ABSTRACT

Title of thesis: SYSTEMS ENGINEERING-BASED MODEL DEVELOPMENT: APPLICATION TO PREDICTIVE SIMULATION OF A NET-ZERO HOME

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Building design has grown increasingly sophisticated throughout the decades. In recent years, assessments of building performance and sustainability has grown in popularity as the U.S. Green Building Council published LEED certifications for new and existing constructs. The LEED rating system utilizes standards made by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) for areas in thermal comfort, air quality, energy building performance, and heat, ventilation, and air conditioning (HVAC) operation. Energy building performance has a more overarching role in this rating as the other three standards play into the overall loads associated with any building. Submittal of energy performance building reports for construction design and green building rating systems is becoming more common as building performance assessment software becomes more widely available.

The University of Maryland currently is a participant in the Solar Decathlon

intercollegiate competition sponsored by the Department of Energy. The University of Maryland's *reACT* team is working to construct a net-zero solar powered house for judging in Denver, CO in October 2017. Concurrently with the housing design, a substantial effort was put into assessing the projected building performance to aid in the design process and to set the stage for model-based home automation. While software such as OpenStudio and BEOPT are available and were used for year-averaged performance reports, a physically based model of the house was built from scratch to serve as a real-time simulation of virtual versions of *reACT* located in College Park, MD and Denver, CO and is described in detail as the Virtual House.

The overall system design of the Virtual House can be described as a general set of inputs, dynamic simulation, and output of overall profiles. Inputs for the system include geometric design of the house, specified materials, schedules, daily weather data, and solar irradiance. Dynamic simulation refers to a simultaneous integration of both independent and dependent fluctuating loads upon the time of day regarding both heat and power balances. Finally, outputs showcase heat and power profiles throughout a day. The bulk of analysis of inputs and simulation has been rooted in fundamental calculations.

In terms of future work, outputs coming from the Virtual House are currently being stored and are now looking towards validation with measured sensor data. As of now *reACT* is not in construction phase and measured data is unavailable. In order to validate the Virtual House, there are current plans to outfit the previous Solar Decathlon 2007 entry *LEAFhouse* with sensors. With this, measured and simulated data can be assessed after modifying the current Virtual House model for

LEAFhouse specific inputs. Ultimately, work will be transitioned back to *reACT* as it is built with Solar Decathlon 2017 in mind.

SYSTEMS ENGINEERING-BASED MODEL DEVELOPMENT: APPLICATION TO PREDICTIVE SIMULATION OF A NET-ZERO HOME

by

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List of Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
DOE	Department of Energy
LBC	Living Building Challenge
LEED	Leadership in Energy and Environmental Design
NREL	National Renewable Energy Laboratory
reACT	resilient Adaptive Climate Technology
SEER	Seasonal Energy Efficiency Ratio
USGBC	United States Green Building Council

Chapter 1: Introduction

1.1 Background

Building design over the last few decades has been greatly influenced by software development that facilitate projection of building performances. The main driving forces behind these developments can be attributed to the growing concern for environmentally conscious building performance and enhanced human well-being. Building performance and human well-being are heavily influenced by energy consumption, indoor air quality, thermal conditions, and lighting [1, 4]. In recent years, buildings that exhibit these traits properly while maintaining positive effects for the environment are heralded as great examples of green buildings.

Multiple green building rating systems have been developed across the world to certify buildings showcasing the two overall aspirations of performance and health, such as Leadership in Energy and Environment Design (LEED), Green Star, and the Living Building Challenge (LBC) certifications [1, 3]. These rating systems judge in a general range of categories including, but not limited to, sustainability, water efficiency, energy usage, atmospheric effects, materials, and indoor environmental quality. In particular LEED, developed by the United States Green Building Council (USGBC), has been growing in popularity as an industry standard for building performance. The number of LEED certified buildings have grown exponentially since the year 2000 and might be due in part to standards set by ASHRAE [1].

While talking about accreditations, it is important to note the efforts made so far to help standardize the rating systems. Early on, these certifications were could not effectively rank performance for buildings. The main obstacle encountered by early efforts of certification could be readily seen by simply making an energy usage comparison for two buildings of a similar square footage in totally different climates [1]. A building requiring air conditioning and heating throughout the entire year would require much more energy than one only requiring air conditioning and would be an unfair comparison. Thus, these accreditations were able to become more relevant when the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) released building standards and guidelines for HVAC systems [2, 3].

LEED utilizes several standards of ASHRAE into its certification process: 90.1, 62.1, 55, and to a lesser extent 34 [4]. Standards 90.1, 62.1, 55, and 34 refer to energy standard for buildings, ventilation for acceptable indoor air quality, thermal environmental conditions for human occupancy, and designation & safety classification of refrigerants respectively. With the qualities desired for green buildings standardized, the Solar Decathlon is highly relevant as the competition pursues comparable qualities for a solar powered house.

1.2 Solar Decathlon

The University of Maryland is currently a participant in the Solar Decathlon, an intercollegiate competition held by the Department of Energy. The Maryland team for *reACT* is currently working to construct a net-zero solar-powered house, transport, and reassemble in Denver, CO by October 2017 [5]. As part of this competition, universities integrate and showcase emerging technologies that make it possible for anyone to improve their level of sustainability [6]. *reACT* hopes to enable lifestyle changes through the houses unique engineering and architectural design.

Winner of the competition will be decided by a panel of juried and measured contests in various categories [6]. For the competition, there are two main methods in which houses will be scored: juried and measured contests. The Department of Energy assigns a jury of professionals to rank architecture, market potential, engineering, communications, innovations, and water. Meanwhile, instruments are set up to measure in the categories of health & comfort, appliances, home life, and energy. Each contest is ranked equally in each category and the winner will be chosen by the highest netted points. Notably, the Solar Decathon's judging criteria for building performance does not deviate far from what is done by LEED and other green building ranking systems [6].

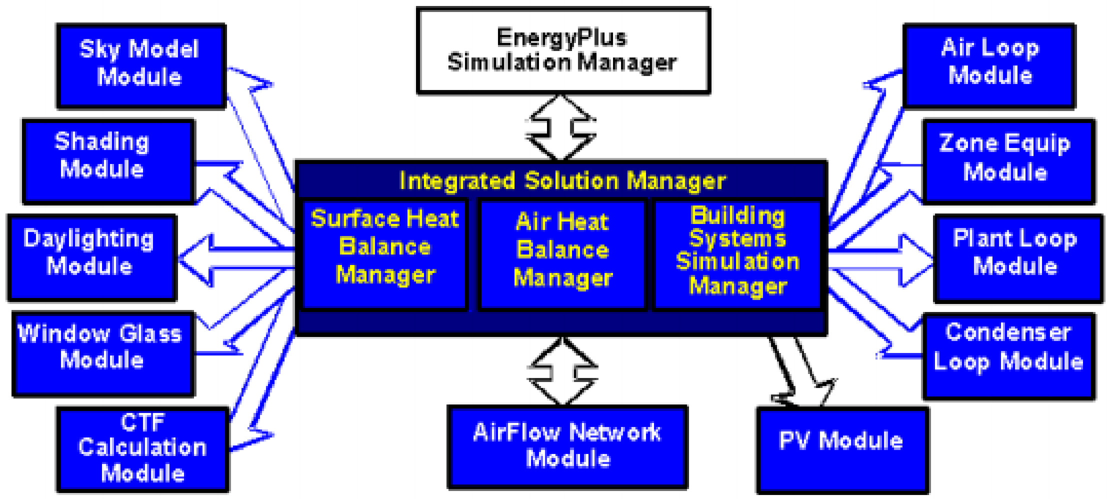

Figure 1.1: EnergyPlus program schematic for overall building simulation. [8]

1.3 Software development

Energy modeling has really only emerged with the aid of computers. Prior to use of computers, fundamental energy balances were calculated by hand [7]. In 1960, ASHRAE began using analog computers for air conditioning calculations. Since then, efforts towards modeling has been focused into several software packages. Some commonly used softwares in recent years used for energy modeling are EnergyPlus, HAP, Trace, and eQuest. Of note, the EnergyPlus is being maintained by the Department of Energy as the successor to DOE-2 and is publicly available [8]. EnergyPlus is widely used because it is open source and is commonly supplemented by use of OpenStudio as a more GUI-friendly interface.

For EnergyPlus, there are several modules that are simultaneously solved as seen in Figure 1.1. As a more basic definition of the variables required, there are three components that refer to the thermal envelope balances, air mass balances, and load & equipment scheduling. Due to the interactivity between the modules, many parameters must be set in order to gain an insightful performance reading after simulation. Examples of specified parameters include the entire expected weather for a year, the heating and cooling unit efficiency, expected hourly occupancy, overall floor plans, where the list goes on and on in order to produce a meaningful report.

1.4 Objective

This work has the spanned over two years. Initially the motivation for this work was to assist and provide support through informed decisions over preliminary architectural designs for Maryland's entry into Solar Decathlon 2017. An example of decisions to be made were window size and location for structural components of the building would be quickly accessed in terms of expected heat loss and gains. Another important decision specific to this kind of work is the sizing of equipment needed to maintain the house at a normal comfort level. Ultimately, decisions were required by the mandates and deadlines listed by the Solar Decathlon competition in the later part of 2016 and decided based on performance and aesthetics.

