UNIVERSITY O
MARYLAND

U.S. DEPARTMENT OF ENERGY SOLAR DECATHLON 2017

reACT
TEAM MARYLAND

Primary Student Contact
Whitney Paige Andros
A James Clark School of Engineering
University of Maryland
1131 Glenn Martin Hall, College Park, MD 20742
andros@terpmail.umd.edu

U.S. DEPARTMENT OF ENERGY SOLAR DECATHLON 2017

ENGINEERING NARRATIVE

August 10, 2017

Engineering Narrative

***reACT*: re**silient **A**daptive **C**limate **T**echnology

Functional requirements: what the house should do

The engineering design of re*ACT* aims to produce a house with an unprecedented combination of resiliency and adaptability. Houses built using re*ACT*'s design adapt to both their fixed location and the surrounding environment that will change continuously over multiple timescales.

To maximize our measures of sustainability over multiple measures, re*ACT* uses or recycles low-value resources that would otherwise go to waste. Resiliency derives from the rational integration of engineering subsystems to manage the functional overlap of the engineering subsystems. Adaptability requires self-awareness, so re*ACT* predicts its state over a reasonable time horizon. With this data, it can work with the homeowners to manage resource use for the upcoming day or carry out its management tasks autonomously.

Engineering design: how engineers achieve the functional requirements

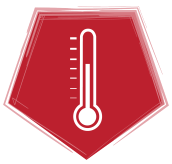
To meet the house's functional requirements, the reACT engineering team integrated a large array of engineering subsystems and built in flexibility so the design wouldn't restrict future upgrades and modifications. The house design uses model-based systems engineering concepts, making extensive use of both existing and in-house open-source simulation tools developed for re*ACT*.

As re*ACT*'s design evolved, so did our simulation tools. We transitioned from static, model-based engineering design to dynamic performance prediction. With that change, we produced **reACT virtual**, a computer simulation that came online a year before construction. re*ACT* virtual predicts future levels of electrical and thermal energy, water, and other states in response to current weather forecasts at a physical address assigned to the house. With this program, the engineering team explored the behavior of its major engineering subsystems at home in College Park, MD, and in many other locations including the 2017 Solar Decathlon competition site in Denver, CO.

Sustainability metrics

re*ACT* integrates the house's engineering and architectural design elements to meet targets for four sustainability measures. These metrics rigorously quantify different aspects of what sustainability with respect to energy, water, and food. More information on the continuing refinement of these metrics can be found at reactvirtual.eng.umd.edu.

Electrical energy This traditional measure of sustainability is defined by the difference between the PV power production integrated over the day and the energy consumption of fixed and variable loads. Note that house primary battery storage charge/discharge is not included in this calculation, even if the battery is being charged from the grid.



Thermal energy A key re*ACT* design element is its greenhouse-enclosed courtyard (Greencourt) that can be transformed into a thermal energy source or sink for the outdoor units of re*ACT*'s heat-pump water heater and HVAC systems. In this context, the usable thermal energy in the courtyard is determined by the temperature difference between the outdoor air and the air in the courtyard. The quantity of this thermal energy is used to define a thermal energy sustainability metric unique to re*ACT*.

Water re*ACT* features rainwater harvesting and a sophisticated greywater filtration and disinfection system to reduce the need for purchasing potable water. Using our model-based estimation of house water resources and precipitation forecast data, we developed a water sustainability metric based on a normalized ratio of reclaimed to total water daily use.

Reduced carbon To quantify the rate of energy embodied as food in our hydroponic and surrounding gardens, we created a carbon sustainability metric based on the production of energy-rich (reduced) carbon compounds by the indoor and outdoor gardens relative to the house occupants' production of CO_2 (oxidized carbon).

To explain the technology responsible for re*ACT*'s excellence in these four sustainability metrics, the following sections highlight the unique design aspects of the major engineering subsystems.

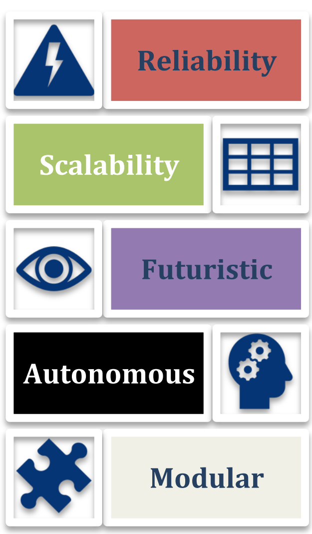
Electrical power system engineering design

The power system, comprising PV modules, inverter, battery, and distribution system is the house's most important mechanical system. In addition to providing power to meet the demands of the other subsystems in a seamless and uninterrupted manner, the power system regulates charge levels in both the primary and electric vehicle batteries to optimize when power is purchased from or sold to the grid.

The power system can be broadly divided into three primary operations: generation (PV modules, optimizers, inverter, and battery); distribution (panels and wiring); and monitoring (power generation and consumption monitoring, system performance and assessment). Given this wide range of equipment combinations and choices, we developed a rational means of selecting the best components for reACT. Our criteria included reliability, scalability, use of state-of-the-art technology, autonomy, and modularity of different designs.

This method revealed that much of the decision should be driven by the inverter configuration. For example, **string inverters**–are well-known, extensively tested, and established in the marketplace, but they fall short in terms of modularity, autonomy, and efficiency when the string is partly shaded. More importantly, without significant modifications, standard string inverter-based systems are incapable of rapidly shutting down in emergency situations. **Micro-inverter** systems address many of the safety concerns associated with string inverters and they are capable of module-level control, but they can suffer when used in long strings, such as those used on each wing of re*ACT*. Moreover, like string inverter systems, the power output of micro-inverters must be rectified when battery storage is used, reducing overall system flexibility and performance.

Our ultimate power system design choice was based on using single inverter and module-level **DC-DC optimizers**. This design choice satisfied all our selection criterion by allowing for modular-level control and safety during emergencies and loss of grid power, sophisticated cloud-based module performance monitoring capabilities, automatic PV array optimization that suits the differing orientation of re*ACT*'s two PV arrays, and direct DC charging of our primary house battery system. Specifically, we chose to use SolarEdge's StorEdge™ inverter and optimizer, a 9.8 kWh LG Chem lithium-ion battery, and two PV arrays each consisting of fourteen SunPower SPR-X21-335 PV modules that produce 9.4 kW at maximum power conditions.



An important aspect of this configuration is its ability to program a battery-charging policy into distinct operating modes, such as prioritizing battery change or maximizing purchasing and selling power based on the power rate schedule. This ability, in conjunction with virtual re*ACT*'s ability to predict and select the optimal mode, forms a key element in our home automation technology.

HVAC and water heating

Heating and cooling

Interior heat pump units provide heated or cooled air using vapor compression cycle technology. In cooling mode, these units also dehumidify the air. Air is drawn from the conditioned space in which each unit is located, heated or cooled / dehumidified and then recirculated into the space.

Interior units are generally installed high on the wall or in the ceiling, and a separate unit generally is installed in each living space (living room, bedroom, etc.). The compressor / condenser unit is normally located outside the house. Its function is to reject heat from the interior (cooling mode) or absorb heat from the exterior (heating mode).

For re*ACT*, we use a variable refrigerant flow (VRF) heat pump system, model-LMU30CHV, from LGE. This system has a capacity of 30,000 BTU and a seasonal energy efficiency ratio (SEER) of 22 and can supply up to four indoor units. Each room is controlled by an individual remote control with sensors that enable zoning control.

Water heating

For water heating, air-source heat-pump cycle technology is used to absorb heat from the air to heat water. For the air-source heat pump water heater (HPWH) system, we use the LG ThermaV split-type heat-pump water heater. The outdoor unit contains the compressor and evaporator, and the indoor unit consists of the heat exchanger, expansion valve, and control panel for the unit pair. The indoor unit heats water in a 50-gallon tank. The outdoor unit has a capacity of 3 kW and a nominal COP of 4.62, with a required power input of 0.65 kW.

Ventilation system

An energy recovery ventilation (ERV) unit is used for house ventilation. The ERV of re*ACT* has four ducts: two interact with outdoor air and two interact with ambient air temperature within the house. CO_2 sensors installed in the control center control the ventilation flow rate. The ERV is a ComfoAir 200 from Zehnder; this unit can move 118 cfm of air at an external pressure of 0.8” WC. The integrated cross-counterflow heat exchanger achieves efficiencies of up to 95%. The top of the ERV contains a supply (w.r.t. the ERV) air duct where air at ambient conditions enters the ERV, preferably the air from rooms that contain excess heat (e.g., bathroom, kitchen, machine room). There also is an auxiliary air duct that feeds air to locations needing heat and fresh air. The bottom of the ERV has an exhaust air duct where outdoor air enters the ERV, providing the home with fresh outdoor air and maintaining healthy CO_2 levels.

System optimization

Based on early re*ACT* energy analysis, we determined that approximately 3,000 kWh/yr of the total 8,000 kWh/yr electrical energy demand was consumed by home heating, cooling, and hot-water production, even with state-of-the-art VRF, HPWH, and ERV units. To further reduce this demand, the HVAC team conducted extensive research and found that preheating and precooling air sent to the VRF outdoor unit (OU) created significant improvements in performance. For example, there was a 10-20% increase in the cooling efficiency with as little as a 4 K decrease in the ambient temperature. Because of the delay in defrosting operations, preheating the outdoor air demonstrated an even more dramatic effect at ambient temperatures near freezing. The HPHW energy consumption was also shown to demonstrate the benefits of preheating air fed to its OU.

This approach to increasing the efficiency of HVAC and heat-pump water heaters fits perfectly with one of re*ACT*'s signature design features: its courtyard's function as a thermal resource. The courtyard's skylight vents allow the homeowner to save energy by maintaining the courtyard air at a temperature that is either higher or lower than the ambient air. For example, the homeowner can generate courtyard air that is warmer than ambient outdoor air by closing the skylight vents during the day and sending air to the OUs of the VRF and HPWH. Likewise, on hot days with cool mornings, the courtyard can be pre-cooled in the early morning, and that air can be harvested later to precool the VRF OU air feed. The OUs would be housed in re*ACT*'s attic with a damper control system to switch between the two modes of operation.

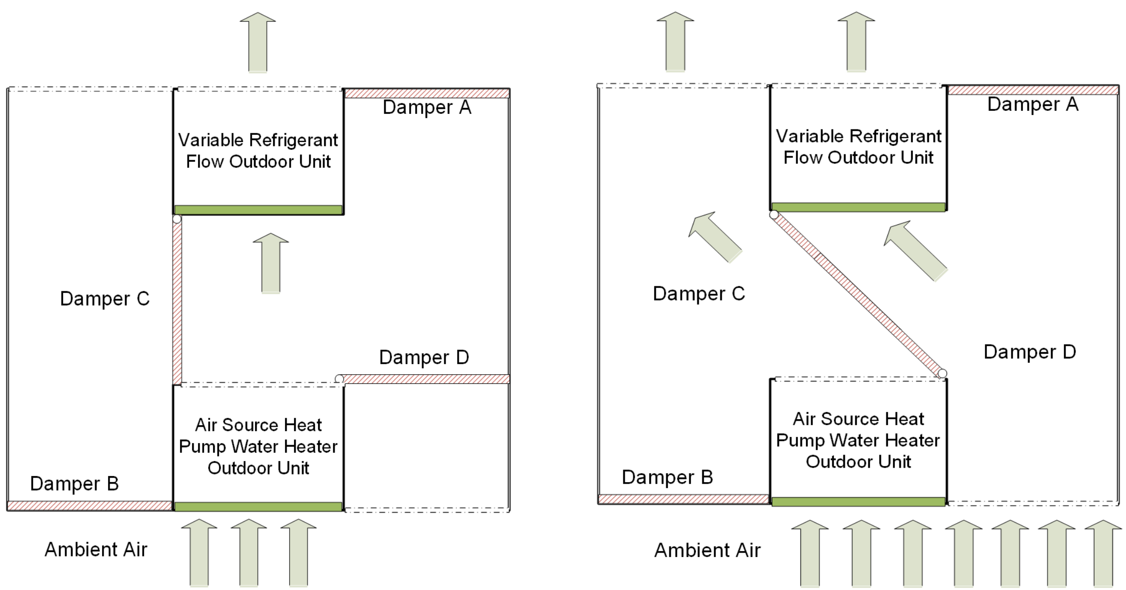


Figure 1. *Cooling season damper (left); damper positions for heating season (right).*

A final courtyard design iteration combines both OUs by directing the air to flow through each in a sequential fashion. Consider the configuration shown in Figure 1 (left). In this arrangement, warm courtyard air flows through the HPHW OU, is cooled, and then flows though the VRF OU to further improve its cooling performance. This constitutes the cooling season (summer) mode of operation. In heating season, the cooler air from the HPHW OU is rejected and warm courtyard air is directed to both OUs through the rearrangement of the dampers shown in Figure 1 (right).

Automation

To be highly adaptable, re*ACT* (and future iterations of its design) must be self-aware and prescient. Since January 2016, the re*ACT* Automation Team has been building and testing a physically based simulator of the house's electrical and thermal energy, water, and CO_2 dynamics that can predict the system's resource inventories and economic performance based on the local weather forecasts.

Among the numerous modeling elements produced by the team is an algorithm that predicts the sun's irradiance as a function of house location and time of year. When combined with daily cloud-cover forecasts, we can determine the instantaneous incident solar irradiance on each external surface of the house, including all windows and PV modules, at any point in time during the day. An equivalent-circuit PV cell model is matched to the manufacturer's performance data to determine the power produced by the PV arrays over the course of the day using the predicted irradiance levels. Nominal scheduled electrical loads have been identified and are stored in a machine-readable (XML) format; the loads are read by the simulator and used to compute energy consumption associated with regularly scheduled events.

