User-Oriented Modeling Tools for Advanced Hybrid and Climate-Appropriate Rooftop Air Conditioners

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1. Executive Summary

Hybrid unitary air conditioning systems offer a pathway to substantially reduce energy use and peak electrical demand for cooling, heating, and ventilation in commercial buildings. Hybrid air conditioners incorporate multiple subsystems that are carefully orchestrated to provide climate- and application-specific efficiency advantages. There are a multitude of hybrid system architectures, but common subsystems include: heat recovery ventilation, indirect evaporative cooling, desiccant

dehumidification, variable speed fans, modulating dampers, and multi-stage or variable-speed vapor compression cooling. Categorically, hybrid systems can operate in numerous discrete modes. For example: indirect evaporative cooling may operate for periods when the subsystem provides adequate sensible cooling, then vapor compression cooling will be included when more cooling or dehumidification is necessary. Laboratory assessments, field studies, and simulations have demonstrated that hybrid unitary air conditioners could reduce energy use for cooling and ventilation by 30-90% depending on climate and application.

Heretofore, it has been challenging - if not impossible - for practitioners to model hybrid air conditioners as part of building energy simulations; and the limitation has severely obstructed broader adoption of technologies in this class. In this project, we developed a new feature for EnergyPlus that enables modeling hybrid unitary air conditioning equipment for building energy simulations. This is a significant advancement for both theory and practice, and confers public benefit by enabling practitioners to evaluate this compelling efficiency technology as a part of building energy simulations. The feature is a black-box model that requires extensive performance data for each hybrid unitary product. In parallel, we also developed new features for the Technology Performance Exchange (TPEx) to enable manufacturers to submit performance data in a standard format that can be used with the hybrid unitary model in EnergyPlus.

Additionally, through this project we expanded university educational resources, and university-manufacturing industry collaborations in the field of energy efficiency technology. Over two years, we involved 20 undergraduate students in ambitious research projects focused on modeling complex multi-mode mechanical systems, supported three mechanical engineering bachelor theses, established undergraduate apprenticeships with multiple industry partners, and involved those partners in the process of design, validation, and debugging for the new EnergyPlus feature. The EnergyPlus feature is described and discussed in an academic article, as well as in an engineering reference, and input/output reference documentation for EnergyPlus. The TPEx features are live and publicly accessible, our manufacturer partners are primed to submit initial product information and performance data to the exchange, and the EnergyPlus feature is scheduled for public release in Spring 2018 as a part of EnergyPlus v8.9.

2. Introduction

HVAC is responsible for 35-40% of commercial building primary energy consumption, which are responsible for 19% of primary energy consumption in the United States , and roughly 8% of energy use globally. In some climates HVAC can account for more than 70% of the primary energy consumption associated with commercial buildings. Moreover, the timing of heating and cooling demand impacts electricity network management in ways that increase the overall public costs associated with these systems. As an example, in California cooling and ventilation can be greater than half of the peak electrical demand from commercial buildings.

Hybrid air conditioners are more efficient than conventional air conditioning technologies. Hybrids incorporate multiple subsystems that are selected for specific climates and applications. Ideally, energy flow between subsystems is organized to gain mutualistic advantages, and operation of each subsystem is coordinated so that a single machine operates in many discrete modes to provide only the needed capacity with the least resource consumption.

Researchers have proposed and evaluated many unique hybrid system architectures. Laboratory studies, field assessments, and simulations have clearly established that hybrid air conditioners can deliver substantial energy savings and demand reduction. These studies have indicated annual energy savings for cooling and ventilation between 30-90%, depending on climate, application, and technology. However, it is difficult to make an informed assessment about which hybrid systems are most appropriate for different buildings in different climates. Most researchers have employed a mix of first-principle and empirical methods to model particular hybrid systems by means of complex component by component models. Given the complexity of this process, no researcher has conducted a thorough parametric assessment of a wide variety of hybrid systems in different climates and applications. Since every researcher employs different analytical methods and uses different performance assessment metrics, literature review to compare the various hybrid systems evaluated in separate studies only provides limited insight. Consequently, thorough assessment of alternative hybrid strategies has heretofore been infeasible for engineers in practice.

In response to these challenges, through this project we developed a generalized empirical method to model the performance of hybrid unitary air conditioners within building energy simulations. We implemented the method as a new feature in EnergyPlus v8.9, populated characteristic performance information for various hybrid air conditioners, demonstrated annual energy simulations, and validated simulation results against field measurements for one system. The new model establishes a structured simulation pathway for practical consideration of hybrid air conditioning equipment in a wide variety of buildings and climates. The model is useful for research, building design, as well as code compliance.

3. Objectives

The primary technical ambition of this project was to develop a new feature for EnergyPlus to enable simulation of hybrid rooftop packaged air conditioners. In route, the project included an array of related activities to support the technical development and successful application of the new feature. The overarching objective of the funding program was to develop university capabilities for education, undergraduate research, and manufacturing-industry collaboration in the field of energy efficient building technologies. We integrated each of the overarching themes into our project approach. Therefore, the project included the following specific objectives:

Technical objectives:

- Develop a new EnergyPlus feature for hybrid unitary air conditioning equipment
    - Develop and test the theoretical model
    - Integrate the model with EnergyPlus
        - Develop a formal input data structure
        - Develop core C++ code
        - Develop documentation
        - Collaborate with EnergyPlus development team
        - Test, debug, and validate the new feature
- Develop resources for the Technology Performance Exchange (TPEx) and Building Component Library (BCL)
    - Develop and test a data structure for manufacturers to provide product performance data
    - Develop and test a program to convert manufacturer data to the format for EnergyPlus
    - Generate equipment performance datasets for multiple products