As mentioned earlier, green building certifications require energy modeling to illustrate projected performance of the construct. Similarly, the Solar Decathlon competition has also required projected performances for deliverables also in the later part of 2016. While the culmination of this project can certainly be used for the required expected performance of the building, more readily available software of BEOPT and OpenStudio was used for these reports.

Thus, the overall scope and motivation for this work has changed alongside the requirements needed for the Solar Decathlon. While publicly available software are able to project detailed performance reports for an entire year, personal experience has made it clear that these software are not so easily used for custom built houses or to consider immediate short-term local weather conditions through weather forecasts. In other words, this model hopes to achieve a more personal and real-time depiction of a building design and will provide a framework in which other buildings may also be modeled.

Chapter 2: *reACT* - Virtual House

2.1 Overview

University of Maryland's entry in the Solar Decathlon, *reACT*, is currently designed as a courtyard style house in an attempt to integrate both architectural aesthetics and technological innovations. An up to date architectural renderings of *reACT* can be seen in Figure 2.1 demonstrating the use of two sets of solar photovoltaic arrays and appeal afforded by the courtyard style [5]. The working design has been in development since 2015 and is now rapidly approaching prototype and construction phases.

2.2 Physically Based Model

The physically based model has been designed to use architecture, material properties, weather effects, solar irradiance, and load schedules for input into the Virtual House to simultaneously run among several locations. In order to characterize the overall performance of a building, several modules have been developed. An illustration of the overall system design flowchart for the model is shown in Figure 2.2 and is similar to EnergyPlus' program schematic. Calculations for the simula-

Figure 2.1: Current Courtyard design for *reACT* [5]

tion were made using Python programming to characterize first-principles regarding the building envelope. For the simulation and outputs, time steps of 15 minutes were chosen. Due to the hard time limit of the Solar Decathlon, the scope of what the model considers had to be narrowed through assumptions which are discussed throughout each section.

2.2.1 Structure & Materials

An accurate depiction of the courtyard house is needed for the simulation. Sizes of buildings tend to correlate with overall energy consumption and performance. Courtyard style houses have traditionally been seen as less efficient due to the increased exterior surface area exposed to the elements. General parameters for each surface (walls, roofs, and windows), such as length, width, R-value, and

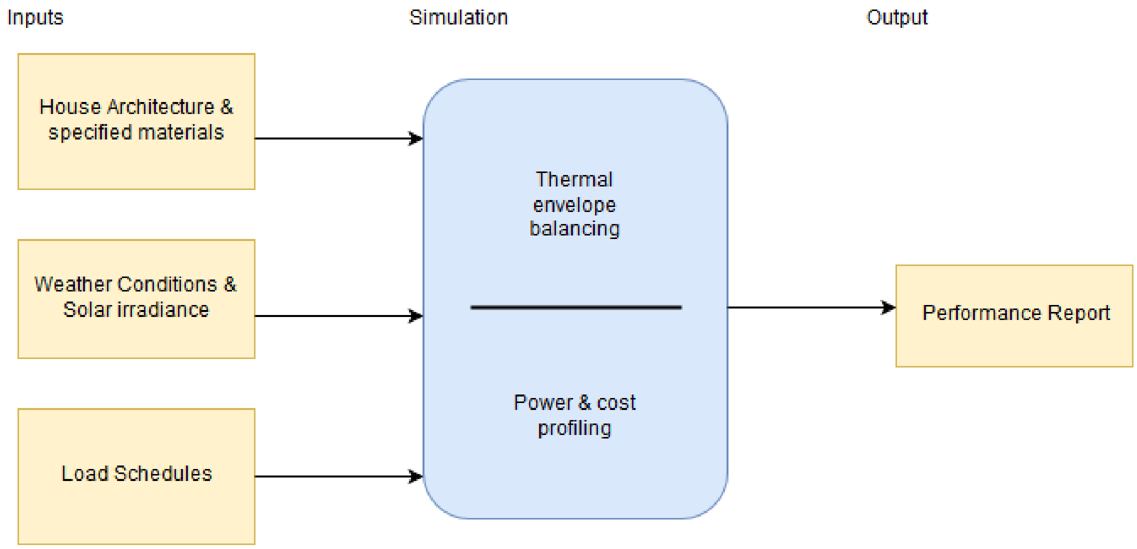

Figure 2.2: Generalized Simulation Design used for reACT

orientation in respect to other surfaces, was adapted from the architectural design for *reACT* and stored in XML as input into the simulation.

A rendering of the simplified courtyard model is generated through our simulation from the parameters and can be seen in Figure 2.3. To note, the current model in use was based off an earlier version of the courtyard design and is evident in the roof structure. Furthermore, window locations are not specifically defined at their designed locations when compared to Figure 2.1. This was ultimately set as simulation and calculations relate mostly only to the orientation of surfaces. For ease of orientational viewing, the red lines in Figure 2.3 uses the right-hand rule for pointing outward directions of surfaces. This was utilized to help separate out exterior surfaces exposed to the elements from internal walls and is also used in part of the solar irradiance calculations.

In order to effectively model the designed building, several parameters must

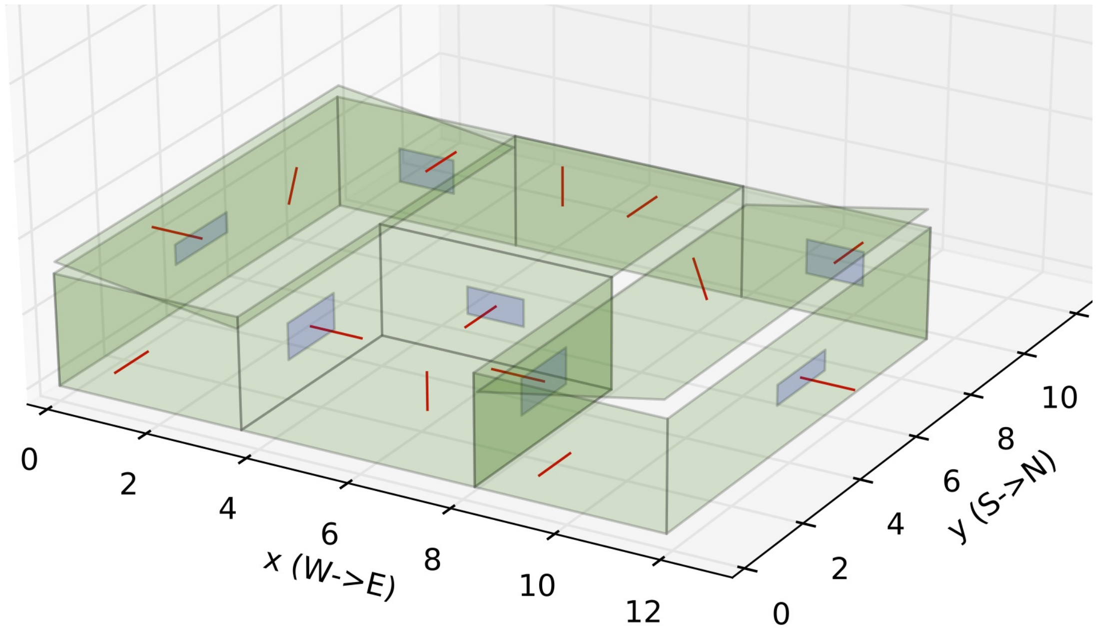

Figure 2.3: Generated graphical representation of physically-based model designed with *reACT* specifications; axes in terms of meters

be specified concerning materials. Due to the competitive nature of the Solar Decathlon, specific components cannot be listed at this time. This said, R-values, color, type of materials, and other material properties were housed in XML for input into the simulation. To note, for numerical calculations sake, wall conduction was not characterized due to the specificity of R-values for materials. These represent pre-solved wall assembly conduction rather than numerically solving for thermal storage within the wall and require much less intensive calculations as these are more algebraic in nature.

2.2.2 Load schedules

Load schedules represent power usage throughout a day. Conveniently, a fairly strict schedule was already specified in its rules as part of the Solar Decathlon [6]. The events in this schedule can be seen as typical family events such as drying clothes, washing dishes, and heating water. Deviating slightly from an typical family use, the Solar Decathlon rules also require an electric vehicle to be driven 25 miles each day of the competition. The electric vehicle battery as well as any residential battery systems must also be fully charged by the end of the competition. Through this information, a general schedule of events was able to be made based off of the conditions specified in the Solar Decathlon as seen in Table 2.1. These values are considered static throughout the year.

In Table 2.1, loads are considered in watts. Typical appliances have been specified by team *reACT* for these values, however again due to the competitive nature of the Solar Decathlon 2017, are omitted in terms of specific models. Instead, these values are found rated as EnergyStar efficient [9]. One exception to this though is that the electric vehicle was specified for a typical electrical vehicle such as the Ford Focus using mileage and unit charge values [10]. Ventilation power is set as that which was calculated to be required by the HVAC subteam in team *reACT* to provide minimum fresh air.