Incident radiation and indoor/outdoor air temperature variations are used to determine heat transfer rates through the house external walls. External wall and window heat transfer, direct radiation through the house windows, and waste heat produced within the house determine HVAC loads, indoor air temperature, and overall net power consumption/production. Water and CO_2 dynamic balances also are accounted for in the complete re*ACT* model.

re*ACT* virtual

re*ACT* virtual is a virtual house that can be placed anywhere in the US, as well as most places in the world. Every day since mid-October 2016, shortly after local midnight, a sequence of Python scripts automatically reads the weather reports for College Park and the 2017 Solar Decathlon competition site in Denver to predict the performance of Team Maryland's virtual re*ACT* houses during that day (reactvirtual.eng.umd.edu).

Since the onset of this project, we have accumulated predicted performance data in terms of solar power produced and power consumed by household events, such as charging the car early each morning. We have then translated those data into projected profits and costs (see Figure 2 below). The plots illustrate that even on the partly cloudy day shown, our virtual houses can produce a significant net-positive energy behavior and a profit for the occupants.

Supervisory control

Based on our model's predictive power, we have developed a hierarchical control system to further optimize the use of water, electrical and thermal energy, and carbon-based resources. The strategy we have developed has house automation being regulated by a model-based (re*ACT* virtual) supervisory control structure. We developed this approach to optimizing the house resources while avoiding the need to micromanage all house functions. This strategy ensures fault tolerance in our system (the house will continue function in a default mode with the system turned off), that the supervisory control system will be minimally invasive and maximize both potential for upgrades and compatibility with existing and future home automation technologies.

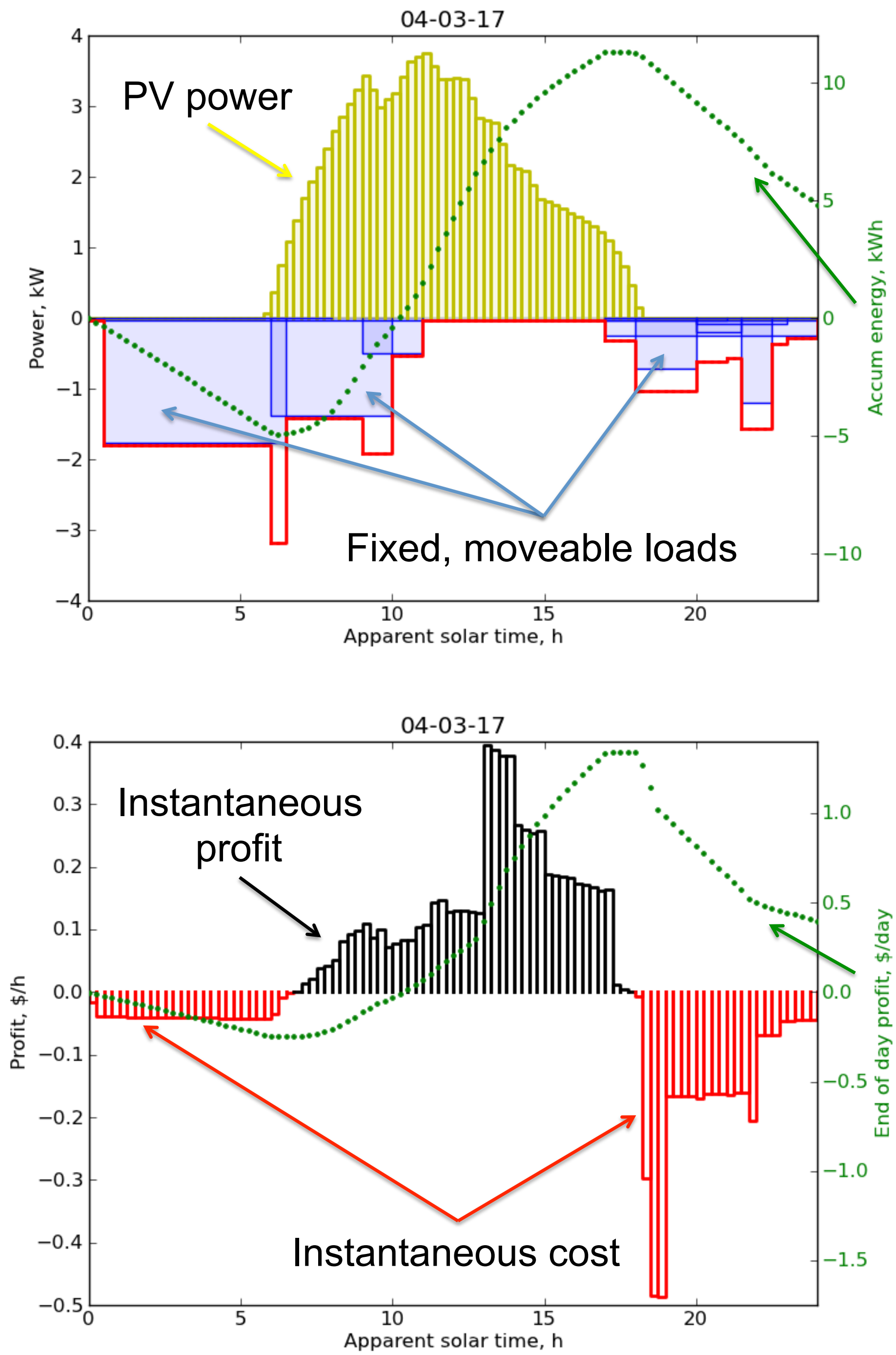


Figure 2. *A representative prediction for instantaneous power and daily energy production for virtual reACT located in College Park (left); a summary of that day's economic performance (right). One can find today's predicted performance online at [reactvirtual.eng.umd.edu.](reactvirtual.eng.umd.edu)*

As such, we optimize the sequencing of events that consume or produce significant quantities of energy, water, and other resources to maximize both the sustainability and economic goals of the household. Given the scalability of our software design, in the future we will seek to optimize the shared resources of entire communities.

Sensors and actuators

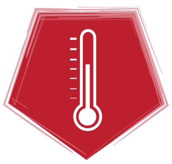
An array of sensors and actuators exits at the interface between the software (for simulation, optimization, and control) and the physical elements of re*ACT*. While some sensors of this set are easy to identify (e.g., the indoor air temperature sensors), we note that this set also includes the software elements that autonomously download and parse each day's local weather forecast. Likewise, we consider the house occupants to be members of the actuator set when they act on virtual re*ACT*'s recommendations for house resource use and allocation to improve the sustainability measures through the day ahead.

Some sensors and actuators are found outside re*ACT*'s physical/virtual interface. For example, the thermostat regulating the operation of the variable refrigerant flow (VFR) HVAC system operates independently of the supervisory level of the home automation system. This choice of a hierarchical control architecture results in a home automation system that is robust to failure of the supervisory control level. This intentional, non-invasive approach to supervisory control system design also simplifies the process of occupants' implementing specific and immediate changes to their environment. We applied the same philosophy to home lighting control and several critical and "invisible" control loops, such as water tank level control.

Because of the distinct climates created by the division of re*ACT* into its core, wings, Greencourt, and attic, a network of wireless air-quality sensors are deployed throughout the house. Temperature and relative humidity are monitored in all segments of the house to assess the states of the thermal and water-vapor resources. CO_2 is monitored in the living quarters. These sensors are used in both active and passive modes: they are used to open/close Greencourt skylights and wing windows, to monitor the performance of the HVAC control system, to validate the fidelity of re*ACT* virtual, and to confirm the daily predictions of the sustainability metric values.

A summary of re*ACT*'s sensing and actuation capabilities are provided in the table below, organized by the sustainability metrics. re*ACT* enables the virtual sensors to estimate states that are difficult to measure directly. Thus, it plays a crucial role in our state estimation strategy.

Electrical energy A Neurio home monitor mounted in the main breaker panel measures PV power generation and re*ACT* total power use. Additionally, the built-in StorEdge monitoring capabilities are used for power monitoring redundancy as well as module-level monitoring. The new sensor system developed at the University of Maryland is minimally invasive and is capable of deconvolving total power-consumption into appliance-level signals.



Thermal energy re*ACT* virtual is key to tracking thermal energy resources within the house in that its modeling algorithms make it possible to convert data from a temperature sensor array and forecast outdoor temperatures to the enthalpy associated with heat sources and sinks. Greencourt skylights, wing window actuators, and a Greencourt shade all can be actuated to manage the thermal resources.

Water The sensing and actuation elements of re*ACT*'s water automation system include rainfall contributions to re*ACT* water inventory, automated irrigation controls, water-tank level controls, a map of scheduled water-use events, re*ACT* virtual modeling elements that model greywater filtration rates, room-air relative humidity measurements, and ERV control. .

Reduced carbon re*ACT* is equipped with a network of wireless CO_2 sensors to determine the amount of CO_2 produced by house residents. The rate at which the CO_2 is returned to food through the edible plants of re*ACT* is estimated using re*ACT* virtual, which estimates plant growth based on the day's irradiance and temperature profiles.

Model validation

LEAFHouse was Team Maryland's entry to the 2007 Solar Decathlon, winning 2nd place in the overall competition (Figure 3). Because LEAFHouse returned to the University of Maryland campus, it provides a unique laboratory for long-term evaluation of its systems' performance. It also proved useful in its role as a surrogate to re*ACT* for testing the modeling and sensing technologies destined for re*ACT*.

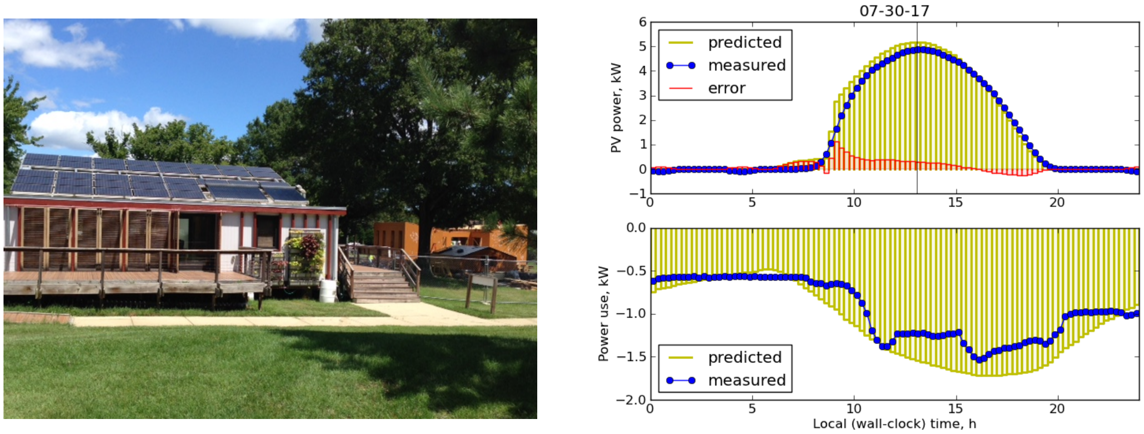


Figure 3. *LEAFHouse (UMCP 2007 Solar Decathlon entry) and reACT under construction on the campus of the University of Maryland (left) and a summary of the power production and consumption over one day of LEAFHouse virtual (right). Note that what is shown is a comparison of the actual measured power profiles to the predicted profiles produced shortly after midnight of the day indicated.*

Because LEAFHouse virtual uses the same simulation engine as re*ACT* virtual, any improvement in LEAFHouse virtual applies immediately to re*ACT* virtual. This was crucial to the development of a high-fidelity model of re*ACT* given the short time available for testing of re*ACT* prototype prior to the 2017 Solar Decathlon competition. Figure 3 shows a snapshot of the measured versus predicted power production/consumption curves over a representative day.

Energy analysis

A detailed thermal and electrical energy analysis for re*ACT* is presented in the **Energy Analysis** document. However, as a preview, we present the predicted net energy production by re*ACT* in Figure 4, together with the projected profit obtained by selling excess energy to the grid using the Solar Decathlon rate schedule.

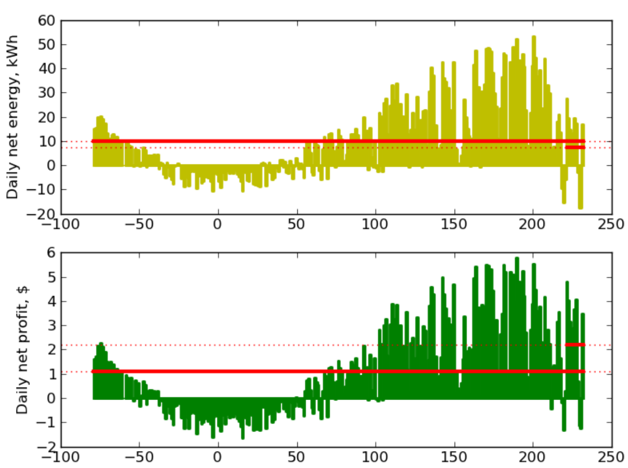


Figure 4. *Top: daily net energy production for reACT virtual located in College Park, MD; daily net profit associated with selling excess power is shown as the green bottom plot. Mean and most-recent 10-day mean values are illustrated by the red horizontal bars.*

UNIVERSITY OF MARYLAND

U.S. DEPARTMENT OF ENERGY SOLAR DECATHLON 2017

reACT
TEAM MARYLAND

Primary Student Contact
Whitney Paige Andros
A James Clark School of Engineering
University of Maryland
1131 Glenn Martin Hall, College Park, MD 20742
andros@terpmail.umd.edu

U.S. DEPARTMENT OF ENERGY SOLAR DECATHLON 2017
ENERGY ANALYSIS
August 10, 2017

Energy Analysis

***reACT*: resilient Adaptive Climate Technology**

The energy analysis of re*ACT* was conducted in two phases: 1) a detailed energy analysis was performed during the design of re*ACT* to evaluate HVAC and other power-related design alternatives using BEOpt, EnergyPlus, and the Modelica Buildings Library, and 2) an in-house physically based model of re*ACT*'s system dynamics in the Python programming language was developed to be used for real-time optimization, sustainability studies, and for energy analysis. Details and results of both approaches are described in the following two sections of this document.