Programmatic objectives:

- Cultivate university - industry partnership and technology transfer

    - Involve manufacturers in designing and testing the new EnergyPlus feature
    - Involve manufacturers in designing data structure TPEx
    - Support manufacturers in developing equipment performance datasets for products
- Expand university educational resources surrounding building technology, energy, and efficiency
    - Recruit students for existing curriculum related to energy efficiency in buildings
    - Develop a design studio curriculum to teach undergraduates building energy simulation
    - Develop a seminar curriculum on Building Energy Efficiency Research and Technology
- Expand undergraduate research and experience in building energy efficiency and manufacturing
    - Facilitate a team of undergraduate student researchers with the following objectives:
        - Develop resources for TPEx
        - Develop equipment performance datasets for hybrid air conditioner products
        - Test and debug the EnergyPlus feature
        - Develop models to demonstrate annual performance for hybrid air conditioners
    - Facilitate summer undergraduate apprenticeships with industry partners

As contracted, these objectives were measured by the following milestones:

- M.1.1.1 - M.5.1.1: Select undergraduate research fellows
- M.2.3.1: Mechanical systems design studio (students working in EnergyPlus)
- M.3.1.1 - M.3.1.4: Develop theoretical modular component models for alternate hybrid systems
- M.3.3.1 - M.3.3.2 and M.7.3.1 - M.7.3.1: Develop new feature for EnergyPlus
- M.4.2.1: Complete equipment performance datasets for hybrid products
- M.4.3.1: Project workshop at NREL and presentation of Year 1 results
- M.7.1.1 - M.7.1.3: Annual building energy use simulations and comparison of alternate hybrid systems in multiple applications
- M.7.2.1 - M.7.2.3: Weekly core research team meetings
- M.8.1.1 - 8.1.2: Student summer apprenticeships with industry partners

4. Project Activities and Accomplishments

Overall, project activities adhered to the objectives. The primary technical ambitions for the project were achieved, and in most cases contracted milestones were completed as envisioned. The following paragraphs summarize the activities and accomplishments over the course of the project - the summary is grouped by each of the technical and programmatic objectives areas outlined previously.

Technical objectives

- Develop a new EnergyPlus feature for hybrid unitary air conditioning equipment

  Activities in this objective area were broad and varied. This was the primary technical intention for the project, and by far, the most complicated effort. Technical design of the EnergyPlus feature was mainly conducted by staff researchers at UC Davis and Lawrence Berkeley National Laboratory (LBNL). Generally, UC Davis developed schematic design, proof of concept model architecture, and explicit mathematical formulae. LBNL translated these designs into a formal computer program for integration with EnergyPlus. These efforts were carried out in regular communication and collaboration with industry partners, and with the EnergyPlus development team. Our core undergraduate student research team was involved in this objective area. In particular, each student was paired with an industry partner, and facilitated regular communication and feedback from manufacturers about the feature design and function. As development versions of the feature were released by LBNL, the students tested the model and provided feedback to the development team about challenges and bugs to resolve.

There were many unexpected challenges associated with this objective, not least of which was the technical and administrative complexity of formally integrating a new feature with EnergyPlus.

Architecture and function of the EnergyPlus feature were revised substantially throughout the course of the project. The goal was to develop a feature that could represent a wide variety of hybrid unitary air conditioning systems without requiring EnergyPlus users to generate custom component-by-component definition of system architecture and controls for every alternate hybrid product. We chose to develop an empirical black box model that would allow data providers - manufacturers or third-party evaluators - to publish characteristic performance information for specific hybrid products so that modelers could download data maps to easily incorporate various packaged products directly into an EnergyPlus building model. This approach shifts the enormous burden of model construction and validation away from the end user. However, since there are a wide variety of hybrid system types, it was challenging to settle on an empirical data structure and model sequence of operations that could accommodate different hybrid products universally. For example, commercially available hybrid systems consume many different resources, including electricity, water, natural gas, or other fuels. To address this issue, we developed a structure for system definition that accounted separately for many different resource types.

One key technical challenge for the feature development was defining how the model would function to meet multiple objectives simultaneously. Unitary air conditioning equipment regularly serves three separate purposes: sensible heating or cooling, ventilation for indoor air quality, and dehumidification or humidification. With empirical knowledge about the possible operating modes and controlled inputs at any given time, the model must choose a combination of settings that will satisfy all three objectives at the same time. We developed multiple approaches to address this function, and implemented a scheme that operates as a constrained optimization problem to choose the combination of settings in each time step that will most nearly satisfy the multiple objectives, subject to constraints such as limitations on the range of each operating mode, and limitations on the allowable supply air conditions delivered to the zone. Technical details for the model developed are discussed in the referenced products.

Ultimately, the project successfully accomplished its core objective: the new EnergyPlus feature was completed, and is scheduled for public release as a part of EnergyPlus 8.9. However, the effort required more time and resources than anticipated, which precluded completing some of the original project milestones. Most importantly, since the feature was not completed as quickly as anticipated, our student team was not able to demonstrate the feature for multiple hybrid systems in various applications. An early version of the feature was available for the last several weeks of our student research program, but all available efforts were spent on testing and debugging the feature, instead of using the feature to demonstrate hybrid system performance. Following the project period, UC Davis committed additional external funds to continue model debugging, and successfully demonstrated annual simulations for various hybrid systems. At the time of this report, those results are not yet incorporated into the article to be published from this work.