It is also important to note the omission of heating and cooling units in this table. The main reason this was omitted in this table was due to the inherent seasonal changes that affect the amount of heating and cooling required for the

n	Event	Load $P_{f,n}$ (W)	Duration $D_{f,n}$ (min)	Start time $t_{f,n}$ (hr:min)	$f_{th,n}$
0	Refrigerator	27	1440	0:00	1.0
1	Personal computer	36	240	17:00	1.0
2	Television	90	240	19:00	1.0
3	Laundry Machine	211	90	19:00$_*$	1.0
4	Dryer	667	90	21:00$_*$	0.5
5	Water Heater	950	90	1:00$_*$	0.0
6	Stovetop	715	120	18:00	0.5
7	Dishwasher	500	120	9:00$_*$	1.0
8	Car charger	2656	240	18:00$_*$	0.0
9	Lighting	250	720	18:00	1.0
10	Ventilation	143	1440	0:00$_*$	0.5

Table 2.1: Summary of fixed-rate and duration electrical power loads; positive values of $P_{f,n}$ indicate power consumed by the house. Start times $t_{f,n}$ marked * indicate a movable start time. Fraction of power that ultimately is converted to waste heat inside the house is denoted as f_{th}.

building. The dynamic nature of heating and cooling is instead represented in section 2.3.1. Load schedule data was stored in XML for input into the simulation.

Meanwhile, power usage costs from the grid are also specifiable and important as an input in simulation. From this, grid-based consumption and sending power back to the grid can be assessed in terms of profitability. These numbers are generally based off of local utility companies. For use in our simulation, power usage costs were taken from that specified in the Solar Decathlon rules [6]. Table 2.2 shows that energy costs are highest around 1-7 PM and the lowest costs are at $.05 per kWh. During the time of peak energy cost, selling back to the grid is also at its highest, however doing so from 12-7 AM generates no revenue.

Rate name	Off-Peak	Morning-Peak	On-Peak	Afternoon-Peak	Off-Peak
Time Period	12 am - 7 am	7 am - 1 pm	1 pm - 7 pm	7 pm - 10 pm	10 pm - 12 am
Net-consumption cost per kWh	$0.05	$0.12	$0.45	$0.15	$0.05
Net-production value per kWh	$0.00	$0.05	$0.20	$0.08	$0.02

Table 2.2: DOE schedule of service cost

2.2.3 Meteorological work

Differences in location will cause performances of similar houses to vary considerably. The location of housing is that determines the overall climate and weather patterns that the building will be exposed to. Houses located in more temperate zones must consider heating units as winter brings on cold temperatures whereas houses located in tropical zones might be seen with only air conditioning units. In the case of the simulation,both Denver International Airport, CO and College Park, MD were chosen as primary locations due to the high relevance for the Solar Decathlon competition.

In order to take climate and weather into account for simulation, the source of weather data must be chosen. Typical meteorological year (TMY) data is commonly used in building simulations. These are hourly based data sets made to represent an expected year based off of averaged data over several years. Over the years, TMY, TMY2, and TMY3 have been developed as the resulting averaged weather datasets over the years 1948-1980, 1961-1990, and 1976-2005 respectively. There are a few subtle differences in terms of locations and measured meteorological events

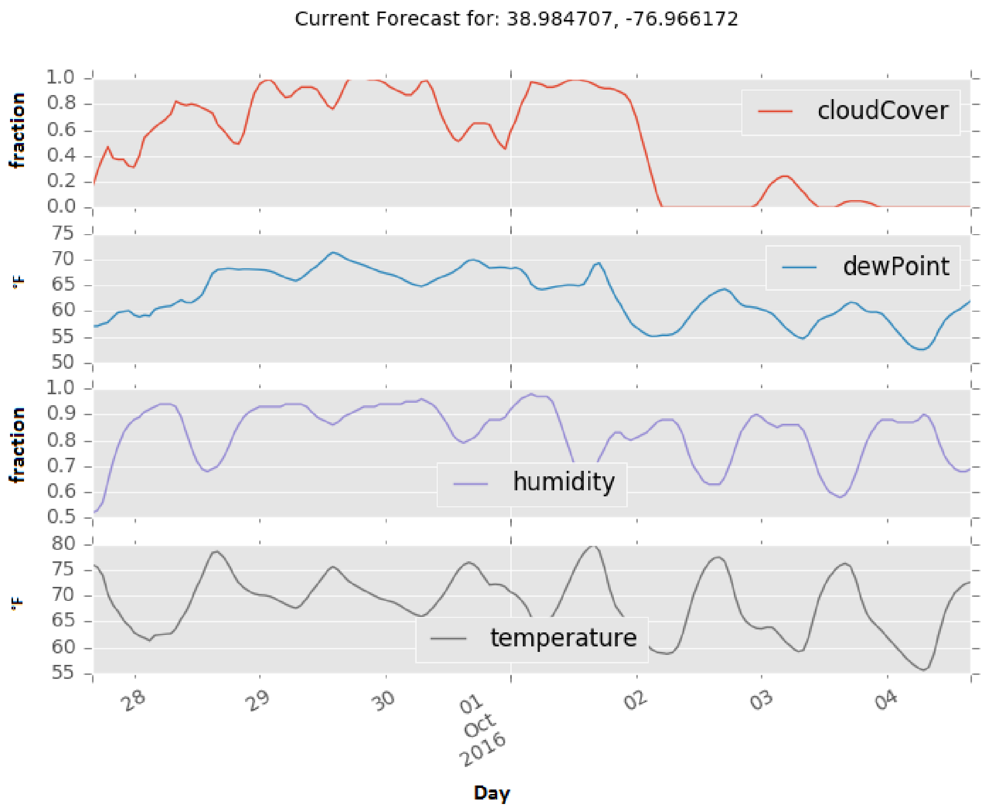

Figure 2.4: A subset of hourly weather forecast data for College Park recorded between September 28th, 2016 and October 5th, 2016 from forecast.io (Darksky API); cloud cover in tenths (1.0 for fully cloudy), dew point & dry bulb temperature in Farenheit, humidity as relative humidity fraction

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but overall contain the necessary information needed to specify outdoor conditions. TMY2 and TMY3 datasets are publically available from NREL for many locations [14]. While TMY3 data initially was used for testing purposes, however it was ultimately decided that weather forecast data be used instead.

The goal of using weather forecast data was to bring in a more accurate depiction of what is the expected performance for the house for the current day. Current conditions allow for a more direct comparison with actual measured performance rather than averaged yearly data. To note, there are actual meteorological year (AMY) data that provide real data for an overall year. The issue remains though that these still represents data logged historically as the year finishes. Furthermore, full sets of AMY data for our specified locations were unable to be found publicly available. On the other hand, forecast data is widely available and allow for more accurate current and future day predictions. Overall, the decision to use weather forecast data was made with the intent to validate our model as $reACT$ is constructed and outfitted with sensors to report measured data. Another motivation was to publicly display reACT's modeled performance for in real-time as a showcase of the Solar Decathlon efforts.

Recording of weather forecast data started in October 1st, 2016, a year before $reACT$ will be shipped and assembled in Denver. Code was developed to automate and facilitate storing of this data. The coordinates (39.86 °N, 104.67 °W) and (38.99 °N, 76.94 °W) were used to specify the locations of Denver International Airport, CO and College Park, MD respectively for forecast requests. A number of services were found to be available for our forecast data requests such as Weather Underground, National Oceanic and Atmospheric Administration (NOAA), and Forecast.io. Forecast.io was ultimately chosen out of the three due to the ease of scheduled requests and intuitive structure of received data in JSON [11]. Daily forecasts were chosen to be requested and stored every day at midnight for both locations because API requests for any weather forecast service are limited to a set number each day.

2.2.4 Solar irradiance modeling

Solar irradiance modeling is essential for this project as the building is required to perform at the very least as net-zero [6]. Solar irradiance represents the amount of energy received by the sun for a given area. Before considering the solar panel, there is a maximum solar irradiance after disregarding any potential effects from surroundings. The maximal amount of solar irradiance can be specified at any given location based solely from elevation and coordinates [12]. This is due to the fact that the earth orbits about the sun in a fairly static fashion. The following calculations referring to expected solar irradiance for modeling is based off the lectures held by Professor Raymond A. Adomaitis regarding photovoltaics. These equations were adapted for the use in the Virtual House.

All radiation can be calculated as blackbody radiation. The classical Stefan-Boltzmann equation is a correlation that can be used to calculate the maximal amount of energy per area at a given point of time:

$$E_{sc} = \sigma T^4 \frac{A_s}{A_{Au}} \tag{2.1}$$

E_{sc} represents the solar constant to be calculated, σ the Stefan-Boltzmann constant

($5.670400 \times 10^{-8} \frac{W}{m^2 K^4}$), and T the source temperature (Sun temperature at 5777 K). A_s and A_{Au} refers to the surface area of the sun's protosphere (A_s = 6.0786 $\times 10^{18}$ m^2) and the area of a sphere corresponding to the mean radius of Earth's orbit about the sun ($A_{Au} = 2.8124 \times 10^{23}$ m^2). Input into equation 2.1 obtains $E_{sc} = 1365.1 \frac{W}{m^2}$, remarkably close to the actual solar constant (1370 W/m^2). Thus, the amount of solar irradiation from the sun for a given area should not exceed this amount without concentration of radiation.