1.0 Parametric study for building environment

BEOpt was used to explore different design options through successive parametric runs. Many different factors including window-to-wall ratio, R-value of the walls, roof and floor, and assumed infiltration rate were studied using this model. These factors were also considered in terms of their impact on architectural expression and site development strategies. Ultimately, these studies led to the configuration shown in Figure 1.1. This is a basic representation of the house geometry in the current U-Shape.

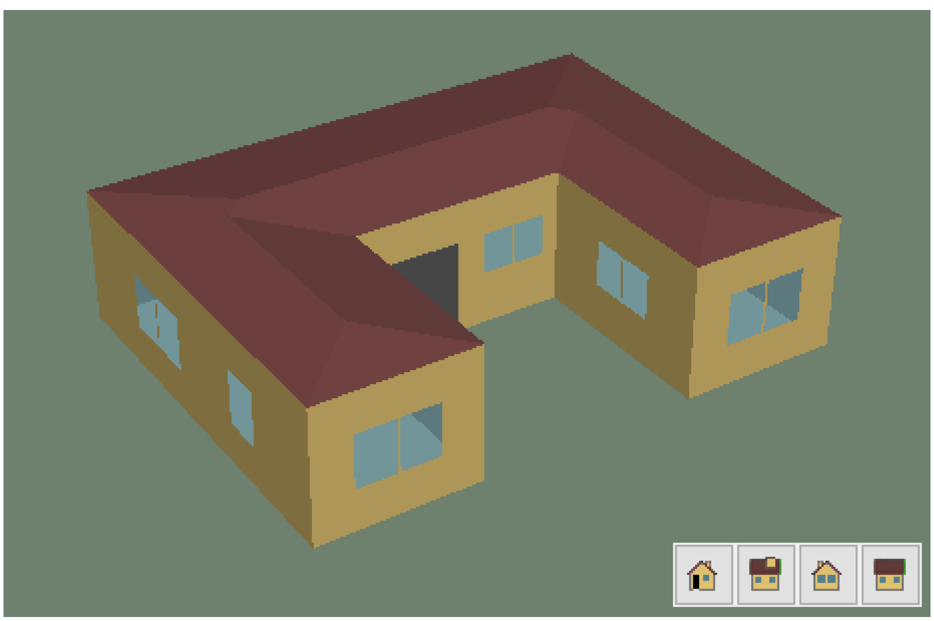


Figure 1.1 3D Geometry of UMD Solar house in BEOpt

The University of Maryland Solar Decathlon Team made use of BEOpt's parametric study capabilities to show how changing certain parameters affected the annual cost and energy consumption. The following four tables and figures show parametric studies for the wall insulation, window type, roof insulation, and total window area. The first parameter of interest is the wall insulation of re*ACT*. As seen in Figure 1.2, the horizontal axis represents the site energy savings (kWh/Year) and the vertical axis the energy related costs ($/year) which are defined as follows:

- Site Energy Savings (kWh/year): The average site energy savings is the difference in average site energy use between a prototype building and the reference (NREL, 2017a).
- Energy Related Cost ($/year): Energy related cost is identical to a life cycle cost (LCC), except for the following:
  - Cash flows are annualized rather than converted to the present value
  - Cash flows are relative to the reference point rather than converted to the present value

A life-cycle cost refers to the total cost of ownership over the life of the technology (NREL, 2017b). When one compares two technologies, the lower energy related cost indicates a more worthwhile investment. Table 1.1 and Figure 1.2 show that as the wall insulation's R-value increases from the reference value of R-33, the site energy savings increases. Hence, the team should use the highest R-value insulation possible to increase energy savings; however, the energy related costs need to be considered as well. As the R-value increases, the energy related costs generally increase as well. The most desirable wall insulation would be a point farthest to right and the bottom of Figure 1.2. A material with high R-value may be too expensive, and the decrease in affordability will outweigh the associated energy savings.

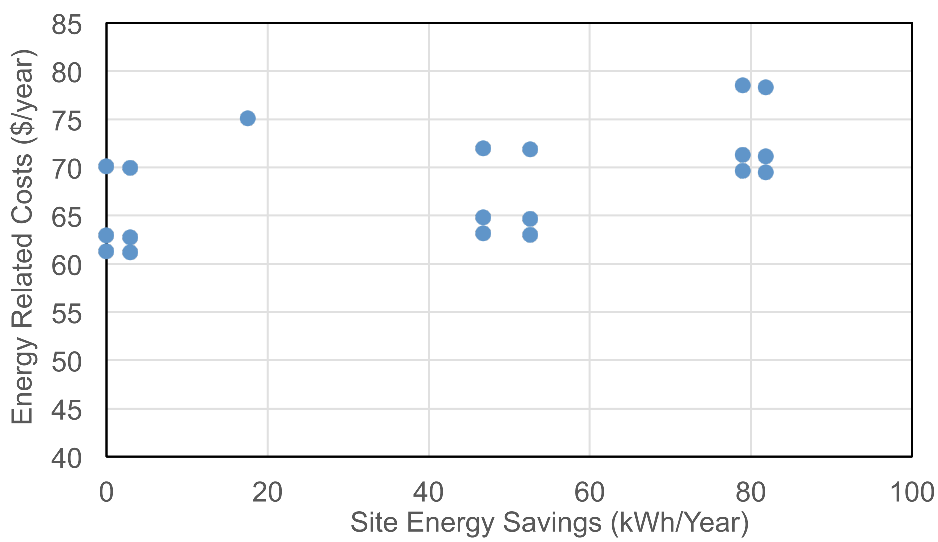


Figure 1.2 Wall Insulation parametric case study

Table 1.1 Parametric case study for wall insulation R-value

Case	Wall Insulation	Site Energy Savings (kWh/yr)	Energy Related Costs Annualizes ($/yr)
Reference R-Value	R-33 Fiberglass Batt, Gr 1, 24 in o.c.	-	70
Point 2	R-33 Fiberglass Batt, Gr-1, 2x4 Staggered, 24 in o.c.	2.92	69.96
Point 3	R-39 Fiberglass Batt, Gr-1, 2x4 Centered, 24 in o.c.	46.77	72.00
Point 4	R-39 Fiberglass Batt, Gr-1, 2x4 Staggered, 24 in o.c.	52.61	71.85
Point 5	R-45 Fiberglass Batt, Gr-1, 2x4 Centered, 24 in o.c.	78.92	78.51
Point 6	R-45 Fiberglass Batt, Gr-1, 2x4 Staggered, 24 in o.c.	81.84	78.29
Point 7	R-33 Cellulose, Gr-1, 2x4 Centered, 24 in o.c.	0.00	62.95
Point 8	R-33 Cellulose, Gr-1, 2x4 Staggered, 24 in o.c.	2.92	62.79
Point 9	R-39 Cellulose, Gr-1, 2x4 Centered, 24 in o.c.	46.77	64.83
Point 10	R-39 Cellulose, Gr-1, 2x4 Staggered, 24 in o.c.	52.61	64.67
Point 11	R-45 Cellulose, Gr-1, 2x4 Centered, 24 in o.c.	78.92	71.34
Point 12	R-45 Cellulose, Gr-1, 2x4 Staggered, 24 in o.c.	81.84	71.12
Point 13	R-33 Fiberglass, Gr-1, 2x4 Centered, 24 in o.c.	0.00	61.31
Point 14	R-33 Fiberglass, Gr-1, 2x4 Staggered, 24 in o.c.	2.92	61.14
Point 15	R-39 Fiberglass, Gr-1, 2x4 Centered, 24 in o.c.	46.77	63.18
Point 16	R-39 Fiberglass, Gr-1, 2x4 Staggered, 24 in o.c.	52.61	63.02
Point 17	R-45 Fiberglass, Gr-1, 2x4 Centered, 24 in o.c.	78.92	69.69
Point 18	R-45 Fiberglass, Gr-1, 2x4 Staggered, 24 in o.c.	81.84	69.47
Point 19	R-35 Cellulose, DR-1, 2x4 Staggered, 24 in o.c.	17.54	75.08

The next parameter varied is the window type. Results are shown in Table 1.2 and Figure 1.3. Differences between the types of windows are the emissivity, number of window panes, and type of gas filling the air gap between panes. Again, the horizontal axis is the site energy savings (kWh/year), and the vertical axis is the energy related costs. Any window type without low emissivity had much lower site energy savings and did not result in a significant reduction in site energy savings. Using argon as the gas filling between panes increased site energy savings, but increased energy related costs. Lastly, as the number of panes increased, so did the site energy savings and the energy related costs. To maximize the amount of energy savings, two or three paned, low emissivity, with argon gas filling should be used for re*ACT*.

The next parameter studied was the roof insulation. Results are shown in Table 1.3 and Figure 1.4. Much like the wall insulation, as the R-value increased, the site energy savings and the energy related costs increased. Better insulation decreases the heating and cooling energy consumption. An insulation value above R-30 is recommended for re*ACT*.

Table 1.2 Parametric case study for window type

Point	Window Type	Site Energy Savings (kWh/yr)	Energy Related Costs, Annualized ($/yr)
Reference	Clear, Single, Non-metal	0.00	124.73
Point 2	Clear, Double, Metal, Air	283.53	266.06
Point 3	Clear, Double, Thermal-Break, Air	397.53	258.23
Point 4	Clear, Double, Non-metal, Air	520.29	249.09
Point 5	Low-E, Double, Non-metal, Air, H-Gain	710.29	240.53
Point 6	Low-E, Double, Non-metal, Air, M-Gain	645.98	250.60
Point 7	Low-E, Double, Non-metal, Air, L-Gain	526.14	268.10
Point 8	Low-E, Double, Non-metal, Argon, H-Gain	762.90	240.54
Point 9	Low-E, Double, Non-metal, Argon, M-Gain	716.14	251.02
Point 10	Low-E, Double, Non-metal, Argon, L-Gain	602.14	269.68
Point 11	Low-E, Double, Insulated, Air, H-Gain	835.98	250.62
Point 12	Low-E, Double, Insulated, Air, M-Gain	777.52	270.60
Point 13	Low-E, Double, Insulated, Air, L-Gain	657.68	295.58
Point 14	Low-E, Double, Insulated, Argon, H-Gain	903.21	268.64
Point 15	Low-E, Double, Insulated, Argon, M-Gain	847.67	302.71
Point 16	Low-E, Double, Insulated, Argon, L-Gain	739.52	335.83
Point 17	Low-E, Triple, Non-metal, Air, H-Gain	786.29	273.19
Point 18	Low-E, Triple, Non-metal, Air, L-Gain	707.37	294.90
Point 19	Low-E, Triple, Non-metal, Argon, H-Gain	815.52	289.95
Point 20	Low-E, Triple, Non-metal, Argon, L-Gain	762.90	309.34
Point 21	Low-E, Triple, Insulated, Air, H-Gain	935.36	491.86
Point 22	Low-E, Triple, Insulated, Air, L-Gain	873.98	512.13
Point 23	Low-E, Triple, Insulated, Argon, H-Gain	1011.36	504.98
Point 24	Low-E, Triple, Insulated, Argon, L-Gain	923.67	527.08

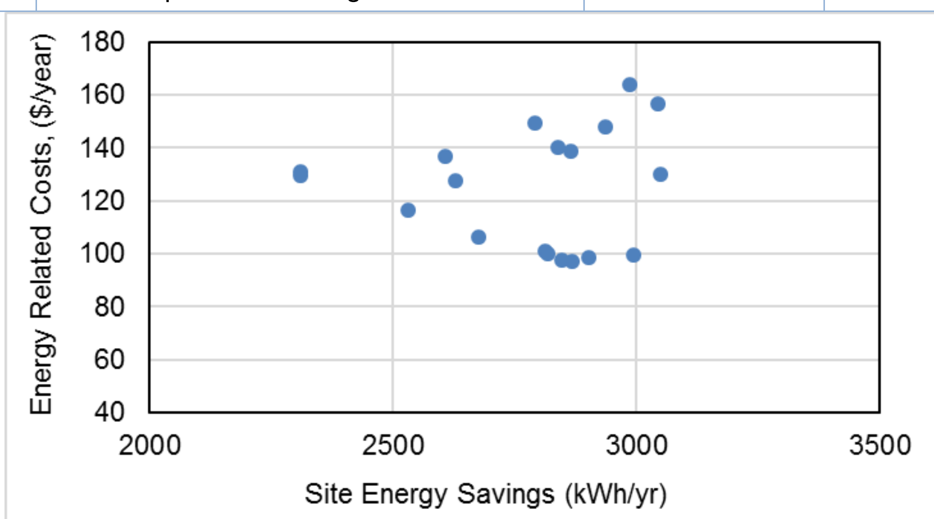


Figure 1.3 Window type parametric case study

Table 1.3 Parametric case study for roof insulation

Point	Roof Insulation	Site Energy Savings (kWh/yr)	Energy Related Costs, Annualized ($/yr)
Reference	Uninsulated, 2x4	0.00	291.22
Point 2	Uninsulated, 2x10, R-15 XPS	2627.97	127.47
Point 3	R-13 Fiberglass Batt, Gr-1, 2x4	2311.20	130.80
Point 4	R-19 Fiberglass Batt, Gr-1, 2x6	2531.18	116.59
Point 5	R-19 Fiberglass Batt, Gr-1, 2x10	2674.90	106.34
Point 6	R-30C Fiberglass Batt, Gr-1, 2x10	2847.94	97.76
Point 7	R-30 Fiberglass Batt, Gr-1, 2x10	2818.61	99.93
Point 8	R-30 Fiberglass Batt, Gr-1, 2x12	2868.47	97.21
Point 9	R-38 Fiberglass Batt, Gr-1, 2x12	2903.67	98.63
Point 10	R-38C Fiberglass Batt, Gr-1, 2x10, R-25 XPS	3050.32	130.25
Point 11	R-30 + R-19 Fiberglass Batt, Gr-1	2994.59	99.81
Point 12	R-13 Fiberglass, Gr-1, 2x4	2311.20	129.35
Point 13	R-30 Fiberglass, Gr-1, 2x8	2812.75	100.81
Point 14	R-36 Closed Cell Spray Foam, Gr-1, 2x6	2839.14	140.46
Point 15	R-47 Closed Cell Spray Foam, Gr-1, 2x8	2935.93	148.08
Point 16	R-20 Open Cell Spray Foam, Gr-1, 2x6	2607.44	136.71
Point 17	R-33 Open Cell Spray Foam, Gr-1, 2x10	2865.54	138.90
Point 18	R-27.5 SIPs	2792.22	149.21
Point 19	R-47.5 SIPs	2985.79	164.12
Point 20	R-63.6 SIPs	3044.45	156.74

