	T db SA	w SA	Power	T db SA	w SA	Power	T db SA	w SA	Power
β_0	3.17E+00	-1.11E-03	3.68E+02	-7.82E+01	1.18E-02	5.39E+03	-5.01E+01	1.21E-02	5.40E+03
β_1	-3.76E-01	1.07E-04	5.04E-11	5.55E+00	-6.15E-04	8.69E-10	9.50E-01	-3.76E-04	8.71E-10
β_2	1.62E+02	-6.32E-02	1.54E-07	3.62E+03	-4.21E-01	2.25E-06	1.25E+03	1.91E-01	2.26E-06
β_3	3.68E-01	2.21E-05	1.50E-09	2.63E+00	-7.44E-05	1.41E+01	7.34E-01	-1.12E-04	2.28E+01
β_4	9.02E+02	9.86E-01	1.89E-06	2.02E+03	5.36E-01	2.90E-05	1.67E+03	7.48E-01	2.99E-05
β_5	1.39E+00	-1.03E-03	-1.68E+03	-6.91E+01	-9.35E-04	-5.93E+03	5.13E+01	-1.15E-02	-5.48E+03
β_6	-1.65E+00	4.95E-04	1.35E-08	1.77E+01	-3.51E-03	-8.75E-09	2.44E+00	-6.53E-04	-1.71E-08
β_7	6.09E-03	-1.04E-06	-8.39E-13	-6.07E-02	2.11E-06	-7.92E-12	-9.50E-03	2.28E-06	-8.29E-12
β_8	-1.85E+00	-2.62E-03	-2.04E-09	-1.48E+02	1.39E-02	-1.28E-08	-3.23E+01	1.92E-02	-1.27E-08
β_9	3.61E-03	-6.11E-07	-6.69E-12	-3.48E-02	1.45E-06	-4.42E-11	-5.44E-03	1.53E-06	-4.41E-11
β_{10}	-5.47E-01	-7.66E-04	-8.13E-09	-4.20E+01	3.83E-03	-8.87E-08	-1.00E+01	5.75E-03	-9.08E-08
β_{11}	-3.38E-02	-2.12E-05	-8.77E-11	-2.94E-01	4.84E-04	-1.61E-10	-5.79E-02	1.27E-04	-1.25E-10
β_{12}	5.58E-01	-2.67E-05	-5.00E-11	-8.78E-02	1.93E-04	1.41E+01	2.93E-01	1.37E-05	2.28E+01
β_{13}	-1.09E+04	-1.16E+00	-4.48E-06	6.20E+04	5.20E-01	-4.30E-05	-1.37E+02	-2.45E+01	-4.37E-05
β_{14}	-5.47E-01	-7.66E-04	-1.51E-08	-4.42E+01	4.04E-03	-8.89E-08	-9.75E+00	5.87E-03	-8.66E-08
β_{15}	-6.44E+03	-6.78E-01	-1.47E-05	3.78E+04	-4.00E-01	-1.64E-04	-4.65E+02	-1.41E+01	-1.68E-04
β_{16}	9.32E+01	2.27E-01	-1.37E-07	7.24E+02	-1.25E-01	-4.00E-07	-2.26E+02	-5.67E-01	-3.55E-07
β_{17}	8.34E+02	9.99E-01	-5.42E-08	-3.12E+01	7.76E-01	-1.16E-07	1.09E+03	6.99E-01	-9.47E-08
β_{18}	1.19E-03	-2.06E-07	-3.34E-11	-1.16E-02	5.07E-07	-5.02E-10	-1.71E-03	5.42E-07	-5.25E-10
β_{19}	-3.60E-01	-5.18E-04	-6.76E-08	-2.83E+01	2.62E-03	-5.15E-07	-6.59E+00	3.99E-03	-5.14E-07
β_{20}	-1.28E-02	-8.05E-06	-4.92E-10	-2.08E-01	1.98E-04	-1.29E-09	-3.41E-02	3.80E-05	-1.12E-09
β_{21}	-4.93E-01	1.56E-05	-3.26E-10	-6.93E-01	-1.73E-04	-1.41E+01	-4.05E-01	-4.03E-05	-2.28E+01
β_{22}	-2.12E+03	-2.29E-01	-3.93E-05	1.25E+04	-3.40E-01	-1.23E-03	-1.93E+02	-4.79E+00	-1.29E-03
β_{23}	3.54E+01	8.61E-02	-5.08E-07	1.75E+02	-6.39E-02	-2.46E-06	-1.01E+02	-2.06E-01	-2.36E-06
β_{24}	-8.43E+02	-1.01E+00	-3.48E-07	-8.91E+02	-6.29E-01	-1.85E-06	-1.20E+03	-6.83E-01	-1.77E-06
β_{25}	3.80E-01	6.17E-04	2.82E+03	3.04E+01	-1.23E-02	2.82E+03	-2.61E+01	4.80E-03	2.82E+03
β_{26}	-1.40E-01	-8.78E-05	-4.73E-10	1.56E+01	2.99E-03	2.31E-09	1.89E+00	2.22E-03	3.92E-09
β_{27}	4.92E-01	-1.44E-04	3.32E-09	-7.28E+00	7.65E-05	1.92E-08	-1.03E+00	-4.44E-04	2.07E-08

Table 7 Coolerado H80 environmental constraints

Range for each environmental variables within which model predicts with acceptable confidence								
	Tdb,OSA (X1) {°C}		ω,OSA (X2), {⍰}		Tdb,RA (X3), {°C}		ω,RA (X4) , {⍰}	
Mode	**Low**	**High**	**Low**	**High**	**Low**	**High**	**Low**	**High**
HMX Only	13	45	0.05	0.95	15	35	0.05	0.95
HMX & S1	14	33	0.05	0.95	15	35	0.05	0.95
HMX & S2	17	45	0.05	0.95	15	35	0.05	0.95

Table 8 Coolerado H80 operational constraints

		$(\dot{m}_{SA}/\dot{m}_{SA}^{RATED})$ (X5) {⍰}	$(\dot{m}_{SA}/\dot{m}_{SA}^{RATED})$ (X5) {⍰}	OSAF (X6) {⍰}	$(\dot{m}_{SA}/\dot{m}_{SA}^{RATED})$ (X5) {⍰}	OSAF (X6) {⍰}
Function operating constraints for system variables (Xi^S)						
Scenario	Mode		Low		High	
Occupied	HMX Only	Low	0.4	0.45	0.4	1
		High	0.8	0.45	0.8	1
	HMX & S1	Low	0.75	0.45	0.75	0.45
		High	0.9	0.45	0.9	0.45
	HMX & S2	Low	0.75	0.45	0.75	0.45
		High	0.9	0.45	0.9	0.45
	Ventilation Only	Low	0	0	0	0