- Develop resources for TPEx and BCL

Activities in this objective area were executed by students and research staff at UC Davis, in close collaboration with industry partners and with the National Renewable Energy Laboratory (NREL). TPEx (www.tpex.org) - hosted by the NREL - is a centralized web portal for cataloging performance data for commercial building energy technologies. Manufacturers list products and performance data with the TPEx, then this data is made available to the public in a format that can be utilized in EnergyPlus. Modelers can access data submitted to the TPEx through the BCL (www.bcl.org). Most importantly, TPEx facilitates input of performance data in a common structure, so that different products from different manufacturers in the same technology category can be compared with one another directly. Through this project, our team designed all of the resources for a new technology class in the TPEx: "Hybrid Unitary HVAC". We developed a web form for submission of general product information and nominal performance data. We also developed an excel calculator to help data providers properly determine nominal performance metrics, and a detailed excel template for input of all characteristic performance data in each discrete operating mode.

These forms and templates were developed in an iterative process as the student team worked together with our industry partners to populate initial product datasets. This iterative process was essential for understanding the variety of needs that the technology category and performance data templates would need to accommodate. For example, some hybrid unitary products are intended mainly for ventilation air dehumidification, while others are intended for sensible space cooling. Therefore, we learned from manufacturers that it would not be fair to represent all systems by the same nominal performance characteristics since they may serve distinctly different purposes.

The student team worked with our industry partners to populate initial performance datasets, with the aim of submitting them to TPEx. Each student-manufacturer pair used different methods to generate these characteristic performance datasets. Some manufacturers had already developed calculators based on in house measurements to estimate performance in each operating mode across an appropriate range of conditions. In this case, the main effort was in properly organizing inputs and outputs for the in-house calculator so as to adhere with the structure imposed by our TPEx performance data template. In this effort, one significant challenge was associated with how to accommodate dependencies between environmental operating constraints and independent variables when our model represents the two independently. A related challenge was in determining a clear definition of what is a discrete operating mode. Some manufacturers were not as prepared to generate detailed performance data for their equipment. In this case, our team collaborated with the manufacturer to develop a component by component model for one product in order to generate characteristic performance information in each mode. In particular, through this project we developed a model for rooftop packaged air conditioners with variable fan speed, multiple compressor stages, and dual evaporative pre-cooling. We then generated characteristic performance maps for one product of this hybrid system type. In doing so, we developed a new method for estimating the simultaneous cooling of water and air within direct evaporative media, which was published as an undergraduate bachelor thesis. The complete dual evaporative pre-cooling model was developed by six different students and two research staff over the course of this project; it represents a substantial enhancement in our ability to predict the performance of this climate appropriate efficiency technology in a variety of circumstances - an originally unexpected product of the project. The dual evaporative pre-cooling model is currently implemented in Matlab, and -upon request - the model is available for use and further development by others. The model is most thoroughly documented in Soren Tinz's bachelor's thesis, and a formal publication of the model is in development.

Lastly, we developed a pre-processing tool to automatically convert the Excel-format characteristic performance data submitted to TPEx, into an IDF format required by the

EnergyPlus feature *ZoneHVAC:HybridUnitaryHVAC*. This was a challenging effort, in part because the input and output data formats were continually revised throughout the project, and because the data input structure required for *Table:MultiVariableLookup* objects in EnergyPlus is incredibly complex. The effort required substantial research into computational tools for interpolation of sparse multi-dimensional datasets. Although the translator is operational, there are still some small but acceptable errors introduced by our translator which could be improved with further efforts. In terms of a permanent solution, TPEx Team at the NREL will need to formally incorporate this translator into the TPEx servers, so that data submitted for hybrid unitary air conditioner products will be automatically converted to an IDF format and posted to the BCL. When this occurs, the translator method we developed will need to be converted from Matlab to Ruby.

Collaboration with the TPEx team at NREL was delayed several times over the course of the project, mainly because necessary staff were on leave or overcommitted. Our original intention was to launch the new technology category on the TPEx by September 2016 so that manufacturers could formally post performance information there during the second year of the project. Our agreement with the manufacturers was that our students would work with their engineering teams to introduce the web-based database and help them to submit product information. Unfortunately, the technology category was not launched until near the end of the project, well after our student team had graduated. As a result, although the technology category is now live and available to the public, our industry partners have not yet posted product information. Future efforts will be required to rekindle manufacturer attention and to help them post product information to the TEPx.

Programmatic objectives:

- Cultivate university - industry partnership and technology transfer

  One overarching aim of the funding program was to advance university - manufacturing industry collaboration and technology transfer related to energy efficiency in buildings. Our project was not about developing a new technology per se, instead our collaboration focused on improving manufacturers' capabilities to simulate their hybrid air conditioning equipment for various climates and building types. Modeling capabilities have been a substantial challenge for hybrid air conditioners. Engineers have been unable to model various hybrid air conditioners during the design phase of a building - let alone consider various hybrid products by way of parametric simulation. Lacking standard modeling methods, there has previously been no code compliance pathway for hybrid air conditioners, and utility energy efficiency programs have been unable to predict energy savings impacts for technologies in this class. Our collaborative effort with manufacturer partners aimed to dissolve these impediments.

  We involved manufacturers in design of the new EnergyPlus feature, and in design of the data structure implemented in the TPEx. Our student team served as the main touch point for this collaboration. Each undergraduate student on our core research team was paired with a technical mentor from our industry partners. During the academic year, our students worked with their manufacturer mentors to develop models and equipment performance datasets. In doing so, our students explained current plans for the EnergyPlus feature and TPEx data structure. Through this process the student-mentor pairs continuously developed review and feedback which led to many constructive technical revisions. Additionally, in September 2016 we hosted a multi-day workshop at the NREL with eight undergraduate researchers, each of the manufacturer mentors, and our technical collaborators at LBNL and NREL. At this workshop, the whole team committed three days to scrutinizing every aspect of the technical developments for the project. The constructive feedback and stakeholder consensus developed through this collaborative meeting was essential to settling many of the technical details for our tool. For example, in this meeting we finally agreed that the EnergyPlus feature would not include an autosizing function, since the performance data submitted to TPEx would represent model-number-specific products, and might not be appropriate for arbitrary scaling.