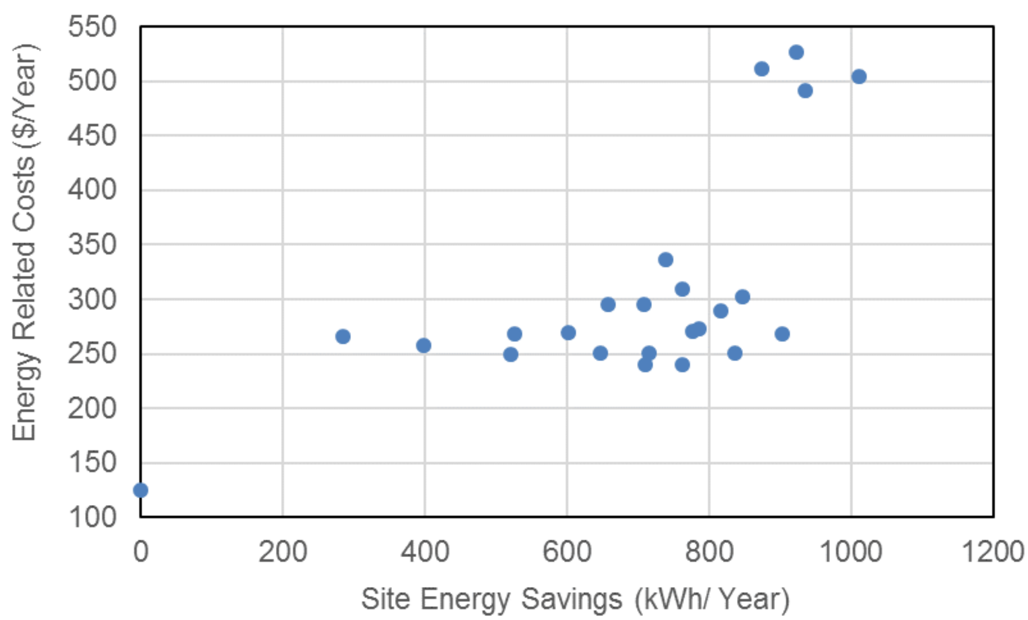


Figure 1.4 Roof insulation parametric case study

The last parameter studied was the amount of window area covering re*ACT*. Results are shown in Table 1.4 and Figure 1.5. As expected, when the window area increased the site energy savings decreased. This was of particular interest due to the Greencourt. The inclusion of the Greencourt causes re*ACT* to have a high amount of window area and potentially decreased energy savings.

Table 1.4 Parametric case study for window area

Point	Window Area (ft^2)	Site Energy Savings (kWh/yr)	Energy Related Costs, Annualized ($/yr)
Reference	306	0.00	79.53
Point 2	255	108.41	13.76
Point 3	120	427.78	-166.64
Point 4	204	202.17	-44.77
Point 5	250	23.44	13.24
Point 6	306	8.79	77.77
Point 7	306	-43.95	74.56
Point 8	200	216.82	-49.55
Point 9	216	237.33	-38.42

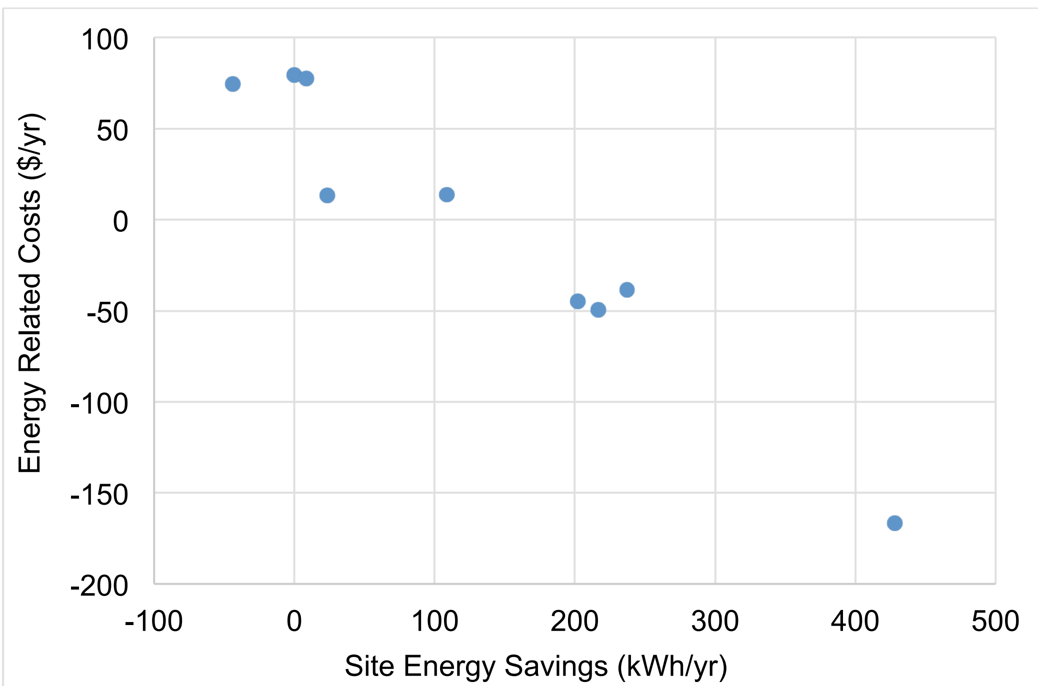


Figure 1.5 Window area parametric case study

After much of the design re*ACT* had been finalized, BEOpt was used to simulate a final energy model. Table 1.5 shows the model parameters and Figure 1.6 shows the annual energy consumption breakdown.

Table 1.5 BEOpt model parameters

Parameter	Value
Finished Floor Area	960 sqft
Neighbors	None
Bedrooms	4
Bathrooms	1
Orientation	South
Double Wood Stud	R-45 Fiberglass, Gr-1, 2x4 Staggered, 24 in o.c.
Wall Sheathing	OSB-with-Rockwool
Exterior Finish	Wood, Light
Finished Roof	R-64, SIP
Roof Material	Metal, Medium
Crawlspace	Uninsulated, Unvented
Interzonal Floor	R-30 Cellulose, Gr-1
Carpet	0% Carpet
Floor Mass	Wood Surface
Exterior Wall Mass	1/2 in. Drywall
Partition Wall Mass	1/2 in. Drywall
Ceiling Mass	1/2 in. Drywall
Window Areas	216 sqft
Windows	Low-E, Double, Insulated, Air, M-Gain
Interior Shading	Summer = 0.5, Winter = 0.95
Door Area	48 sqft
Doors	Fiberglass
Overhangs	2ft, First Story, East and West Windows
Air Leakage	1 ACH50
Ventilation	ERV, 72%, 2010 ASHRAE 62.2
VRF Heat Pump	2.5 Ton, SEER 14.5
Water Heater	HPWH, 50 gal
Lighting	100% LED
PV Panels	10 kW
Cooling Set Point	74°F
Heating Set Point	68°F
Humidity Set Point	50%
Refrigerator	236 kWh/year
Cooking Range	Electric, Induction, 552 kWh/year
Clothes Washer	137 kWh/year
Clothes Dryer	Electric, Energy Factor = 8.22 lb/kWh
Dishwasher	139.1 kWh/year
Schedules	Standard Residential

Table 1.6 Annual energy consumption breakdown

Source	Energy Use (kWh/Year)
Misc.	2,092.6
Ventilation Fan	427.9
Large Appliances	1,987.1
Lights	548.1
Cooling Fan/Pump	11.7
Heating fan/Pump	23.45
Cooling	471.86
Heating	1,817.1
Hot Water, Suppl.	275.5
Hot Water	404.5
Total	8,060
PV	12,547
Net (PV-Total)	4,487

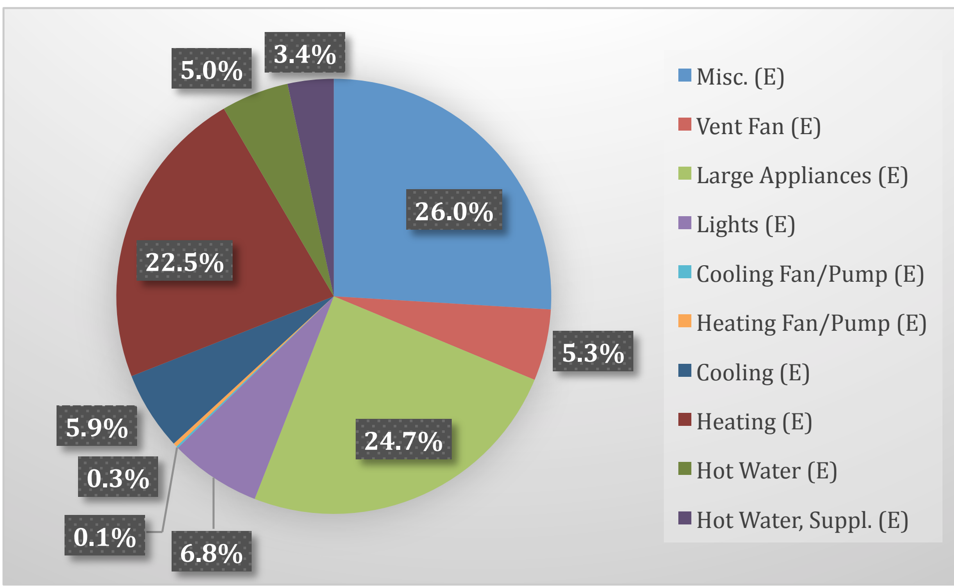


Figure 1.6 Annual energy breakdown of re*ACT*

During the initial design of the HVAC system, the team planned to use a variable refrigerant flow (VRF) system with heat recovery function. However, the team discovered that commercially available VRF systems with heat recovery function were oversized for the heating and cooling needs of re*ACT*. The lowest capacity VRF system with heat recovery function found was 3.5 tons, and a system with a capacity of 2.5 tons is desired. The team set to find out if the inefficiencies of using an oversized 3.5-ton unit outweighed the benefits of using a heat recovery function VRF system. For this analysis, BEOpt was used to model re*ACT* with the 2.5-ton VRF unit and the oversized 3.5-ton VRF unit. Both systems are not modeled with a heat recovery function. All other parameters of the model were kept the same between the two cases, except the VRF system used. The results are shown below in Table 1.7.

Table 1.7 Mini split system energy consumption comparison

Operation	2.5 Ton, SEER 22	3.5 Ton, SEER 15.9	Percent Increase
Cooling	471 kWh/Year	680 kWh/Year	44.7%
Heating	1,817 kWh/Year	2,057 kWh/Year	13.2%

The oversized 3.5-ton VRF system increases the cooling and heating energy consumption by 44.7% and 13.2%, respectively. The oversized unit operates at part-load operation so that typically its COP is reduced. The increase in energy efficiency using the heat recovery system will not outweigh the inefficiency of using an oversized 3.5-ton VRF system. Thus, the team made the design decision to use the 2.5-ton VRF system without a heat recovery system.

1.1 Modeling the Greencourt

An important architectural feature of re*ACT* is the courtyard (Greencourt), which takes the form of a greenhouse or sunspace. The potential of this space is not only to energize the social life of the house, but also to serve as a reconfigurable passive solar collector making it one of the driving concepts behind the overall design of re*ACT*.

BEOpt and most other conventional modeling tools do not support the transient analysis of the Greencourt, and so the Energy Modeling Team had to develop the dynamic model from scratch. The basic formulae used to model the space are found in the literature [Joudi and Farhan, 2015], and are summarized below.

The Greencourt model includes 10 control volumes: south wall, north wall, east and west walls in contact with conditioned space, east and west walls in contact with outside, eastward and westward tilted roof, and courtyard air and floor. Modelica Buildings Library and components from Modelica Standard Library – Thermal Package were used for the model with some custom components developed. TMY3 weather data for Denver International Airport was used as input using the Weather Input block. For glass covers the energy equation can be written as:

$$\rho_g c_g \frac{dT_g}{dt} = q_a^r - q_e^r + q_i^{co} - q_o^{co}$$

Equation 1.1

where ρ is the density, c is the specific heat capacity, T is the temperature of glass, t is time, and the subscript "g" refers to glass. The right-hand side has four heat flux (q) terms with superscript "r" referring to radiative heat transfer and "co" to convection. Subscripts for radiative heat flux include "a" for absorbed, "e" for emitted, while for convective terms "i" denotes inside space while "o" is for outside space.

Constant heat transfer coefficients were given as inputs for convective heat transfer obtained by averaging the parameters from the empirical relations reported in Abdel-Ghany and Toyoki [2006]. For radiation absorbed from the sun by each glass surface, the dot product of direct normal radiation at solar hourly angle and the glass surface normal was calculated. This was then multiplied by the glass surface area and absorptivity to obtain net radiation absorbed from the sun. The radiation reflected by the floor and absorbed by the glass surface is neglected because its effect is small (about 10%) as described in Joudi and Farhan [2015]. Another assumption used was that the radiative heat transfer between various glass surfaces is negligible. This assumption prevents accounting for 28 possible heat transfer combinations of the control volumes. In reality, there will be slight temperature differences between various glass surfaces, but these differences are expected to be less than 5 K.