With a maximal value understood, it is important to consider real data concerning expected irradiation. NREL provides publically available experimentally measured solar spectral irradiance data in regards to wavelength (ASTM G-173) as well as standardized tables in regards to airmass (AM1.5) [13]. Air mass plays an important role as it allows us to consider absorptive atmospheric effects on spectral irradiance [12]. A correlation of AM is calculated for these effects on solar irradiation with the following equation,

$$AM = \frac{0.89^z}{\cos\zeta}, for\ z < 3\ km \tag{2.2}$$

in which ζ is the zenith angle, which will be discussed later and z as the altitude of location in km [15]. AM is subsequently inputted into an equation to compute overall solar irradiance (global) as,

$$E_G = [E_{sc} \times 0.73^{AM^{\cdot 678}}](0.11 + \cos\zeta) \tag{2.3}$$

[12].

Of note, cloud effects represent times in which direct component of solar irradiance is zero and only a diffuse component remains. Calculation for this diffuse component, E_F (insolation effect) is based on arguments described by Wenham, et al. 2007 as the following,

$$E_D^{\perp} = E_{sc} \times .73^{AM^{.678}} \tag{2.4}$$

$$E_F = .2 \times E_D^{\perp} \tag{2.5}$$

in which $E_D^{\perp}$ refers to direct irradiance on a surface oriented normal to the Sun's rays and E_F refers to the diffuse components due to insolation effects [16]. From weather data, cloud cover is reported in tenths, a fraction between totally cloudy (1.0) and clear (0). Input of this data allows for an overall calculation of solar irradiance for the day as a simple weighted average

$$E_{total} = (1 - CloudCover) \times E_G + CloudCover \times E_F. \tag{2.6}$$

For instantaneous irradiance modeling, the zenith angle ζ is dependent on the sun's angle relative to the earth's location. The current position can be specified as a function of time and coordinates projected for a sphere in the (x,y,z) coordinate system as

$$x = R_E(\cos\delta(t_d)\sin\phi\cos\lambda + \sin\delta(t_d)\cos\phi) \tag{2.7}$$

$$y = R_E \sin\phi \sin\lambda \tag{2.8}$$

$$z = R_E(-\sin\delta(t_d)\sin\phi\cos\lambda + \cos\delta(t_d)\cos\phi) \tag{2.9}$$

where $\delta(t_d)$ represents an angle derived from the amount of days after winter solstice as

$$\delta(t_d) = 23.44^\circ \cos(\frac{2\pi t_d}{365}) \tag{2.10}$$

[12]. ϕ and λ represent the latitude and longitude and R_E refers to the radius of Earth. Positions x, y, and z, can be vectorized as a normal vector as

$$\vec{n} = \frac{x\vec{x} + y\vec{y} + z\vec{z}}{R_E} \tag{2.11}$$

where $\vec{x}$, $\vec{y}$, and $\vec{z}$ refer to the basis directional vectors in the direction of x, y, and z. Through the time dependent model, the sun's rays can be assumed fixed directly overhead in an orientation of

$$\vec{s} = 1\vec{x} + 0\vec{y} + 0\vec{z} \tag{2.12}$$

where finally through a dot product,

$$\cos\zeta = -\vec{s} \cdot \vec{n} \tag{2.13}$$

ζ is finally calculated for input into equation 2.2 & 2.3 to calculate solar irradiance as ultimately a function of time and coordinates.

With solar irradiance now computable for a certain coordinate and day, we turn a bit towards panel work. Solar panels as a whole represent areas in which the surface is either consider flat (horizontal) or tilted. Because the earlier considerations are for a point, we consider a modified angle, θ_{tilt}, which refers to the degrees of tilt towards the south pole for the panel. A new normal must be calculated, and is done so with R_E and ϕ being replaced with $R_{E,tilt}$ and ϕ_{tilt}:

$$R_{E,tilt} = 2R_E \cos\theta_{tilt}/2 \quad \& \quad \phi_{tilt} = \phi + \theta_{tilt}/2 \tag{2.14}$$

The two variables are inputted into equations 2.7, 2.8, and 2.9 to measure $\vec{x}_{tilt}$, $\vec{y}_{tilt}$, and $\vec{z}_{tilt}$ respectively [12]. Through this, a modified ζ_{tilt} is calculated with the following equations,

$$\vec{n}_{tilt} = \frac{1}{R_E}[(x - x_{tilt})\vec{x} + (y - y_{tilt})\vec{y} + (z - z_{tilt})\vec{z}] \tag{2.15}$$

$$\cos\zeta_{tilt} = -\vec{s} \cdot \vec{n}_{tilt} \tag{2.16}$$

where computation of ζ_{tilt} allows for replacement of ζ in equation 2.3.

One thing to note after all of these geometric considerations, is that shading effects are not currently assessed in this model. The Virtual House makes use of the normals calculated based from *reACT*'s architecture as definable by the four corners of each surface. The $\vec{n}_{tilt}$ as can be seen facing outwards in Figure 2.3 to be used later in a thermal balance for the surface multiplied by the area for overall radiation energy at the exterior surface of a wall, window, or rooftop. Specific panel work is discussed later in power simulation (Section 2.3.2).

2.3 Dynamic profiling

Due to the transient nature of weather conditions, performance of the house varies. Thermal loads may change significantly throughout the day depending on the weather conditions. As a result, the power required to heat and cool via the HVAC system also varies in correlation to the thermal loads throughout the day. While solar panel output is fairly static in nature, this is still dependence on the time of day and cloudiness. Due to the time dependencies, several variables must be calculated based on the current condition. Thus, there are two transitive functions to be considered in this model: heat and power.

2.3.1 Heat profile simulation

Indoor temperature is always in flux. The Solar Decathlon delineates that comfort level in part will be judged on how well indoor temperature stays within the range of 68-74 $^\circ F$ [6]. In turn, one of the main objectives of this work is to characterize the proper amount of heating and cooling needed to stay within specified indoor temperature range in relation to heat generation and transfer.

Heat transfer consideration into and out of the building requires the input of several parameters. For simulation purposes, the HVAC unit was specified to provide cooling at 30000 Btu/hr and heating at 32000 Btu/hr with SEER rating of 13. SEER refers to the seasonal energy efficiency ratio which is commonly advertised similar to an efficiency for the unit as the ratio of cooling/heating output in BTU/hr to power used in watts and is currently federally mandated of manufacturers to be at 13 or greater [17]. Weather data was inputted from the meteorological work in the form of dry bulb temperature as well as cloud cover indirectly through the solar irradiance work. Insulation properties for enclosure of house were specified for input into the overall convective and conductive effect through the wall and window in the form of typical wood R-values and glass U-values [18]. Window property of transmittance is also specified to account for direct transfer of solar irradiance through. Appliance heat loads were considered based off of the type and use to denote conversion into the waste heat during operation as noted by a multiplier, $f_{th,n}$ in Table 2.1.

Meanwhile, several assumptions were made regarding heat effects for the house.

The overall design of $reACT$ is attempting informal integration of heat coupling with several appliances. Due to the complex relationships that arise from heat coupling, this effect is not currently considered in the model. Similarly, no relationship between the roof and solar panels were specified due to the complex nature of shading and efficiency. Instead it was assumed that radiation effects only affected the solar panel and that the roof was subject to any effects similarly to other exposed surfaces. While preliminary work of heat modeling in Appendix A has indicated that the sky radiation effects from infrared may be significant, it was ultimately decided to be omitted for pending further research and revision. Lastly, internal multi-zone interaction is not currently considered within the house.

With the key assumptions and parameters specified, we can move onto discussion of the internal dynamic heat transfer model. The model primarily uses first principle fundamental heat equations in order to characterize temperature profiles throughout the day.

$$\frac{d(mH)_{rm}}{dt} = \Sigma Q_{env} \tag{2.17}$$

The transitive variable regarding $(mH)_{rm}$ refers to the mass and enthalpy regarding a room environment, while ΣQ_{env} refers to the summation of considered heats affecting the enclosure of the building as well as those being generated within. More specifically Q_{env} can be termed with as the following,

$$\Sigma Q_{env} = Q_{surf} + Q_{hvac} + Q_{load}. \tag{2.18}$$

Q_{surf} refers to the overall heat conduction or transmittance through exterior surfaces such as the wall, window, or roof. The overall Q_{surf} was modeled with the following stipulations for exterior surfaces in general:

- The interior wall is equal to indoor air temperature, T_{in}.
- The temperature profile of exterior wall T_{ow} varies linearly based with overall conduction.
- The wall does not show any thermal mass effects (no capacitance) and instantly responds to changes from surface temperature.

To specify the heat for wall (or roof) $Q_{w,n}$ we specify,

$$Q_{w,n} = k_w A_{w,n} \frac{T_{ow} - T_{in}}{W_w} \tag{2.19}$$

where k_w, $A_{w,n}$, and W_w are wall thermal conductivity, total area, thickness respectively. n is used to denote an index of the surface. The wall outside surface temperature T_{ow} is found from a total energy balance at the surface:

$$E_{total,n} - k_w \frac{T_{ow} - T_{in}}{W_w} - \sigma T_{ow}^4 + h_{ow}(T_{out} - T_{ow}) = 0 \tag{2.20}$$

σ is the Stefan-Boltzmann coefficient, h_{ow} refers to outside surface convective heat transfer coefficient that can be found through literature or modeled equations [8]. $E_{total,n}$ is calculated through Equation 2.6 modified for tilt angle for surface n.