Additionally, our manufacturer partners also supported summer apprenticeships for students on our undergraduate research team. After working as a student research team for the entire academic year, students worked as interns with their industry partner for the summer months. During this time, the students continued working on their objectives for this project, but were also involved in a variety of activities within the manufacturers' engineering teams. Our industry partners found it especially helpful to have undergraduate interns that had been well prepared for work in the industry of manufacturing energy-efficient building technologies.

- Expand university educational resources surrounding building technology, energy, and efficiency

  As a part of this project we recruited new students for existing courses and student programs related to energy and efficiency, including a course on fundamentals of energy efficiency, and an engineering course on introduction to design and analysis of HVAC systems. For our core undergraduate student research team, we encouraged participation in an energy efficiency intern development program, focused especially on business and policy in the field of energy and efficiency.

  As a part of this project, we hosted a graduate-level journal review seminar focused on a wide range of topics related to building energy efficiency research and technology. This course covered many issues, including: assessment of embodied energy in buildings, the rebound effect following behavior or technology interventions, water and energy relationships, carbon sequestration, zero net energy policy, occupancy sensing systems, and solar cooling. For each topic, the whole group focused on a central academic article on the topic. Each student read and contemplated the central article, then researched related research on the topic. The group then assembled a library of references that give context and balance to the issue at hand.

  Most significantly, as part of this project, we hosted several undergraduate mechanical engineering students for their capstone bachelor thesis projects. One student - a visiting scholar from Aachen - developed a new numerical model to estimate the simultaneous cooling of water and air within direct evaporative media. The other students - who worked on teams of 3-5 in two consecutive years - focused on developing and calibrating a complex EnergyPlus model of a zero-net-energy commercial building. The building modeled used internal thermal mass, a variable speed air-to-water heat pump, radiant cooling and heating, and natural ventilation for night flush cooling and indoor air quality. Constructing such a detailed multi-zone EnergyPlus model is an extensive endeavor, and introduced the team to many concepts related to systems and control. Each bachelor thesis project represented a significant research contribution, and broadened undergraduate education at UC Davis related to energy efficiency.

- Expand undergraduate research and experience in building energy efficiency and manufacturing

  Typically, undergraduate research assistants have limited responsibility in university research. Research is regularly envisioned and managed by senior research staff, and executed by postdoctoral researchers, assistant researchers, and graduate students. Usually, undergraduates are involved only as task-level assistants, with little opportunity to participate in the many aspects of a research project. Often, an undergraduate will contribute to a research project through data entry, data processing, construction, programming, or measurement without understanding how that task fits into the broader research puzzle. Breaking from standard practice for this project, we gave our undergraduate fellows a substantial level of project responsibility. Our students acted as the direct and regular point of contact between industry partners and the research program. This forced them to develop an understanding of the entire project purpose, and to coordinate amongst one another to communicate consistently with external project partners, while balancing varied and sometimes conflicting perspectives. Instead of task-level direction, our students were given project-level end goals, and asked to work together as a team to develop day-to-day activities needed to work toward these objectives. Staff researchers worked with the student teams on a weekly basis to review their activities, troubleshoot challenges, and guide them toward effective methods. Students developed all content for these meetings as a team, and steered staff research advisors toward helping in the ways that they felt was most needed. This was an ambitious arrangement for the project, as it gave critical responsibilities to our undergraduate students. In the end, the approach may have limited the technical achievements of the research project - because so much effort was involved in teaching and learning - but the process advanced several excellent researchers who are now much more well prepared to contribute to research in the field of building energy efficiency and manufacturing.

5. Products

We generated several tangible products through the course of this project. The following paragraphs discuss each product, and link to their current versions:

EnergyPlus Feature

We developed a new object class within EnergyPlus (*ZoneHVAC:HybridUnitaryHVAC*) to allow modeling hybrid unitary air conditioners. This new feature is currently slated for public release with EnergPlus v8.9.

- C++ source code (March 5 2018). The feature was developed within the Github repository for EnergyPlus development: NREL/EnergyPlus.
- Compiled release (March 5 2018). A compiled version of EnergyPlus with the new feature ZoneHVAC:HybridUnitaryHVAC.
- Documentation (March 5, 2018)
    - Engineering reference
    - Input output reference
    - New feature proposal
- Example model

Technology Performance Exchange

- New technology class: Hybrid Unitary HVAC.
- Data entry form. This excel spreadsheet defines the web based fields requested for any new hybrid unitary product submitted to TPEx.
- Performance map template. This template is used to record the steady state performance characteristics for each discrete operating mode for a hybrid unitary product submitted to TPEx.
- Nominal performance information calculator. In addition to characteristic performance data, the TPEx also lists nominal performance metrics for products. Since there is currently no industry

standard nominal performance calculation for hybrid unitary air conditioners, and since different hybrid systems may have different primary objectives - and therefore should be represented by different nominal performance metrics - this tool assists data providers in calculating several different nominal performance metrics.

Academic Paper

- Manuscript for academic article: A Universal Model for Hybrid Unitary HVAC Equipment in Building Energy Simulations. This article, reviews a range of literature on hybrid air conditioning systems, explains the need for a universal model for use in building energy simulations, and describes the explicit mathematical formulation of the model. The paper concludes with a validation against one month of field data, and an example annual simulation to demonstrate model function. At the time of this report, the paper is waiting some final additions and author revisions before submission to Applied Energy for editor consideration and peer review.