For radiative heat losses to the outside, sky temperature is calculated by an equation given in [Swinbank, 1963]. The radiative heat transfer block from Modelica standard library was used to model this heat transfer. For the floor, the energy equation can be written as:

$$\rho_f c_f \frac{dT_f}{dt} = q_a^r - q_e^r + q_i^{co} - q_o^{co}$$

Equation 1.1

The absorbed radiative heat transfer term represents the radiation that is transmitted through glass surfaces and is absorbed. In reality, the transmitted radiation through each glass surface undergoes multiple reflections on other surfaces or even is reflected to outside the Greencourt. For the purpose of modeling, it was assumed that 60% of the radiation emitted from other surfaces would be absorbed by the floor. The absorptivity of opaque surfaces of the floor is typically in the range of 0.8 – 0.9 while reflectivity of glass is about 0.1 and transmissivity 0.85 [Bouadila et al., 2014]. Thus 10% of radiation falling onto each glass surface is reflected, 85% of which is transmitted through and 80% of which is absorbed by the floor (0.9*0.85*0.8 = ~0.6). The radiation emitted to the glass surfaces was modeled using the radiation block. View factors from floor to walls are 0.18, while from floor to each of the roof is 0.14.

The heat transfer by convection was modeled in a manner similar to that of the glass surfaces. Since the house was raised over a platform the heat losses term to the outside air was also modeled.

Lastly, to model the air inside the Greencourt the energy equation is as follows:

Equation 1.2

$$\rho_a c_a \frac{dT_a}{dt} = q_s^{co} + q_g^{co} + q_{\text{inf}}$$

The absorption of radiation in the air was neglected. This is a very common assumption in greenhouse modeling [Joudi and Farhan, 2015; Abdel-Ghany and Toyoki, 2006; Bouadila et al., 2014]. The first term on the right-hand side is the convective heat transfer from soil, the second term is convective heat transfer from the glass surfaces while the final term is infiltration. The heat transfer from the air coming in by infiltration was calculated as:

$$q_{\inf} = \rho_a c_a V * \frac{ACH}{3600} * (T_{in} - T_{out})$$ **Equation 1.3**

This model was implemented in Modelica to find the temperature of Greencourt for various ventilation rates since the actual infiltration cannot be predicted at this modeling level. A typical ACH = 2 was set for the condition when outdoor unit was not operational. When the outdoor unit is working, it draws in more air from the Greencourt increasing the infiltration. Based on the steady state mass balance, the infiltration in this condition would equal the air drawn by the outdoor unit. The value of this mass flow rate was obtained from EnergyPlus and fed back to the Modelica model to find the Greencourt temperature. Thus, an iterative approach between two models was used to determine the energy savings possible when using the Greencourt.

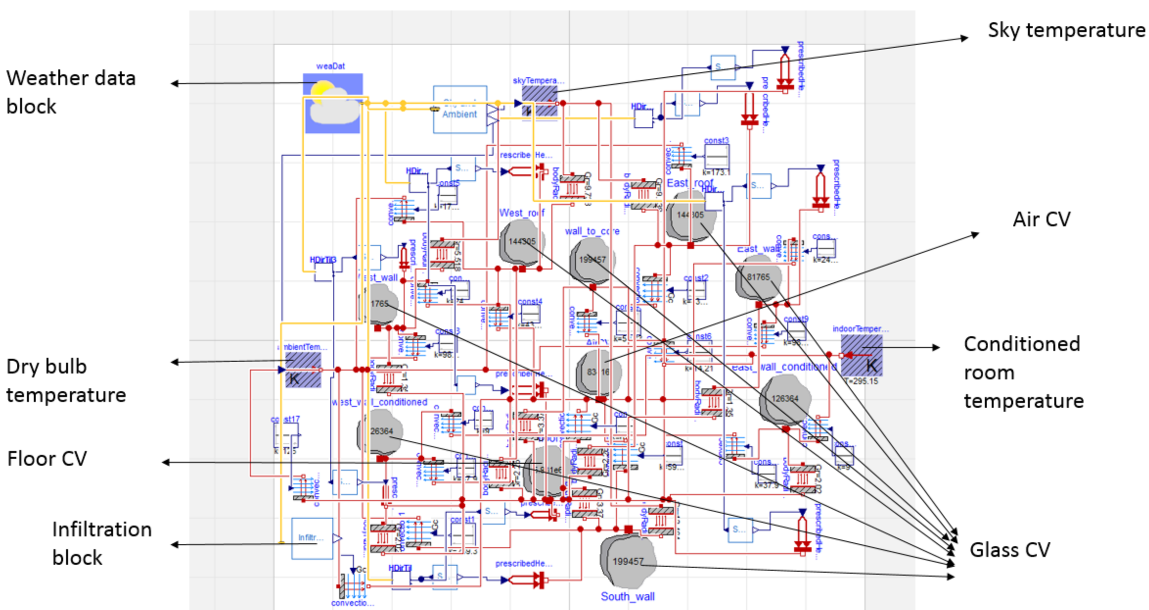


Figure 1.7: Modelica GUI for the Greencourt model

As can be observed from Figure 1.8, the model can predict the increased temperature of the Greencourt from the greenhouse effect. The floor has the highest specific heat capacity among the materials and captures most of the solar radiation. This energy is then transferred to Greencourt air by convection. The heat transfer coefficient for this transport was set from Cholewa et al. [2014]. This factor adds to the Greencourt air temperature.

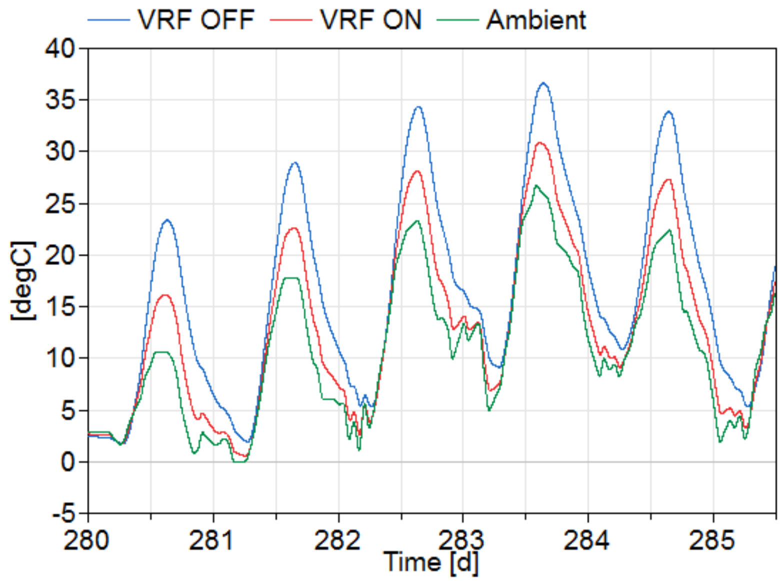


Figure 1.8 Greencourt temperature with VRF ON and VRF OFF in comparison to outdoor temperatures near competition dates (Oct. 8 = 281, Oct. 12 = 285)

Infiltration is the second important factor affecting the Greencourt air temperature. This leads to the heat loss from the Greencourt air temperature. Infiltration depends heavily on the construction and so some assumptions were made based on judgment. For the VRF OFF case from Figure 1.8, ACH = 2 was selected. The typical rates for cold climate houses are of the order of 0.5 for conditioned space and so a much higher number was set for the Greencourt. Another assumption is that when the VRF is running, the air that is ventilated from the Greencourt is accounted for by the infiltration from outside air. In reality, there would be infiltration from the indoor space. Thus, the modeled scenario represents the worst-case scenario.

1.2 Pre-cooling and pre-heating effects

Pre-cooling and pre-heating of the air sent to the VRF outdoor unit (OU) could reduce the energy consumption of the VRF system during the cooling and heating seasons. The benefits of pre-cooling and pre-heating of the inlet air are shown in Figures 1.9 and 1.10, respectively. Figure 1.9 demonstrates the effect of two levels of pre-cooling when the VRF system delivers the same amount of cooling capacity. The cooling capacity was selected to be 8.8 kW, which is the rated cooling capacity of the VRF system installed in re*ACT*. Similarly, in Figure 1.10, it was assumed that the VRF system could deliver a heating capacity of 9.4 kW.

In Figure 1.9, the first level pre-cooling reduces the VRF OU inlet air temperature by 2 K and the second level by 4 K. Similarly, in Figure 1.10, the first level pre-heating increases the OU inlet air temperature by 2 K and the second by 4 K. As can be seen in Figure 1.9, the cooling energy consumption of the system increases along with the increase of ambient temperature. With the pre-cooling of the OU inlet air, the energy consumption is reduced as compared to the baseline. In addition, the second level of pre-cooling has a higher COP and lower energy consumption than the first level of pre-cooling. On average, the first level of pre-cooling reduces the energy consumption by 175 W and the second level by 339 W. Figure 1.10 shows similar results to Figure 1.9. As compared to the baseline, the pre-heating could reduce the heating energy consumption. Results of Figure 1.10 can be classified into two regions. When the ambient temperature is lower than 5°C, the performance of the baseline system degrades due to the defrosting operation. However, when pre-heating is introduced, the system maintains a higher COP until the preheated OD inlet air temperature becomes lower than 5°C. As shown in Figure 1.10, when the second level of pre-heating is applied to the system, the performance of the system does not drop until the ambient temperature reaches 0°C. Overall, the first level of pre-heating reduces energy consumption by 239 W and the second level by 472 W.

The air-source heat pump water heater (HPWH) provides hot water to the building. The air-source HPWH is similar to the VRF OU in the heating mode. Therefore, it could also benefit from the Greencourt pre-heating. The benefit of preheating the inlet air of the HPWH OU is shown in Figure 1.11. The pre-heating levels are the same as Figure 1.10. In Figure 1.11, the water heating capacity was assumed to be 1.2 kW with a hot water set point of 45°C. The rated COP is 4.62 and the rated energy consumption is 259 W. On average, the first pre-heating level saves 17 W and the second by 34 W.

The concept of pre-cooling and pre-heating was applied to re*ACT*. In the cooling season, the HPWH is used to pre-cool the air entering the OU of VRF system. In the heating season, the preheated Greencourt air, which has a higher temperature than the ambient air, is used.

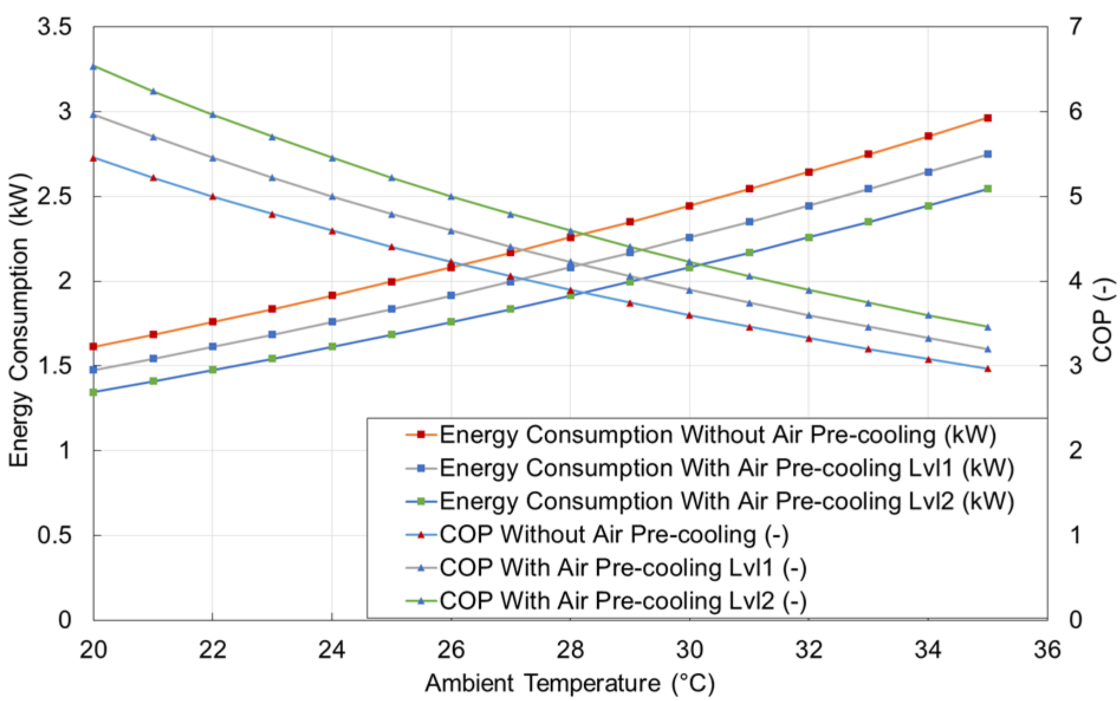


Figure 1.9 Benefit of pre-cooling of VRF OU inlet air in cooling season.