Heat transfer through windows was treated a bit differently, using the following equation

$$Q_{win,n} = \tau E_{total,n} + h_{win}(T_{out} - T_{in}) \tag{2.21}$$

Windows were considered to be double-paned with corresponding typical material values. The parameter τ refers to the fraction of solar irradiance is directly transmittable through. τ is commonly considered as transmissivity and is typically 0.7 for a typical double pane window [18]. It is assumed that the window is uniform in temperature and that there is no overall absorbance. Reasoning for this is that window thickness in comparison to walls are generally much thinner and as a result less significant outer surface and inner temperatures are similar, although this effect may be incorporated in a future revision. Through this assumption, energy balance is avoided for the outer surface temperature and heat transfer is only based from the overall heat transfer coefficient h_{win} and temperatures T_{out}, T_{in} [18].

Q_{hvac} refers to the amount of heating or cooling provided by the HVAC unit. It is important to note that the load required of Q_{hvac} to stay within temperature bounds is variable throughout the day. While basic HVAC parameters were set, a bit more detail is needed to explain this in the context of expected heating/cooling output as well as power load associated. To start with, no lag between the HVAC unit output into the air heat content is assumed. A proportionality of heating and cooling was introduced to mimic thermostat control. This was defined as the following:

$$\Phi_h = (T_{h0} - T_{step})/(T_{h0} - T_{h1}), \quad for\ T_{h0} < T_{step} \tag{2.22}$$

$$\Phi_c = (T_{step} - T_{c0})/(T_{c1} - T_{c0}), \quad for\ T_{c0} > T_{step} \tag{2.23}$$

Φ_h and Φ_c refer to the proportional heating and cooling rates to be used to modify the amount of heating or cooling from the HVAC. This coefficient was used in the following manner regarding projected temperature from Euler function T_{step} and operational set of temperature ranges of heating and cooling, (T_{h0}, T_{h1}) and (T_{c0}, T_{c1}) respectively. The ranges of heating were set at (70.5 °F, 69 °F). The ranges of cooling were set at (71.5 °F, 73 °F).

$$Q_{hvac} = Q_{h,maxrate}, \qquad T_{step} \leq T_{h1} \tag{2.24}$$

$$Q_{hvac} = Q_{h,maxrate} * \Phi_h, \qquad (T_{h1} < T_{step})\ and\ (T_{step} < T_{h0}) \tag{2.25}$$

$$Q_{hvac} = 0.0, \qquad (T_{h0} < T_{step}) and (T_{step} < T_{c0}) \tag{2.26}$$

$$Q_{hvac} = Q_{c,maxrate} * \Phi_c, \qquad (T_{c0} < T_{step})\ and\ (T_{step} < T_{c1}) \tag{2.27}$$

$$Q_{hvac} = Q_{c,maxrate}, \qquad T_{step} \geq T_{c1} \tag{2.28}$$

As noted before from the specifications, the considered HVAC unit is assumed to have a cooling and heating rate of 30,000 Btu/hr and 32,000 Btu/hr, and thus represent $Q_{c,maxrate}$ and $Q_{h,maxrate}$ respectively. While simple thermostat controls may work binary in nature in regards to setpoints, the HVAC system that was designed for $reACT$ was known to allow for variable heating and cooling output and served as the motivation for this specificity. The overall effect of such design is to provide a linear progression of power consumption from the HVAC system to cool an area. Illustration of this design can be seen in Figure 2.5, where notably there is a specified dead-zone range of temperatures $\pm 0.5°F$ in which the HVAC is off. When the projected temperature reaches T_{h1} and T_{c1}, the HVAC runs at its max power setting. Through this, Q_{hvac} is defined dynamically as well and subsequent power consumption of HVAC is calculated through SEER efficiency.

Q_{load} refers to the total heat generation from scheduled events throughout the day as specified in Table 2.1. One additional parameter for this is the inclusion of a simple occupancy schedule for a family of four. A more detailed schedule may be considered in the future, but as of now, the four family members were assumed to

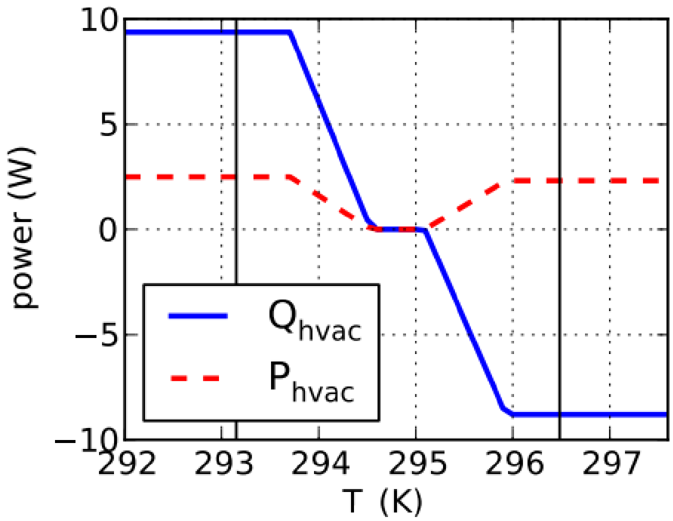

Figure 2.5: HVAC system power inputs and outputs as a function of room interior temperature T (Kelvin). Vertical bars denote SD competition indoor room temperature limits.

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generate 75 W of heat and are within the house only between times between 6 pm and 8 am. Overall, the family is added in as a fixed load of 300 W between those times.

This said, the overall goal is to consider room temperatures. Thus, air volume of each zone was assumed homogeneous, calculated as the dimensions of their respective walling, and converted into thermal mass. The heat capacity of air used for simulation was assumed constant at 29 $\frac{J}{mol*K}$. The final equation regarding heat is thus,

$$\frac{dT_{rm}}{dt} = \frac{Q_{surf} + Q_{hvac} + Qload}{m_{rm,air} Cp_{air}} \tag{2.29}$$

With the differential equation set, Euler's method was used to numerically calculate the temperature profile throughout the day.

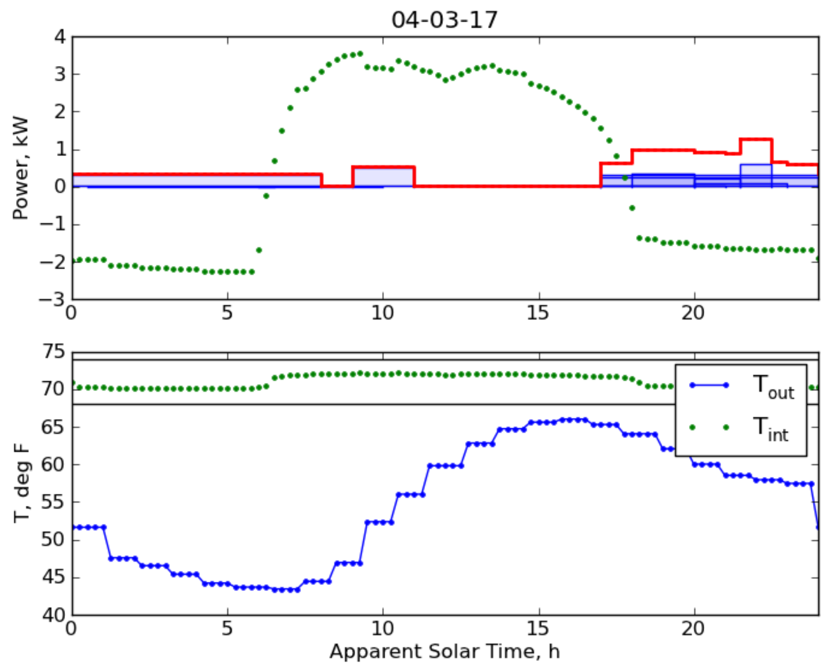
At the start of the day simulation (midnight), the initial room temperature is assumed to be T_{stpt} at 71 °F, the average of temperature range set as goal for Solar Decathlon. As noted earlier, the chosen step size for Euler's method was set to 15 minutes. The overall profile of both temperature and heat loads can be seen in Figure 2.6. Figure 2.6 showcases individual Q_{load} in blue and total Q_{load} in red, while total calculated $Q_{surface}$ is green for the top half. Meanwhile the bottom half illustrates the hourly forecasted outdoor temperatures and simulated indoor temperatures. For the simulation, interpolation of the hourly data was considered but ultimated decided against due to unpredictable gaps in forecast data. Thus, due to the hourly resolution of data, outdoor temperatures appear in a step-wise like profile for this model. Overall, it is exciting to see that Figure 2.6 shows that the temperatures do stay within temperature ranges with the specified thermostat control.