Characteristic Performance Model for Dual-Evaporative Pre-Cooling

- Model for dual-evaporative pre-cooling on a rooftop packaged air conditioner. The EnergyPlus feature ZoneHVAC:HybridUnitaryHVAC relies on empirical performance data. This data must be generated from laboratory measurements, field measurements, or a first principles based component-by-component model developed for the hybrid product in question. As a part of this project we developed a component-by-component model for dual evaporative pre cooling. The model is most thoroughly documented in Soren Tinz's bachelor thesis, but the most current version of the model (referenced here) incorporates further additions including: an alternate method to estimate the simultaneous cooling of water and air on the direct evaporative media, and a first principles approach to estimate performance of the water to air heat exchanger. Inputs for the model include environmental conditions, and the choice of mode and settings for the system. Outputs include the steady state supply air conditions for the system, as well as electricity use, and water evaporation rate.

Bachelor Theses

- Bachelor Thesis - Soren Tinz - Comparison and evaluation of three methods to estimate evaporative cooling performance with elevated inlet water temperature and computational modeling of a hybrid cooling system.
- Bachelor Thesis - Kieran Wolk, Stephen Sucheski, Stephen Becker, Adam Alemnew, Maxfield Herrenbruck - "Net Zero:Building Energy Modeling."
- Bachelor Thesis - Lynn Huynh, Yitian Liang, Yuanxian Chen "Final Design Report: Net Zero Building Energy Model."

NREL Project Workshop Presentations

- Research presentations. In September 2016, we hosted a multi-day workshop at NREL for the core research team and our industry partners. The research team presentations from that workshop are compiled here.

6. Model Explanation

6.0.1. Background and model objectives

A "hybrid unitary HVAC system" is any packaged forced air system that has multiple discrete operating modes. Broadly speaking, a hybrid system is any system that exhibits both continuous and discrete dynamic behavior – a system that can both flow (as could be described by a differential equation) and jump (as must be described by distinct modes). In regard to building mechanical systems, most HVAC equipment could technically be considered hybrid systems. For example, performance of a conventional rooftop air conditioner with an economizer mode must be described by both continuous and discrete functions. However, more commonly, practitioners use the term "hybrid" to describe unitary HVAC equipment that have many discrete operating modes. Most commonly, these discrete operating modes arise from the incorporation of components such as heat recovery devices, indirect evaporative cooling, or desiccant dehumidification.

Until the contributions of this project, EnergyPlus was not capable of modeling most hybrid HVAC systems. Although EnergyPlus included many features that would be included in many hybrid HVAC systems (indirect evaporative cooling, multi-speed DX, heat recovery) the architecture of sub-component relationships within EnergyPlus is generally not flexible enough to accommodate the bewildering multitude of alternate hybrid system architectures. Moreover, the mathematical construction of existing sub-component models precludes complete representation of some market available products.

We hope that in time existing EnergyPlus sub-components can be expanded so that end users could model customized hybrid system architectures. However, creating and adapting all of the sub-components to satisfy this hope will require enormous effort. For example:

- Consider the Munters HCU, a hybrid unitary DOAS system that incorporates multi-stage vapor compression cooling, a variable speed supply fan, and a desiccant dehumidification wheel. The system is unique in that it uses waste heat from the condenser on one of four vapor compression circuits as the heat source for desiccant regeneration. EnergyPlus includes models for vapor compression systems, and for desiccant dehumidification, but currently these components cannot be connected in a way that would fully represent the Munters HCU. To do so would require revision of Coil:Cooling:DX:multispeed to calculate vapor compression condenser outlet conditions, and to allow division of the condenser waste heat from each stage between different air streams.
- Consider the DualCool, a hybrid unitary RTU that incorporates multi-stage vapor compression cooling, a variable speed supply fan, direct evaporative condenser air pre-cooling, and a type of indirect evaporative cooling for ventilation air. The system circulates water collected in the sump of the direct evaporative condenser air pre-cooler to a water-to-air heat exchanger in the ventilation air stream. As ventilation air is cooled by this water-to-air heat exchanger, the water temperature increases, and the warm water is returned to the top of the direct evaporative condenser air pre-cooler. EnergyPlus includes models for evaporatively cooled vapor compression systems, and models for water to air heat exchangers, but these components cannot be linked in a way that will properly represent the interactive effects between the two. These existing EnergyPlus components could certainly be revised to accommodate the DualCool, it would mainly require explicit definition of a direct evaporative media that predicts the simultaneous cooling of water and air. Often, the DualCool is deployed in such a way that direct evaporative condenser-air pre-cooling is only provided for some of the vapor compression circuits, so Coil:Cooling:DX:multispeed would need to be adapted to allow definition of multiple condenser air streams.

The challenges with representing most hybrid air conditioners as component-by-component models within EnergyPlus is mainly related to two issues:

- Most EnergyPlus HVAC sub-component models are designed to evaluate the thermodynamic impact on the zone, and do not fully evaluate all secondary physical phenomena that influence system performance. For example, Coil:Cooling:DX:multispeed does not explicitly model the condenser, and does not explicitly model separate vapor compression circuits.

- Some hybrid system sub-components do not exist at all. For example, there is not currently a way to represent desiccant enhanced evaporative air conditioning.

Future EnergyPlus revisions ought to continue to expand and adapt HVAC sub-component capabilities to accommodate more hybrid system architectures. However, the component-by-component modeling approach typically employed in EnergyPlus also puts a significant burden on the EnergyPlus end user. Modelers must carefully interpret manufacturer performance information, system architecture, and control strategies then replicate them within EnergyPlus. This requires custom effort by each modeler for every hybrid air conditioner they wish to simulate. The level of effort required to conduct parametric analysis of multiple design alternatives is untenable. Moreover, with this approach it is difficult to have confidence that all modelers will handle all system details similarly and accurately.