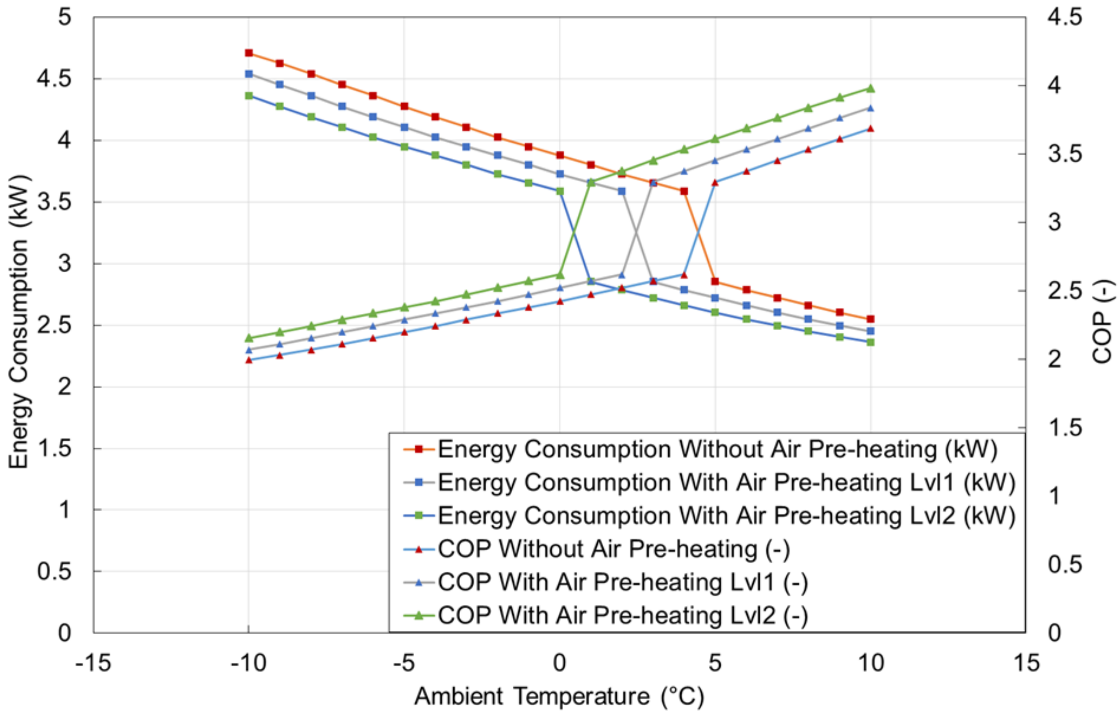


Figure 1.10 Benefit of pre-heating of VRF OU inlet air in heating season.

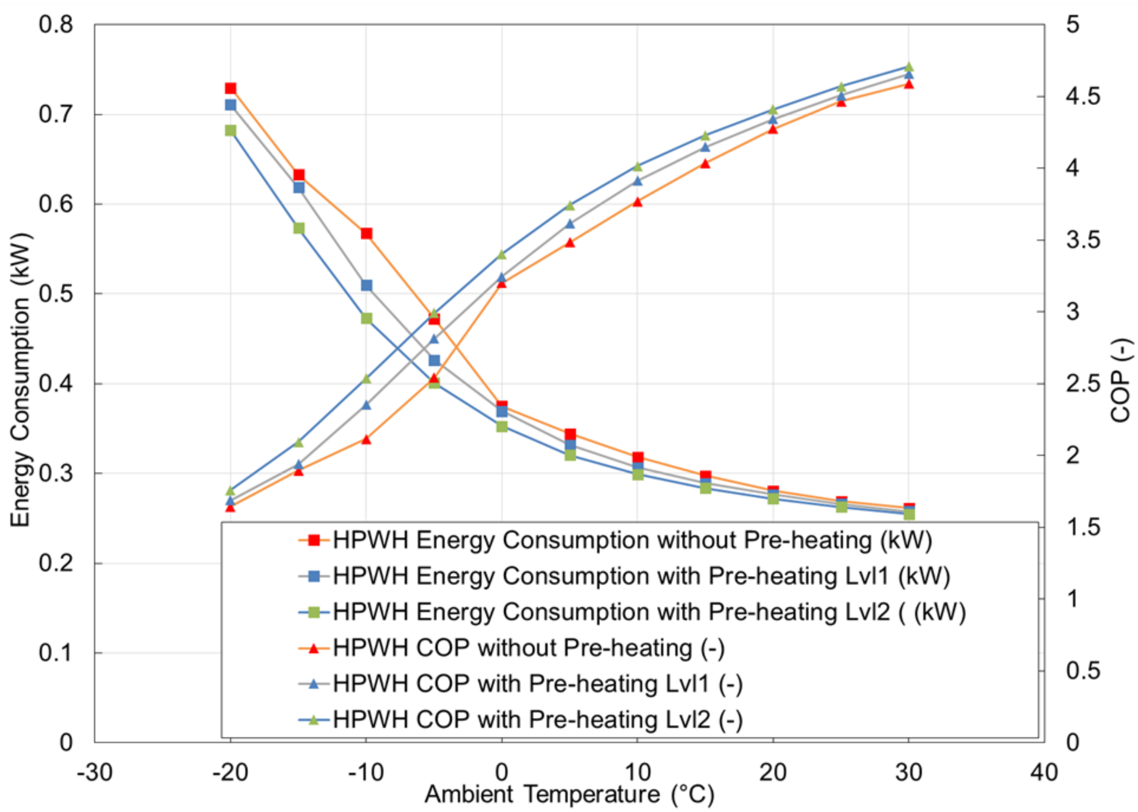


Figure 1.11 Benefit of pre-heating HPWH OU inlet air.

1.3 Effect of Greencourt Control

With the movable rooftop installed in the Greencourt, it is possible to harvest the solar radiation. In the heating season, a higher air temperature in the Greencourt relative to ambient is expected. When the VRF system uses the Greencourt air instead of the ambient air during the heating operation, a lower heating energy consumption can be achieved. Based on the reACT model described above, an annual simulation of the Greencourt air temperature was simulated. The effect of using Greencourt air as the VRF OU heat source was estimated in EnergyPlus. The running period was selected to be January to March. TMY3 weather data of Denver was used. From 10 AM to 10 PM, the rooftop was assumed to be controlled to ensure that a higher Greencourt temperature than the ambient is achieved. The HPWH was assumed to be turned off to eliminate the cooling effect of the HPWH OU. It was assumed that the VRF system constantly draws 1,728 m^3/h of air from the Greencourt, which is the highest flow rate it could possibly reach in heating operation. The relationship between the hourly Greencourt temperature and ambient air temperature is shown in Figure 1.12. The highest temperature difference achieved is 5.6 K. The summarized daily results are shown in Figure 1.13. As can be seen in that figure, when using the Greencourt air as heat source, the VRF system's monthly energy consumption is reduced from 583 kWh to 572 kWh.

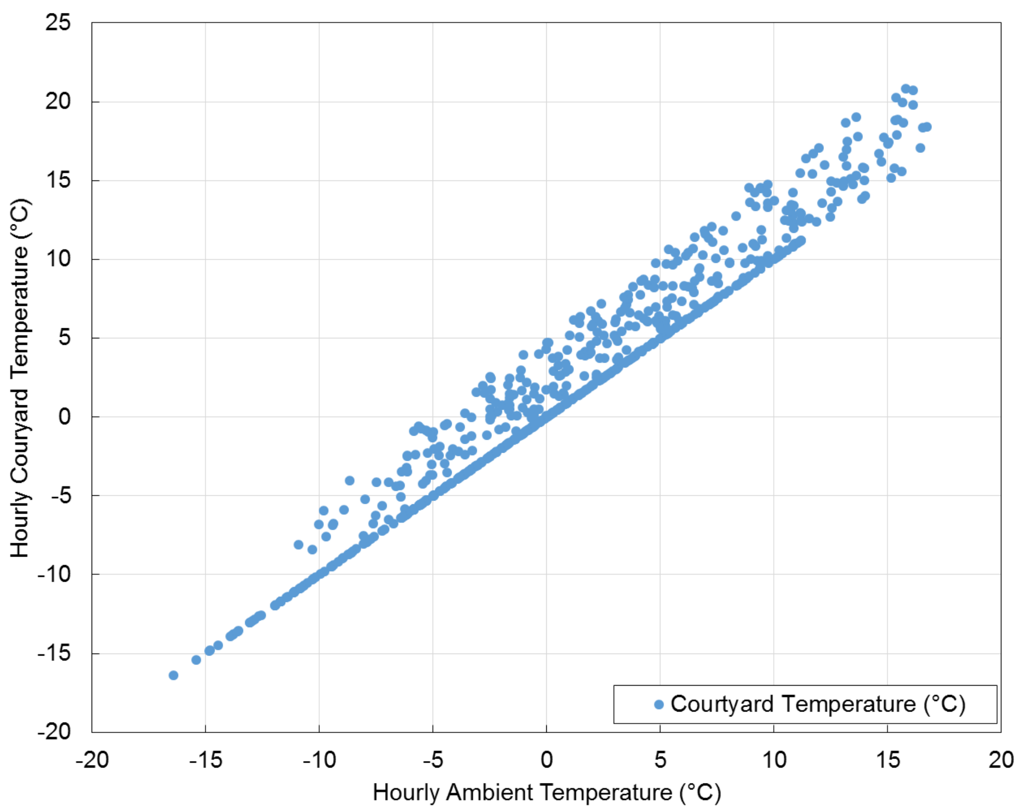


Figure 1.12 Greencourt temperature with the roof top radiation.

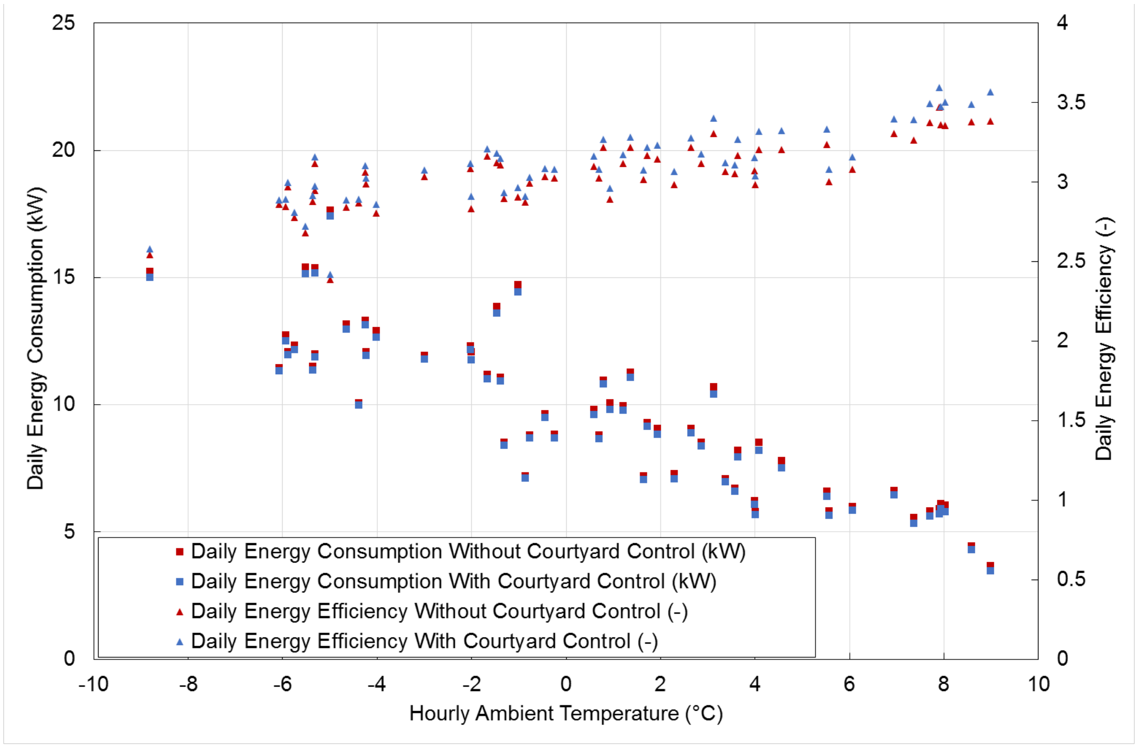


Figure 1.13 Performance of VRF System with and without Greencourt control.

A typical hourly temperature elevation profile in the Greencourt in shown in Figure 1.14. The date is January 25th, which is also the design day. As can be seen, the highest temperature increase is 2.25 K and the average increase is 1.2 K. The effect of a 1.2 K Greencourt temperature increase on the HPWH performance is shown in Figure 1.15. Based on the ambient temperature of January 25th, the power consumption of HPWH could be reduced by 13 W when operated under with the highest preheating of 2.25 K.

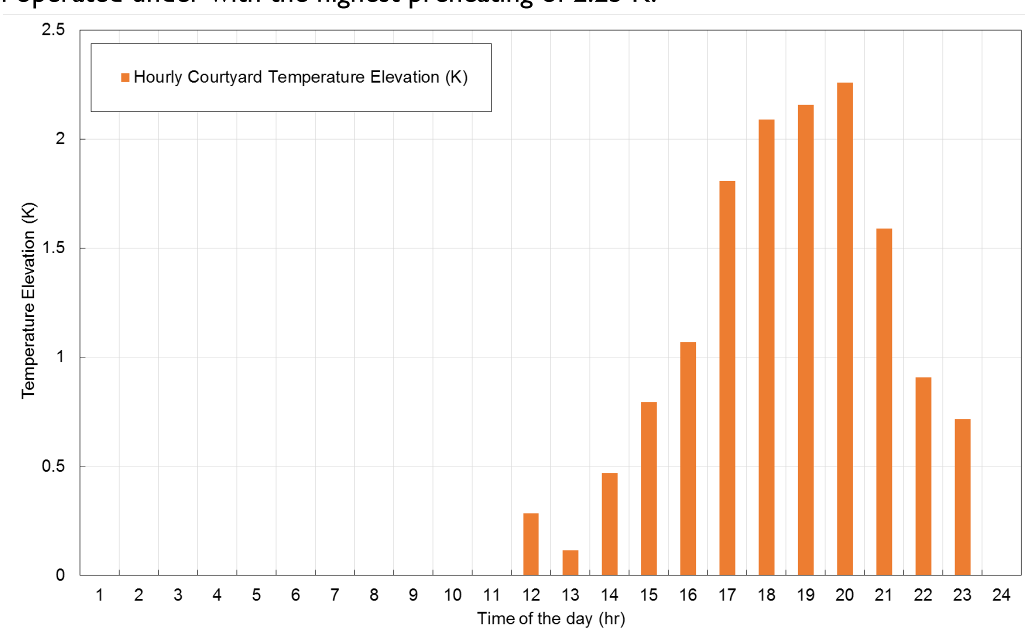


Figure 1.14 Hourly Greencourt temperature elevation on January 25th.