2.3.2 Power profile simulation

While solar irradiance and schedule load events are assumed to remain independent of the temperature profile, the power load needed to heat and cool the building is dependent. Due to this nature, power must be concurrently calculated alongside the heat differential equation. In terms of considering the power for HVAC,

$$P_{hvac} = \epsilon Q_{hvac} \tag{2.30}$$

where ϵ is the efficiency based from specified SEER rating. As such, the power for HVAC is relatively straightforward with the heat load required already specified



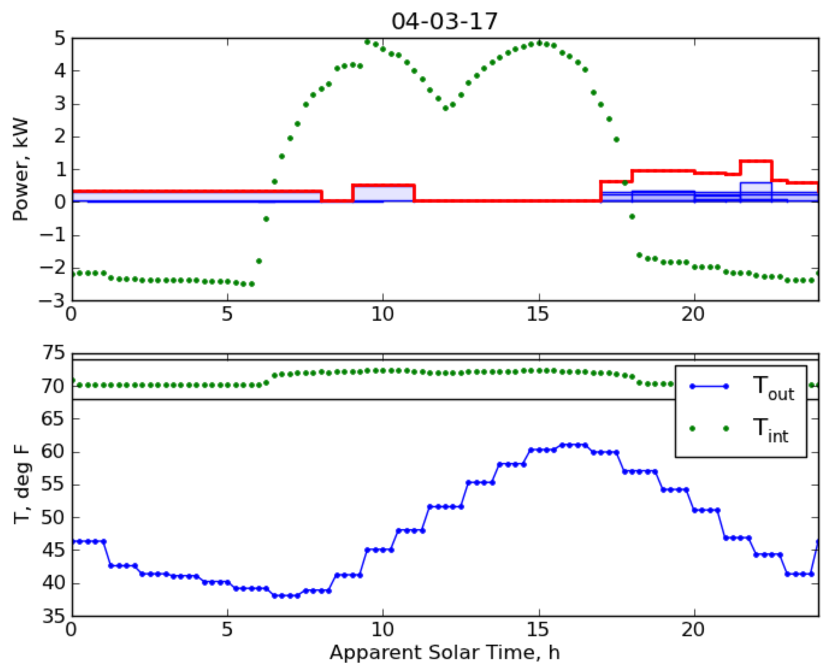


Figure 2.6: Simulated heat and temperature grouped profiles on April 3rd, 2017 for College Park, MD (top) and Denver International Airport (bottom). Grouped top half: Total house thermal loads due to scheduled events (red) and due to heat transfer with the environment (green). Grouped bottom half: outdoor/indoor temperatures shown as blue/green respectively

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earlier.

Schedule plug loads are relatively straightforward. This is similar to the scheduled heat loads, in which typical events were earlier mentioned such as the electric car battery charge and appliance use. The only difference is that all of the events in Table 2.1 were included as electrical loads, as opposed to only a fraction of loads specified for heat. From the schedule, a total plug load, P_{load} is calculated.

Aside from loads based from events and equipment, power incoming from the solar panels, P_{PV} also is required to be calculated. Despite the earlier calculation for projected solar irradiance through equation 2.6, the power is still required to be converted into useful energy and is done so by solar panels. To start with, panel parameters must be specified. The typical parameters required from solar panel data are listed Table 2.3, however the actual manufacturer data that is currently proposed for use in *reACT* is again not disclosed for competitive reasons.

As mentioned earlier, shading effects are not currently considered. Building upon this, each solar cell is assumed to work identically. The following diode equation is considered (based from circuit analysis) for a voltage-current profile for an array of M parallel rows of N identical cells in series,

$$I = M\{-I_{ph}X(t) + I_o[exp(q\frac{(V/N - I/M)R_s}{\beta k_B T}) - 1] + \frac{V/N - (I/M)R_s}{R_{sh}}\} \quad (2.31)$$

[12]. The parameters are defined as the following:

- I_{ph} - diode photocurrent
- I - conventional current
- I_o - diode dark saturation current

- β - diode nonideality factor
- R_s - diode series resistance
- R_{sh} - diode shunt resistance
- q - elementary coulombic charge
- k_B - Boltzmann constant
- X(t) - dimensionless concentrating factor such that X(t) = $E_g(t)/(1000/W/m^2)$

Four variables N, M, V_{oc}, and I_{sc} are derivable from manufacturer data and are able to be inputted into the formula. However, there are five unknowns, β, I_o, I_{ph}, R_s, and R_{sh}. Usage of the four inputs are able to result in 4 independent equations through evaluation at the (1) maximum power point ($P_{mp} = I_{mp}V_{mp}$), (2) its derivative, (3) short circuit condition, (4) and open circuit condition:

$$I_{mp} = M\{-I_{ph} + I_o[exp(q\frac{(V_{mp}/N-(I_{mp}/M)R_s}{\beta k_B T}) - 1] + \frac{V_{mp}/N-(I_{mp}/M)R_s}{R_{sh}}\} \tag{2.32}$$

$$0 = V_{mp}M\{-I_{ph} + I_o[exp(q\frac{(V_{mp}/N-I_{mp}/M)R_s}{\beta k_B T}) - 1] + \frac{V_{mp}/N-(I_{mp}/M)R_s}{R_{sh}}\} \tag{2.33}$$

$$I_{sc} = M\{-I_{ph} + I_o[exp(-q\frac{I_{sc}R_s}{M\beta k_B T}) - 1] - \frac{I_{sc}R_s}{MR_{sh}}\} \tag{2.34}$$

$$0 = M\{-I_{ph} + I_o[exp(q\frac{V_{oc}}{N\beta k_B T}) - 1] + \frac{V_{oc}}{NR_{sh}}\} \tag{2.35}$$

Due to the under-defined system of equations, a model of operating parameters for diode are assumed in which $\beta = 1$, $R_s = 0$, $\frac{1}{R_{sh}} = 0$. These parameters refer more so to an ideal diode system, however this results in now an overspecified set of parameters. Overall, a least-squares solution procedure is used to find parameters on a per-module (M=1) basis. After specifying design solar panel data, the solution converged and simulated P_{mp} was found to be -10.056 kW after specifying 30 modules (M = 30) of overall area of 48.89 m^2. An overall current-voltage and power-voltage graph from solving these equations is seen in Figure 2.7.

Manufacturer	N	M	V_{mp} (V)	I_{mp} (A)	V_{oc} (V)	I_{sc} (A)	width (m)	length (m)
Solaria	72	1	35.0	-4.0	44.5	-4.6	1	2
Gigawatt	60	1	30.9	-8.24	37.39	-8.6	1.04	.992

Table 2.3: Typical Solar Panel Manufacturer data: N and M refer to the number of PV cells in a string and the number of strings in a module, V_{mp} & I_{mp} voltage and current for maximum power, V_{oc} as open circuit voltage, I_{sc} short circuit current, followed by size parameters of width and length [19].

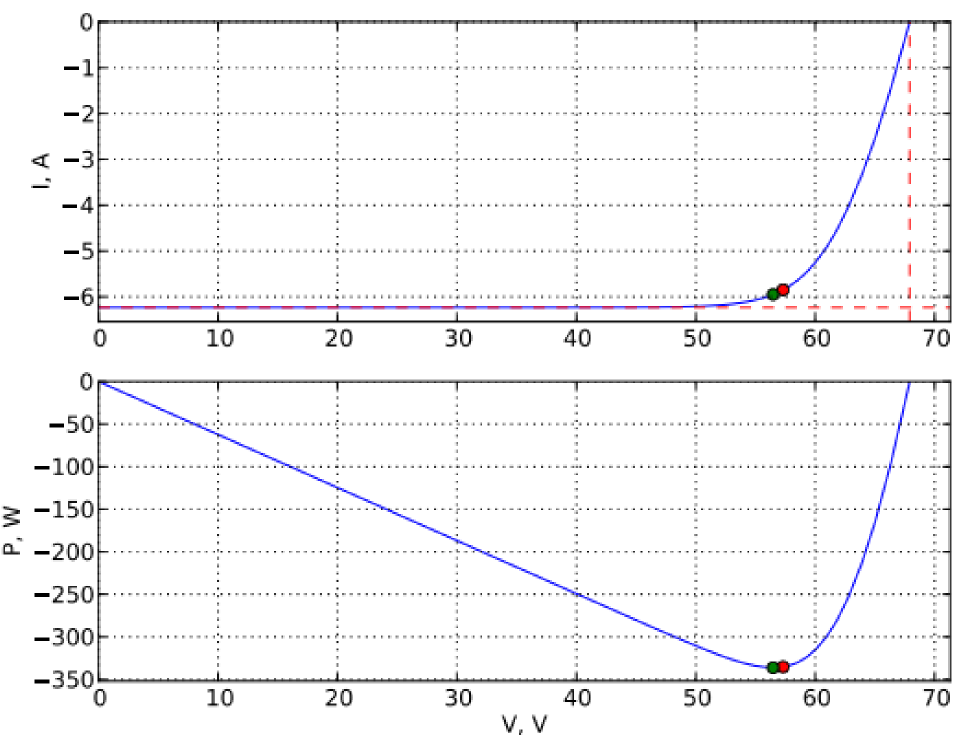

Figure 2.7: Modeled performance for solar panels used in design; modeled maximum power point denoted in green, actual maximum power point in red. Top: I vs V curve. Bottom: P vs V curve

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Before moving on, it is important to discuss this analysis. In Table 2.3, current and voltage specifications for maximum power were already specified. This would have been able to be used without solving of simultaneous equations. However, it is important to note that this is in the context of the Solar Decathlon. The overall basis for modeling panel current-voltage curves is two-fold:

- To qualify the manufacturer's data with measured V_{oc}, I_{sc}
- To generate suitable expected power outputs other than the maximum power point

The second point is crucial as performance quickly degrades after the maximum point, where common practices of panel use is to set voltages below the maximum power point V_{mp}.