In response to these challenges, through this project we developed a new feature for EnergyPlus that is wholly empirical, and structured in a general way so that it can represent a wide variety of hybrid unitary air conditioning equipment. The model is designed to represent packaged unitary forced air equipment. The strengths and weaknesses in our approach are related to the fact the model does not employ any first principles representation of system subcomponents. The model is a black-box with data structures that can apply to almost any type of forced air system.

The new feature - *ZoneHVAC:HybridUnitaryHVAC* - is a black-box model designed to allow empirical representation of a wide variety of hybrid unitary systems. The model does not require information about internal system architecture, however it requires extensive data to describe the performance of a product in every operating mode. The model is intended for forced air equipment and can represent unitary systems that consume electricity, water, and up to two additional fuel types.

6.0.2. Model function within EnergyPlus

The new EnergyPlus feature - *ZoneHVAC:HybridUnitaryHVAC* - operates to provide cooling, heating, ventilation, humidification, or dehumidification for a zone. A *ZoneHVAC:HybridUnitaryHVAC* object is assigned to a zone in EnergyPlus using *ZoneHVAC:EquipmentList* and *ZoneHVAC:EquipmentConnections*. The object must be assigned a supply air node (which must be a zone inlet node), a return air node (which must be a zone outlet node), and an outdoor air node. In the case when the hybrid system modeled does not utilize either return air or outdoor air, a return air node and an outdoor air node must still be assigned. The resulting mass flow rate on those nodes will be zero.

The zone sensible cooling or heating load is determined in each time step according to temperature set points specified in a *ZoneControl:Thermostat* object. The zone humidification or dehumidifaction load is determined in each time step according to relative humidity set points specified in a *ZoneControl:Humidistat* object. The intended zone ventilation rate is specified in a *DesignSpecification:OutdoorAir* object..

The performance of a hybrid system is not solely dependent on the loads and the environmental conditions. A hybrid system may have numerous discrete operating modes, within which other variables may be adjusted in fine intervals. There may be many settings in which a hybrid system could feasibly operate at a given time. Therefore, *ZoneHVAC:HybridUnitaryHVAC* is structured as a constrained optimization problem that is solved in each time step. The feasible settings are the unique combinations of operating mode, outdoor air fraction, and supply air mass flow rate that satisfy constraints. In each time step the hybrid model will choose to operate at one or more settings so as to best satisfy the sensible load, latent load, and scheduled ventilation rate while minimizing resource consumption.

Inequality constraints for the optimization include the ranges of indoor and outdoor psychrometric conditions within which each mode is allowed to operate, and the allowable ranges for supply air temperature and absolute humidity generated by the system. These inequality constraints are specified directly as inputs to each *ZoneHVAC:HybridUnitaryHVAC* object. The scheduled ventilation rate, the zone sensible load, and the zone latent load act as soft inequality constraints.

EnergyPlus simulations occur on user defined time steps, accordingly, the hybrid system may operate in multiple settings within each time step. The portion of each time step spent in a setting is described as the part runtime fraction for that setting. If no combination of settings and part runtime fractions will satisfy all of the soft constraints the system will choose the combination of settings and part runtime fractions that most nearly satisfies all soft constraints.

During any time step that the combination of settings can satisfy all of the soft constraints with part runtime fractions that sum to less than one, the system will operate in a standby mode (Mode 0) for the remainder of the timestep. If the indoor and outdoor psychrometric conditions are beyond the constraints that limit each operating mode, or if no setting will satisfy the constraints on supply air temperature and absolute humidity, the system will operate in standby mode (Mode 0). Furthermore, in circumstances when no combination of settings will satisfy all of the soft constraints, the model will choose the combination of settings that is most nearly satisfactory.

It is important to recognize that the constrained optimization solution will not necessarily correspond to the way that any particular hybrid air conditioner would be controlled in reality. Manufacturers and installers may employ a wide variety of control sequences to choose operating mode and controlled independent variables in response to coincident conditions. The constrained optimization solution employed in this model represents one hypothetical control sequence – the optimal one. Although this solution may be somewhat unrealistic, it should be noted that every HVAC feature in EnergyPlus model makes similar assumptions, and that real control sequences are typically design in an attempt to choose the optimal settings. Nonetheless, we envision that future revisions to this EnergyPlus feature would allows users to implement custom control sequences using the EnergyPlus EMS features..

6.0.3. Model inputs and data

The model requires extensive empirical data to describe system performance in each operating mode as a function of several independent variables. Uncontrolled independent variables include outdoor air conditions and indoor air conditions. Controlled independent variables within each mode include supply air flow rate and outdoor air fraction. Dependent variables include supply air temperature, supply air humidity, electricity use, fuel uses, water use, fan electricity use, and external static pressure. The dependent variables are mapped with lookup tables.