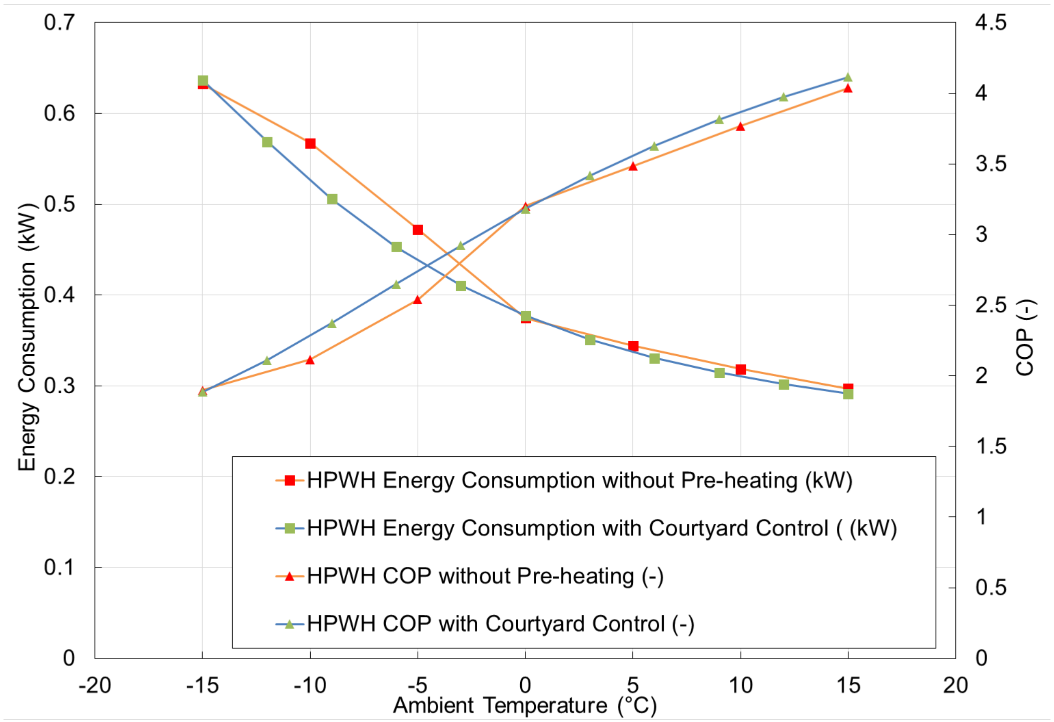


Figure 1.15 Effect of Greencourt control on HPWH

Table 1.8 Energy savings from HVAC systems

Source	Energy Use Baseline (kWh/Year)	Energy Use ReACT (kWh/Year)	Change (kWh/Year)
Misc.	2,092.6	2,092.6	N/A
Ventilation Fan	427.9	427.9	N/A
Large Appliances	1,987.1	1,987.1	N/A
Lights	548.1	548.1	N/A
Cooling Fan/Pump	11.7	11.7	N/A
Heating fan/Pump	23.45	23.45	N/A
Cooling	471.86	457	-14.8
Heating	1,817.1	1,782.7	-34.4
Heating, Suppl.	275.5	0	-275.5
Hot Water	404.5	384.2	-20.3
Total	8,060	7,714.7	-345.3
PV	12,547	12,547	0
Net (PV-Total)	4,487	4,832.3	345.3

1.4 Effect of Air Damper Control

re*ACT* has OUs of both the VRF system and air-source HPWH installed in the attic. The air-source HPWH absorbs heat from the attic air to heat the water tank indirectly through the indoor water tank loop. On the contrary, the VRF system rejects heat to the attic in order to cool down the rooms. For a VRF system, a lower attic air ambient temperature could lead to lower energy consumption. Therefore, in re*ACT*, an air damper control concept was introduced to use the air-source HPWH to pre-cool the attic air before entering the VRF OU.

The concept is shown in Figures 1.16 and 1.17. The two OUs are installed on the opposite ends of the attic. The HPWH OU is installed next to the air inlet where the ambient air is drawn into the attic. The outlet of the attic air is downstream of the the VRF OU. Dampers A and B are closed to prevent unnecessary air leakage during the operation but are open for natural ventilation when the OUs are not used. Between the two OUs, there are two dampers installed to control the direction of air flow.

In the cooling season, when HPWH is operating, both dampers C and D are still closed. Therefore, the ambient air is pre-cooled by HPWH OU before it reaches the heat exchangers of VRF OU. This control is only designed for cooling season since a lower inlet air temperature could degrade the heating performance of VRF system. In the heating operation, both dampers C and D open up, as shown in Figure 1.18; in this figure, the air flow of VRF OU is not affected by HPWH. The effect of air damper control was also simulated in EnergyPlus for the cooling season. The running period was July to September. TMY3 weather data of Denver, Colorado was used. It was assumed that the VRF system constantly draws 1,431 m^3/h of air from the ambient, which is the highest flow rate it could possibly reach in heating operation. The results are shown in Figure 1.19. Due to the pre-cooling effect of the HPWH OU, the cooling performance of the VRF system is slightly improved. Overall, the energy consumption is reduced from 471.9 to 457 kWh. The overall annual savings of re*ACT* is listed in Table 1.8.

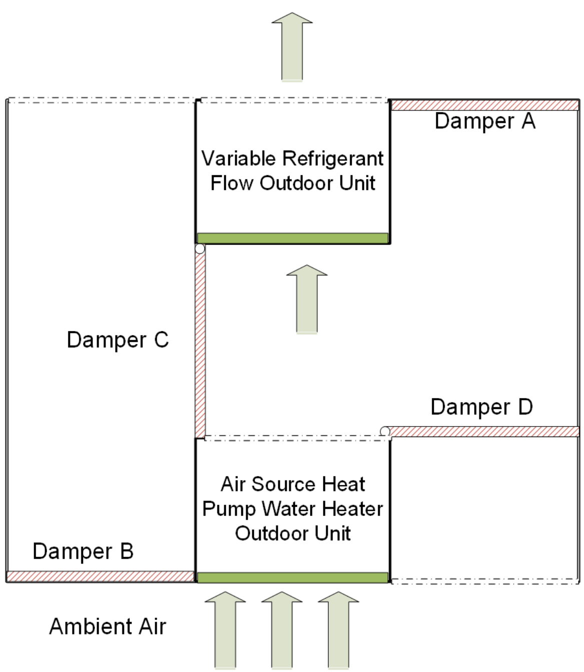


Figure 1.16 Cooling season damper control.

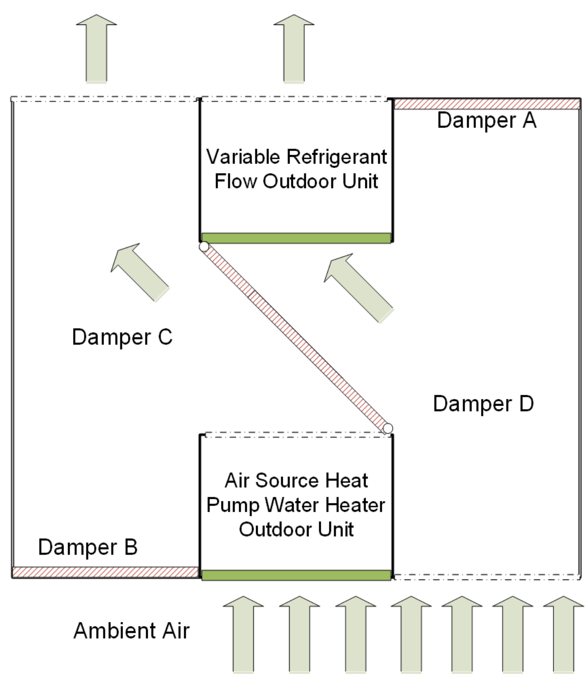


Figure 1.17 Heating season damper control.

1.5 Conclusions

BEOpt was used to explore different design options through successive parametric runs. Many different factors including window to wall ratio, R-value of the walls, roof and floor, and assumed infiltration rate were studied using this model. The team made use of BEOpt's parametric study capabilities to show how changing certain parameters affected the annual cost and energy consumption. Detailed charts containing energy savings and cost for these materials were developed for making trade-offs while selecting the building envelope.

BEOpt caters to only conventional residential simulation. For modeling the innovative Greencourt, a first-principles based model was developed using Modelica. This model was used to predict the air temperature of Greencourt during the year-round operation. The outdoor unit of VRF system draws air from the Greencourt after the HPWH OU to either pre-cool or pre-heat inlet air based on the season. The savings of this operation were calculated by exporting the data from Modelica to EnergyPlus. The savings from this calculation shows that the net savings from the VRF operation is estimated to be 7.7%. Savings in hot water generation are 5%. Total savings in HVAC (Heating and Cooling combined) are 12.7%.

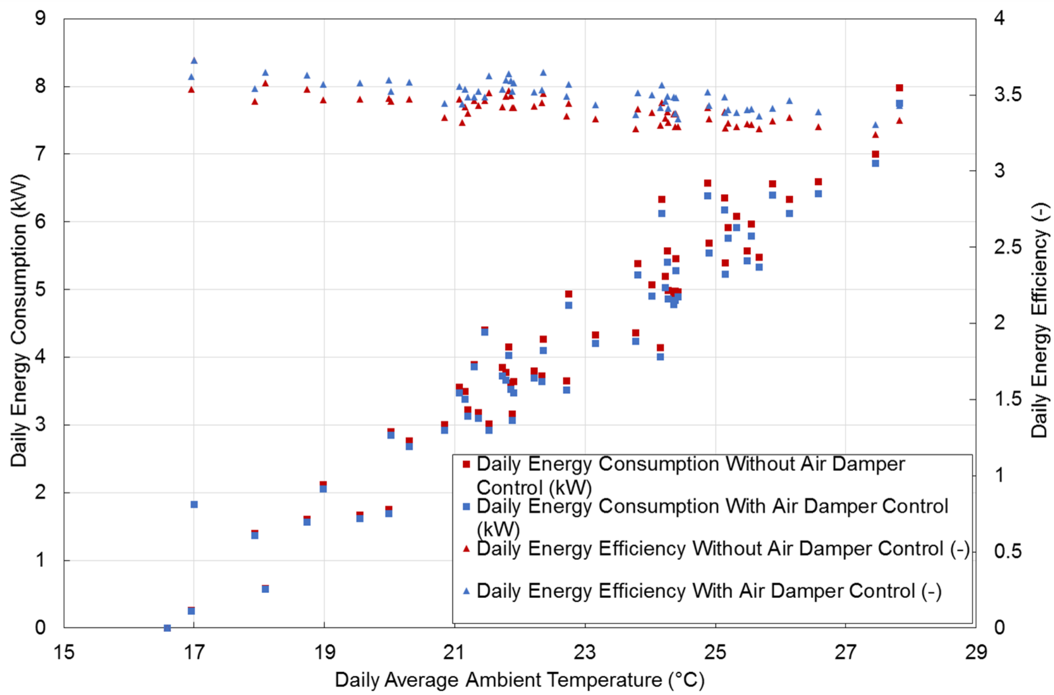


Figure 1.18 Performance of the VRF System with and without air damper control.

2.0 Dynamic model development

A physically based model of Team Maryland's SD2017 entry has been under development since January of 2016, a model similar in character to the Greencourt dynamic model described earlier. The motivation for creating such a model derives from its potential utility in evaluating design alternatives, dynamic optimization of our house resources, use in real-time model-predictive control, and to ultimately exist as multiple implementations of "virtual" houses located at the University of Maryland and in Danville, WI, Denver, CO, and Irvine, CA.

2.1 Model electrical and thermal energy elements

Numerous physically based re*ACT* modeling modules were written by Team Maryland in the Python programming language; they continue to be refined to this day. A summary of elements relevant to re*ACT*'s electrical and thermal energy dynamics are briefly summarized below.

1. Everything begins with the sun and so a considerable effort was invested in understanding and programming the geometry of our solar system and atmospheric absorption effects to create a solar irradiance module that predicts the direct and diffuse irradiance on all PV and building structure surfaces at any time and location on Earth.
2. A Python routine capable of automated reading and parsing of local weather data was written and is used to determine the irradiance attenuation by cloud cover.
3. A nonlinear regression technique was developed to identify parameters in an equivalent-circuit PV cell model from the manufacturer's performance data to determine the power produced by the PV arrays over the course of the day using the predicted irradiance levels. A regularization procedure was developed to determine a solution to this under-determined identification problem.
4. Nominal scheduled electrical loads were identified and stored in a machine-readable (XML) format; the loads are read by the simulator and used to compute energy consumption associated with regularly scheduled events. Movable loads are distinguished from fixed loads to allow for schedule optimization.
5. Incident radiation and indoor/outdoor air temperature variations are used to determine heat transfer rates through the house external walls. External wall and window heat transfer, direct radiation through the house windows, and waste heat produced within the house determine HVAC loads, indoor air temperature, and overall net power consumption/production.

2.2 Interpreting the simulator output

Figure 2.1 illustrates the predicted power production and consumption profiles for 3 April 2017. The weather forecast read at 12:05AM predicted a partly cloudy day – the effect is clearly visible in the reduction of peak power, which would otherwise be near the peak PV array output of 10kW. Fixed and movable loads are shown as negative values with the total outlined in red; movable loads are denoted in green – none are shown in this Figure. The net energy produced up to any point in the day is shown as the green dotted curve and corresponds to the right axis of the plot. We note that despite the cloudy conditions, re*ACT* will produce a net positive amount of energy for that day.