With panel data assessed for power output in which P_{PV} is limited in the range of $(0,P_{mp})$, we can finally discuss the overall power consumption in the midst of a residential battery storage system while being tied to the electrical grid. The following differential equation has been used to express this system as

$$\frac{dC}{dt} = P_{PV}(t) - P_L(t) - P_{hvac} + P_{u,buy}(t) - P_{u,sell}(t) \tag{2.36}$$

$\frac{dC}{dt}$ refers to the transitional charge that will ultimately affect the battery. $P_{u,buy}(t)$ and $P_{u,sell}(t)$ refer to necessary power utility buying from and selling to the grid. Simplification for this can be made as the keyword of necessary would only really be made once the initial capacity of the battery, C_o, declines to 0. The equation would then follow more simply as

$$\frac{dC}{dt} = P_{PV}(t) - P_L(t) - P_{hvac} \tag{2.37}$$

Therefore, as a test for the system, the initial charge is set to 0 kWh. With the other parameters set and Euler's method done concurrently with the thermal functions, the output of power and accumulated energy profile throughout a day can be seen in Figure 2.8. Overall for April 3rd, 2017, a net charge for battery is accumulated in both cases. It is interesting to note the magnitude of apparent local weather effects in the P_{PV} (simulated yellow) and the overall difference of accumulation of charge over a day at roughly 5 kWh in College Park, MD and 20 kWh in Denver International Airport, CO.

2.3.3 Profit Analysis

With the bulk of the simulation finally completed, the model's analysis of profits is relatively simple and straight-forward. Using the information provided by the DOE regarding utility cost in Table 2.2, a price can be directly associated with the accumulation of charge seen green in Figure 2.8. The utility cost is scheduled statically similarly to that of schedule loads. Overall the value of accumulated charge (kWh) is directly multiplied by the rate of utility cost ($/kWh) for an instantaneous profit per hour. These values are then integrated in the fifteen minute time steps to track the accumulation of profit profile throughout the day and are visualized in Figure 2.9.

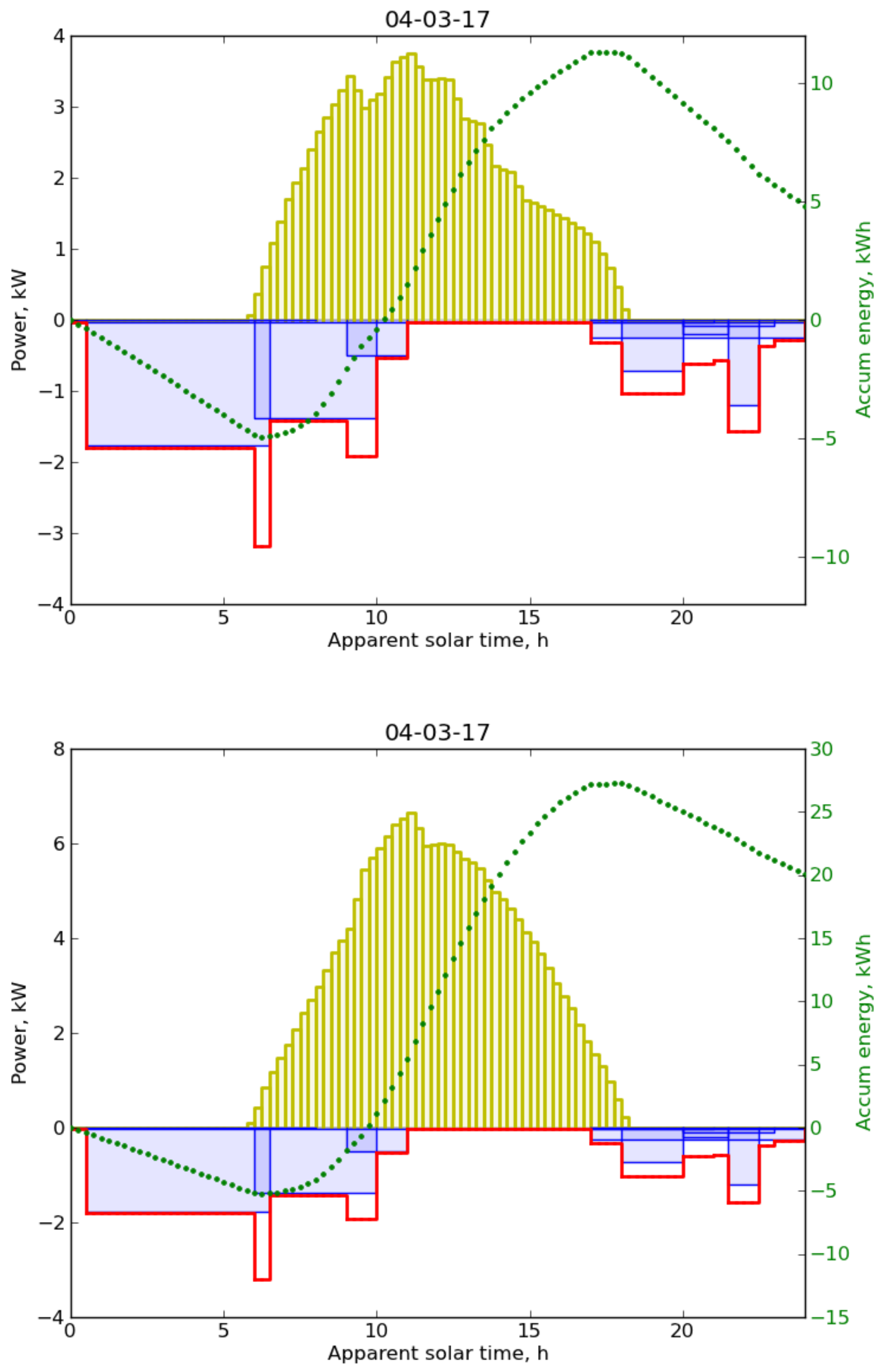

Figure 2.8: Simulated power & accumulated energy profile for April 3rd, 2017 for College Park, MD (top) and Denver International Airport (bottom). Power generation by PV panels shown as yellow, total scheduled power loads as red (individual loads as blue), and net energy production for the day as green.

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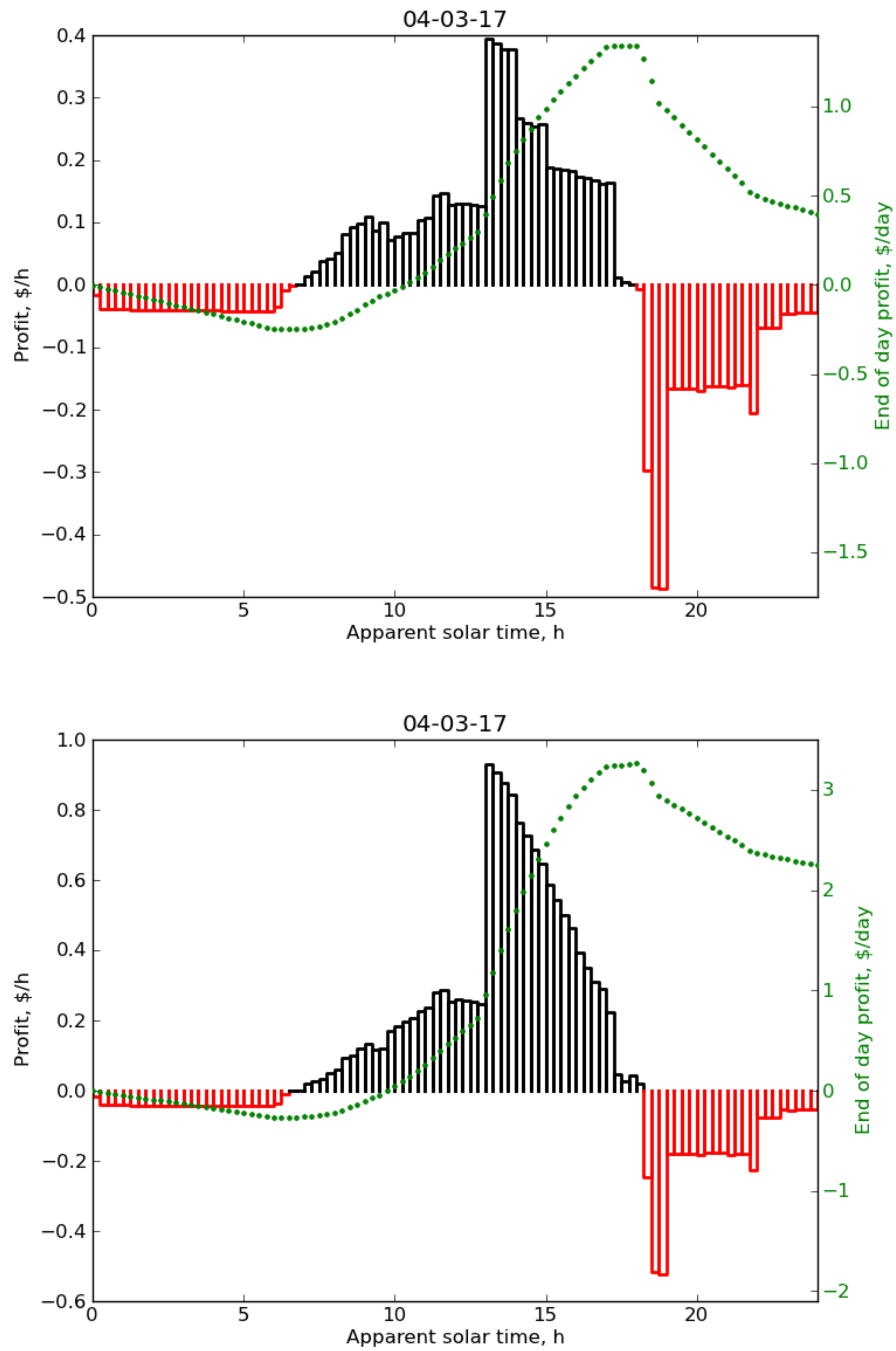

Figure 2.9: Projected profit based on DOE specified utility rates on April 3rd, 2017 for College Park, MD (top) and Denver International Airport, CO (bottom). Instantaneous profits noted as black and costs as red. Accumulated profile of profits throughout day shown in green.