Independent variables (x_k) for the model include:

$x_1 =$ outside air temperature (dry bulb) (°C) $= T_{OSA}$
$x_2 =$ outside humidity ratio ($g_{H2O}/g_{\text{dry air}}$) $= \omega_{OSA}$
$x_3 =$ return air temperature (dry bulb) (°C) $= T_{RA}$
$x_4 =$ return air humidity ratio ($g_{H2O}/g_{\text{dry air}}$) $= \omega_{RA}$
$x_5 =$ normalized supply air mass flow rate (–) $= m_{SA}/m_{SA}^{max}$

$x_6 =$ outside air fraction (–) $= OSAF$

Dependent variables (y_i) for the model include:

$y_1 =$ supply air temperature (dry bulb) (°C) $= T_{SA}$
$y_2 =$ supply air humidity ratio ($g_{H2O}/g_{dry\ air}$) $= \omega_{SA}$
$y_3 =$ total electric power (kJ/kg) $= W'_{elec}/m_{SA}^{max}$
$y_4 =$ supply fan electric power (kJ/kg) $= W'_{fan\ elec}/m_{SA}^{max}$
$y_5 =$ second fuel consumption (kJ/kg) $= W'_{fuel}/m_{SA}^{max}$
$y_6 =$ third fuel consumption (kJ/kg) $= W'_{fuel}/m_{SA}^{max}$
$y_7 =$ water consumption (liters/kg) $= V'_{water}/m_{SA}^{max}$
$y_8 =$ external static pressure (Pa) $= \Delta P_{ESP}$

The relationship between the independent variables and each dependent variable must be specified as lookup tables using Table:MultiVariable Lookup objects. A table must be created for each relevant dependent variable in each operating mode. Every operating mode must have a table for supply air temperature and a table for supply air humidity ratio. If tables are omitted for other dependent variables the model will assume that they are not relevant for the associated operating mode. The model can accommodate up to 26 discrete operating modes, including a standby mode.

To permit scaling of performance data, all extensive dependent variables are normalized by the system maximum supply air mass flow rate $\dot{m}_{SA}^{max}$. To rescale performance data, extensive parameters are multiplied by a desired maximum supply air flow rate, which is specified as an input to each *ZoneHVAC:HybridUnitaryHVAC* object.

6.0.4. Model calculations

The constrained optimization problem solved in each time step can be stated explicitly as:

min	$\dot{W}_{resource}(t) = f(\ T_{OSA}(t),\ \omega_{OSA}(t),\ T_{RA}(t),\ \omega_{RA}(t), \ldots$ $\ldots [\ mode_i(t), \dot{m}_{SA_i}(t), OSAF_i(t), RF_i(t)\ ]_{i=1}^{N}\ )$
$subject\ to$	
soft constraints (sensible load, latent load, ventilation rate)	
	$\dot{Q}_{sensible}(t) \geq \dot{Q}_{sensible}^{requested}(t)$
	$\dot{Q}_{latent}(t) \geq \dot{Q}_{latent}^{requested}(t)$
	$\dot{m}_{ventilation}(t) \geq \dot{m}_{ventilation}^{requested}(t)$
constraints on supply air temperature and humidity ratio	
	$T_{SA}^{min}(t) \leq T_{SA}(\check{t}) \leq T_{SA}^{max}(t)$
	$\omega_{SA}^{min}(t) \leq \omega_{SA}(\check{t}) \leq \omega_{SA}^{max}(t)$
limits for each operating mode	
	$T_{OSA}^{min\ mode\ j} \leq T_{OSA}(t) \leq T_{OSA}^{max\ mode\ j}$

	$\omega_{OSA}^{min\ mode\ j} \leq \omega_{OSA}(t) \leq \omega_{OSA}^{max\ mode\ j}$
	$RH_{OSA}^{min\ mode\ j} \leq RH_{OSA}(t) \leq RH_{OSA}^{max\ mode\ j}$
	$T_{RA}^{min\ mode\ j} \leq T_{RA}(t) \leq T_{RA}^{max\ mode\ j}$
	$\omega_{RA}^{min\ mode\ j} \leq \omega_{RA}(t) \leq \omega_{RA}^{max\ mode\ j}$
	$RH_{RA}^{min\ mode\ j} \leq RH_{RA}(t) \leq RH_{RA}^{max\ mode\ j}$
	$\dot{m}_{SA}^{min\ mode\ j} \leq \dot{m}_{SA}(\check{t}) \leq \dot{m}_{SA}^{max\ mode\ j}$
	$OSAF^{min\ mode\ j} \leq OSAF(\check{t}) \leq OSAF^{max\ mode\ j}$

Since the model may select multiple settings within each time step, the outputs reported are weighted averages of the outputs determined for each setting independently.

Intensive output variables are determined as a supply air mass weighted time step average.

- Supply air temperature is determined as a supply air mass weighted time step average:

$$\overline{T_{SA}}(t) = \frac{\sum_{i=1}^{N} RF_i(t) \cdot \dot{m}_{SA_i}(t) \cdot T_{SA_i}(t)}{\sum_{i=1}^{N} RF_i(t) \cdot \dot{m}_{SA_i}(t)}$$

- Supply air humidity ratio is determined as a supply air mass weighted time step average:

$$\overline{\omega_{SA}}(t) = \frac{\sum_{i=1}^{N} RF_i(t) \cdot \dot{m}_{SA_i}(t) \cdot \omega_{SA_i}(t)}{\sum_{i=1}^{N} RF_i(t) \cdot \dot{m}_{SA_i}(t)}$$

- Outdoor air fraction is determined as a supply air mass weighted time step average:

$$\overline{OAF}(t) = \frac{\sum_{i=1}^{N} RF_i(t) \cdot \dot{m}_{SA_i}(t) \cdot OAF_i(t)}{\sum_{i=1}^{N} RF_i(t) \cdot \dot{m}_{SA_i}(t)}$$

Extensive output variables are determined as time weighted time step averages.