Using the rate schedule provided in the Solar Decathlon rulebook, the instantaneous net power can be used to determine a net profit generation rate. As shown in Figure 2.2, the net profit is negative in the early morning and late evening, but that is more than canceled by a large positive profit rate in the afternoon. Accumulated profit is shown as the green dotted curve and in this case, represents a small positive quantity at the end of the day, despite the partial cloudiness.

The contributions to the thermal energy balance are illustrated in Figure 2.3. In this figure, we see that waste heat from regularly scheduled events combine with heat transfer through exterior walls and radiant energy transmitted through the windows to define the total thermal load which must be removed by the HVAC system. It is interesting to observe in the bottom plot of Figure 2.3, that even though the outside temperature is cooler than the allowed temperature range (denoted by the two horizontal lines), that cooling must be provided due to the radiant heating of the outside walls and the radiation which enters through the windows.

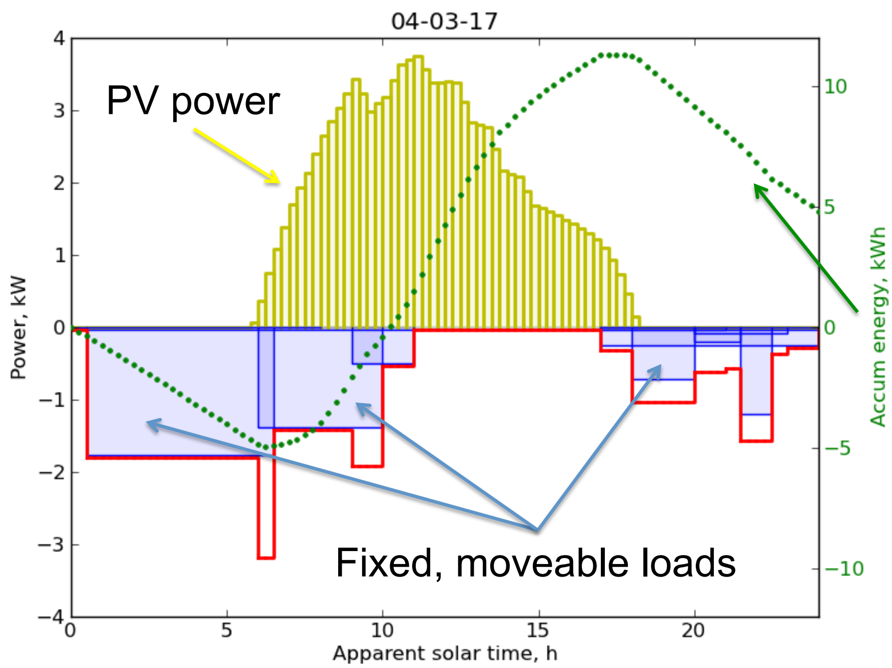


Figure 2.1 Predicted electrical power produced by the PV system is represented by positive values and is denoted in yellow; total power used due to scheduled events correspond to negative values and are shown in red; net energy production for the day is shown in green.

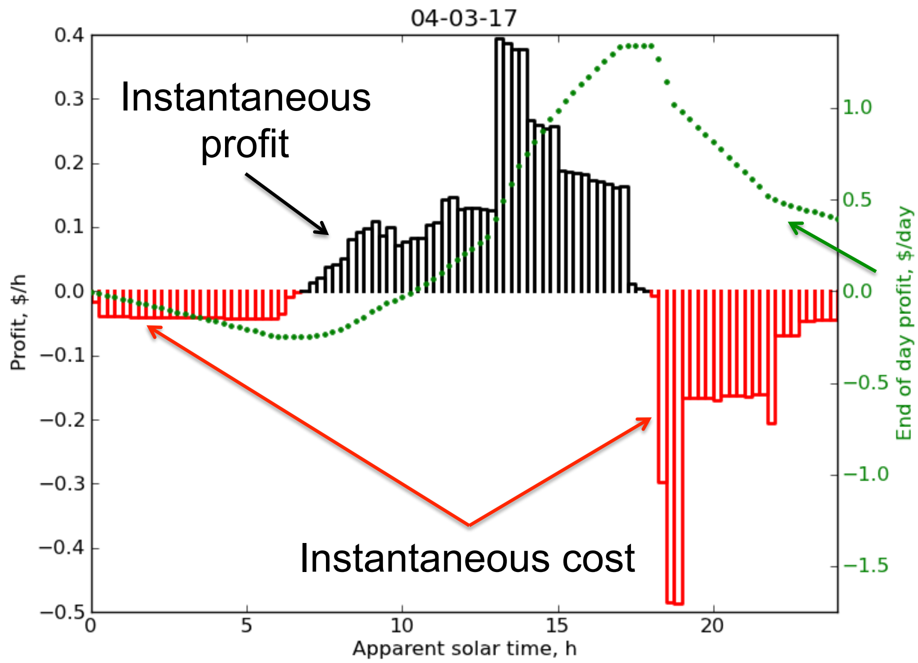


Figure 2.2 Instantaneous profit (black) and costs (red), with accumulated profit shown in green.

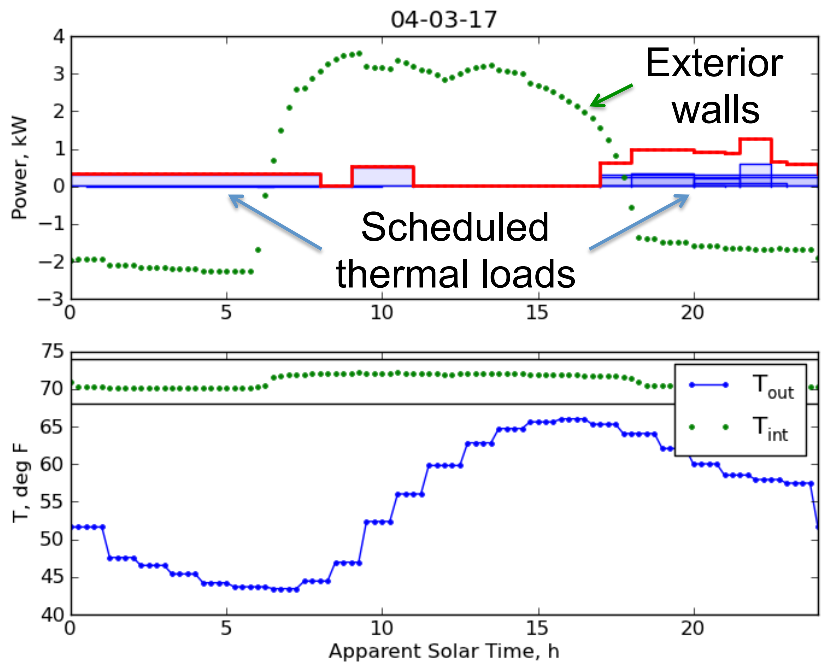


Figure 2.3 Top: house thermal load due to scheduled events (red) and due to heat transfer with the environment (green). Bottom: outdoor/indoor temperatures shown as blue/green.

2.3 Extended analysis

Figure 2.4 (top) summarizes the net energy production (kWh) corresponding to the College Park, MD re*ACT* virtual on a daily basis since that simulator was started. The abscissa of each plot corresponds to the number of days after winter solstice (December 21, 2016) and the simulations make use of actual weather data for all dates. Overall, the trends are very clear: that while being a net consumer of energy deep in the middle of winter, the performance of re*ACT* during the remainder of the year more than makes up the deficit, resulting in an annual average surplus of 10 kWh/day. The electrical energy economics (Figure 2.4, bottom) also follow this trend, resulting in an annual-average profit of approximately $1/day.

Figure 2.5 presents the same energy and economic summary for re*ACT* virtual in Denver, CO. The net energy and economic performance measures mirror those trends and values corresponding to College Park, providing numerical evidence of the adaptability of re*ACT* to different environments.

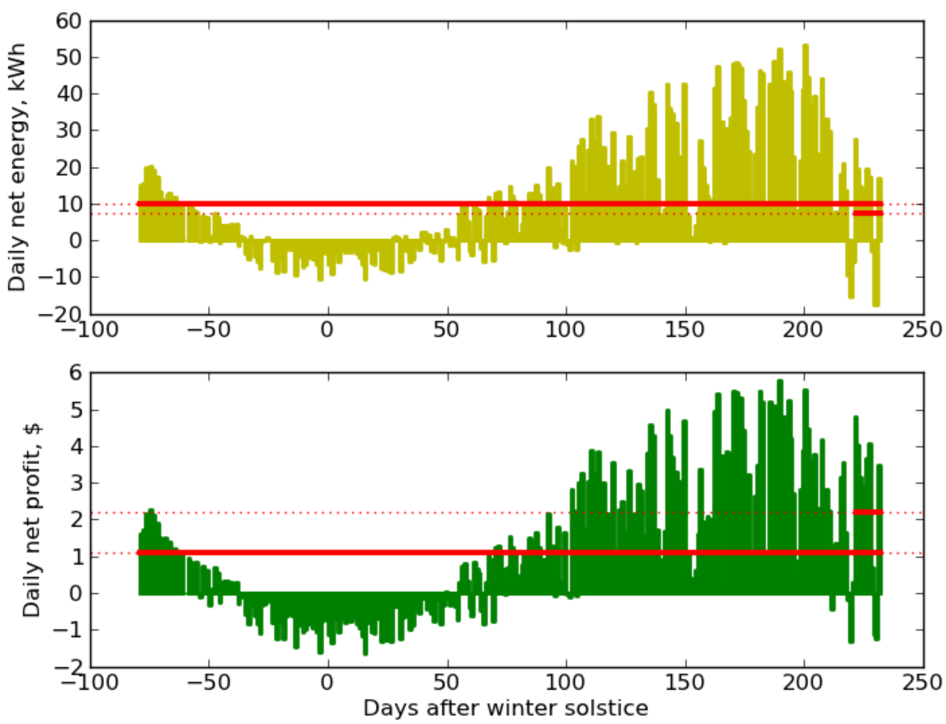


Figure 2.4 Top: daily net energy production for re*ACT* virtual located in College Park, MD; daily net profit associated with selling excess power is shown as the green bottom plot. Mean and most-recent 10-day mean values are illustrated by the red horizontal bars.

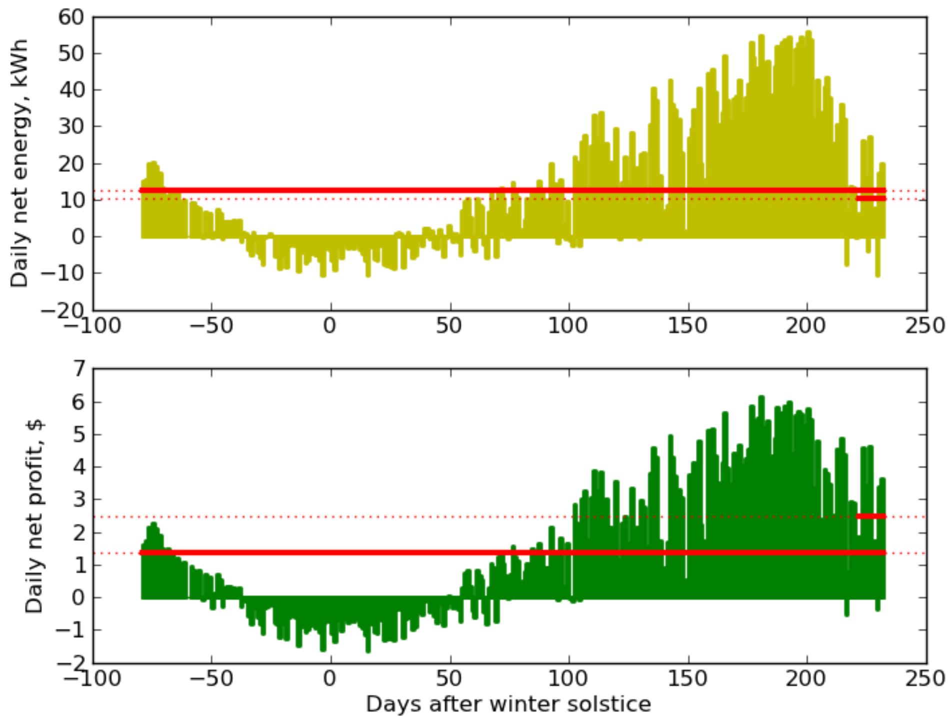


Figure 2.5 Net daily energy production and profit for re*ACT* virtual located in Denver, CO. Notation is the same as in Figure 2.4.

References

[1] NREL, Site Energy Savings, Website, Accessed on Feb. 13, 2017, https://beopt.nrel.gov/sites/beopt.nrel.gov/files/help/Site_Energy_Savings.htm.

[2] NREL, Energy Related Cost, Website, Accessed on Feb. 13, 2017, https://beopt.nrel.gov/sites/beopt.nrel.gov/files/help/Energy_Related_Costs__Life_Cycle_Cost.htm.

[3] Joudi, K.A., A.A. Farhan, A dynamic model and an experimental study for the internal air and soil temperatures in an innovative greenhouse. *Energy Convers Manag* 2015; 91:76–82.

[4] Abdel-Ghany A.M., K. Toyoki, Dynamic modeling of the environment in a naturally ventilated, fog-cooled greenhouse. *Renewable Energy* 2006; 31:1521–39.

[5] Swinbank W. C., Long wave radiation from clear skies. *Q J R Meteorol Soc* 1963;89:339.

[6] Bouadila S., S. Kooli, S. Skouri, M. Lazaar, A. Farhat, Improvement of the greenhouse climate using a solar air heater with latent storage energy. *Energy* 2014; 64:663-672.

[7] Cholewa, T., M. Rosiński, Z. Spik, M.R. Dudzińska, A. Siuta-Olcha, On the heat transfer coefficients between heated/cooled radiant floor and room. Energy and Buildings, 2013; 66:599-606.