- Supply air mass flow rate is determined as a time weighted time step average of the supply air mass flow rate in each setting:

$$\overline{\dot{m}_{SA}}(t) = \frac{\sum_{i=1}^{N} RF_i(t) \cdot \dot{m}_{SA_i}(t)}{\sum_{i=1}^{N} RF_i(t)}$$

- System electric power, fan power, fuel consumption, and water consumption are determined as time weighted time step averages of each resource use in each setting.

$$\overline{\dot{W}_{resource}}(t) = \frac{\sum_{i=1}^{N} RF_i(t) \cdot \dot{W}_{resource_i}(t)}{\sum_{i=1}^{N} RF_i(t)}$$

In this way, calculations of cooling capacity and other metrics can proceed according to typical functions at the time step scale. For example:

$$\begin{aligned}\dot{Q}_{SystemSensible}(t) = \overline{\dot{m}_{SA}}(t) \cdot \ldots \\ \ldots \tfrac{1}{2} \cdot (c_{p,RA}(t) + \overline{OAF}(t) \cdot (c_{p,OA}(t) - c_{p,RA}(t)) + \overline{c_{p,SA}}(t)) \cdot \ldots \\ \ldots (T_{RA}(t) + \overline{OAF} \cdot (T_{OA}(t) - T_{RA}(t)) - \overline{T_{SA}}(t))\end{aligned}$$

and:

$$\dot{Q}_{SystemLatent}(t) = \frac{1}{(1+\overline{\omega_{SA}}(t))} \cdot \overline{\dot{m}_{SA}}(t) \cdot \ \lambda \cdot ... \\ (\omega_{RA}(t) + \overline{OAF} \cdot (\omega_{OA}(t) - \omega_{RA}(t)) - \overline{\omega_{SA}}(t))$$

and:

$$\dot{Q}_{ZoneSensible}(t) = \overline{\dot{m}_{SA}}(t) \cdot \frac{1}{2} \cdot (c_{p,RA}(t) + \overline{c_{p,SA}}(t)) \cdot (T_{RA}(t) - \overline{T_{SA}}(t))$$

and:

$$\dot{Q}_{ZoneLatent}(t) = \frac{1}{(1+\overline{\omega_{SA}}(t))} \cdot \overline{\dot{m}_{SA}}(t) \cdot \ \lambda \cdot (\omega_{RA}(t) - \overline{\omega_{SA}}(t))$$

where:

$\dot{Q}_{SystemSensible}(t)$	= system sensible cooling capacity for time step
$\dot{Q}_{SystemLatent}(t)$	= system latent cooling capacity for time step
$\dot{Q}_{ZoneSensible}(t)$	= zone sensible cooling capacity for time step
$\dot{Q}_{ZoneLatent}(t)$	= zone latent cooling capacity for time step
$\overline{\dot{m}_{SA}}(t)$	= time weighted average supply air mass flow rate for time step
$c_{p,RA}(t)$	= specific heat capacity of return air for time step
$c_{p,OA}(t)$	= specific heat capacity of return air for time step
$\overline{c_{p,SA}}(t)$	= supply air mass weighted average specific heat capacity of supply air for time step
λ	= latent heat of vaporization for water
$\overline{OAF}(t)$	= supply air mass weighted average outdoor air fraction for time step
$T_{RA}(t)$	= return air temperature for time step
$T_{OA}(t)$	= outdoor air temperature for time step
$\overline{T_{SA}}(t)$	= supply air mass weighted average supply air temperature for time step
$\omega_{RA}(t)$	= return air humidity ratio for time step
$\omega_{OA}(t)$	= outdoor air humidity ratio for time step
$\overline{\omega_{SA}}(t)$	= supply air mass weighted average supply air humidity ratio for time step

7. Conclusions

Through this project, we advanced a suite of resources within and surrounding EnergyPlus to support modeling hybrid unitary air conditioners in building energy simulations. We developed an empirical structure for characteristic performance data that can accommodate a wide range of hybrid air conditioner products, and we developed resources for TPEx to allow manufacturers and third-party data providers to post performance information on hybrid air conditioner products according to this empirical structure. We developed a method for estimating the behavior of a hybrid system in response to demand for sensible cooling, latent cooling, and/or outdoor air. Importantly, we implemented this method as a new object class in EnergyPlus: *ZoneHVAC:HybrdiUnitaryHVAC*. The feature is slated for release with EnergyPlus v8.9. Furthermore, we developed a script to automatically translate characteristic performance data from the format that data providers submit through TPEx to the format that is required for the input definition of an EnergyPlus model.

The overarching intention of the funding program was to advance university educational resources, undergraduate research, and university-industry collaboration surrounding on energy efficiency in buildings. In honoring that aim we involved twenty different undergraduate students in the technical project efforts over two years. We hosted three mechanical engineering bachelor thesis projects, developed a graduate-level literature review course, and arranged six different summer apprenticeships for undergraduate students with manufacturer partners. We gave undergraduate researchers ambitious long term goals and facilitated their team efforts to achieve those aims in collaboration with industry mentors and project partners at LBNL and the NREL. In addition to developing and testing the new EnergyPlus feature, we developed a first-principles model for dual-evaporative pre-cooling, helped manufacturer partners to generate sample performance data to populate the EnergyPlus feature, and trained several young mechanical engineers on design and modeling of complex mechanical systems within building energy simulations.

The achievements of this project represent substantial contributions to both theory and practice of modeling efficient building energy technologies. We developed and validated a unique strategy for representing complex hybrid air conditioning systems within building energy simulations. Prior to the efforts of this project, it would be very difficult for an engineer to model any hybrid air conditioning system as part of the building design phase, and it would be nearly impossible to evaluate alternatives parametrically. Importantly, since there were previously no publicly available modeling resources for hybrid air conditioners, there is currently no reasonable code compliance pathway for such equipment. This project has made the development of code compliance pathways a more reasonable possibility. The tools and resources produced by this project alleviate some of the severe technical challenges that hinder broader adoption of hybrid air conditioning systems, and should be incredibly useful to manufacturers, design engineers, customers and regulators.