2.4 Discussion

The main driving force for this work has been to generate projected performances for a design case, specifically *reACT* in the context of Solar Decathlon 2017. This has been achieved through extensive work to characterize an accurate depiction of building structure and scheduling, automated weather forecast data retrieval, many theoretical calculations regarding first principles, and simultaneous dynamic thermal & power equations. Results of this Virtual House simulation are now being stored daily at 12:30 am EST. The simulator engine is noted separate from the inputs, allowing for use in characterizing other buildings.

Along the way, many assumptions have been made as noted throughout the work. As of now, Maryland's entry for the Solar Decathlon is still slated for construction in the summer. Unfortunately this means that validation of this model is unable to be obtained until *reACT* is finally built and is reporting performance itself. Ultimately, it is hoped that through data analysis, a magnitude of significance can be attributed towards each parameter to allow for narrowed model refinement towards the variables that impact the house the greatest. As a result, we turn to future work for further development and revision of the Virtual House.

Chapter 3: Future work

The framework for simulation has been developed, in which now any set of inputs can be used to generate reports. As noted last in the previous chapter, a goal is to compare the current simulation with actual data. Since *reACT* has not been built yet, there are plans to instead make use of the existing Solar Decathlon entry, *LEAFhouse* as a test case scenario. While the model itself would need input from *LEAFhouse*'s designed parameters, actual performance from the building would have to be derived from data taken by sensors.

3.1 *LEAFhouse* overview

The *LEAFhouse* is the University of Maryland's 2007 entry in the Solar Decathlon [20]. The team in 2007 had won 2nd place in the competition. After the competition, the building was brought back to the University of Maryland and is currently housed on campus. The house is still in operation as an office for the Potomac Valley American Institute of Architects (PVAIA). Current conversation between the PVAIA and team *reACT* has led to a mutual agreement that work conducted at the *LEAFhouse* would be exciting to see as it promotes awareness of previous Solar Decathlon activity and may be able to bring in new perspectives into

Figure 3.1: *LEAFhouse* at the Solar Decathlon in 2007 [20]

its current use.

3.2 Proposal

In order to gain a grasp of actual performance at the *LEAFhouse*, raw data is needed. As most of the model is based from thermal and power quantities, much of the relevant data needed would be in the form of temperatures and wattage. Considerations of humidity and CO_2 levels are also common parameters of indoor conditions typically measured in terms of human comfort and safety. Since we are interested in the same data for both Solar Decathlon entries, the package of sensors that would be installed at the *LEAFhouse* to record data could also be used in *reACT*.

As the virtual house is outputting entire daily performance profiles, the data incoming from the sensors needs to be capable of autonomously exporting machine readable data. With this all in mind, a proposed general list has been developed as follows:

- Personalized weather station
- Indoor comfort level monitor
- Home power monitoring at the electrical box level
- DC/AC power meter to measure solar panel output
- Raspberry Pi 3 for autonomous data logging

A personalized weather station refers to a set of weather instrumentation devices set for personal use at a home or business. The data measured from these devices generally try to mimic the kind of data seen in TMY data and/or weather forecasts. As such these stations typically measure outdoor temperature, relative humidity, rainfall, wind speed, and pressure. As a bonus, the Weather Underground is currently heading an effort to freely house a network of personalized weather stations [21]. Because of this, many of these weather stations come built in with intuitive export of data via wireless networking and are able to receive cloud services through Weather Underground.

Indoor monitors typically measure temperatures, relative humidity, and CO_2 levels. These all are general useful parameters to consider for homeowners, as measurements of these data can assess general heating and cooling needs as well as to help alert of unsafe environments. While these sensors are relatively common, after specifying the functionality of freely exportable data, finding an appropriate product may be a challenge.

Power sensors are key in monitoring scheduled loads and overall performance of the house. By measuring current at the fuse box level, any plug load can be assessed for the amount of power draw and length of use. However, what this does not show is the overall flow of power, which is particularly important in solar electrical systems. An electric meter would able to measure either DC current at the solar panel level or AC current at the inverter level. Flow at either of these levels can be back calculated to the overall power output of the solar panel and efficiency coming from current conditions.

Lastly, a Raspberry Pi is specified as a vehicle in which to disentangle data from manufacturer software and log data output of sensors. The Raspberry Pi is commonly used in educational purposes as a relatively cheap barebones computing system [22]. By storing data, comparisons can then be finally made between actual and modeled data for validity of model.

3.3 Conclusions

The current virtual house model in use will be updated with parameters specific to the LEAFhouse. With these products considered, it is important to note the handling and ideal locations of these products. After acquirement of these products, proper setup must be done for these sensors to provide meaningful data. Because of the relatively unknown reliability and actual performance of these products, it will also be good to compare its outputs with that expected from the Virtual House.

As stressed before, the overall vision of this work is not to recreate the efforts already made by ASHRAE's updated DOE-2 model (EnergyPlus) throughout the decades. The amount of detail and complex algorithms in there require much more detailed work and research to confirm and code. Furthermore, although the amount of sophisticated design and considered parameters may provide a more accurate depiction of the average performance for the house, the overall simulation requires at least a full set of yearly data [8]. Instead, the development of this simulation is to showcase projected performance for the current day given hourly daily forecasts for a more personalized set of parameters.

There are considerations to also expand the Virtual House simulation to include water and carbon balances. Water consumption is also a resource typically measured and is commonly rated in green building assessments [4]. Carbon balance typically refers to the carbon cycles related to carbon dioxide and monoxide. These values are typically measured for health and safety reasons and will affect the overall assessment of the design at the Solar Decathlon.

In terms of a controls perspective, it may be interesting to consider the effect of weather forecast data resolution for minute by minute data. Currently, hourly data seems to be the standard for most publicly accessible data. There are minutely data, however these datasets seem to be limited only to within the current hour [11]. As such, there is potential future work in this case, however there is the question of how much the forecast data significantly changes by the minute, needing further preliminary analysis.

The University of Maryland's Solar Decathlon entry, reACT, will be assembled for competition in Denver, CO in October 2017. The bulk of this work has been in reference of helping to design and predict how the house will perform at the competition. Revisions so far have been made in context to the needs of the Solar Decathlon. That said, there has been questions such as, what happens to the house after the competition? In a similar fashion, what will happen to the work provided here?

For the first point, there has been consideration of bringing back the building as a resource for sustainability information and education. In that regard there may be room to formally package the Virtual House as software for data utility. That said, it is important to note the overall lack of influences on the model other than variable inputs of weather, building parameters, and scheduled events into the simulation. The simulation is totally based from fundamental equations and calculations. There is nothing to really prevent this simulation from being transitioned over into more chemically oriented work, for instance other research being currently conducted in the research group in atomic layer deposition and thin films. Thus, regardless of the overall outcome, the knowledge and experience gained from this work will remain invaluable.

Appendix A: Thermodynamic Effects on Buildings

A.1 Overview

Thermodynamics regarding scale at the building size is fairly complex in nature. There has been many efforts to help characterize heat transfer in buildings, particularly by ASHRAE [23]. Heat is able to transferred in and out or be generated within building envelopes through sensible heat, radiation, ventilation & infiltration, plug loads, lighting, and the human factor. Heat modeling for buildings is also very dependent on weather conditions and parameters of the building regarding insulation and heating/cooling units.

Heat transfer through the envelope are typically considered through convective and radiative sources. Specifically, sensible heat convected from outside, long wave radiation, short wave radiation, heat conduction through the surface are considered at the exterior surface in the fundamental calculations for heat transfer regarding buildings [8]. Thermal effects through radiation can be significant in regards to irradiation from the sun as well as infrared radiation emitted back from the house into the sky. Black body radiation is much lesser in terms of the earth and house however can still be quantified.

Quick analysis of radiation can be considered by the Stefan-Boltzmann equation for blackbody radiation,

$$j^* = \sigma T^4 \tag{A.1}$$

in which j^* represents energy radiated per unit surface area, σ is the Stefan-Boltzmann constant ($5.670373 \times 10^{-8} W m^{-2} K^{-4}$), and T refers to the temperature of black body radiation source. Through consideration of this relationship with the temperature of a typical household (298 Kelvin) and that with sun (4777 Kelvin), solar radiation is roughly 66,000 times greater than that of the house. As intensity of energy is also related to the wavelength inversely through Planck's equation ($E = h\nu = \frac{ch}{\lambda}$), lower radiation energies are mostly associated with the longer wavelengths in the infrared spectrum. This said, complexities arise with irradiation due to earth's atmosphere and is accounted for using a model from EnergyPlus.

A.2 Preliminary thermal modeling

As a preliminary foray of heat modeling, models used by both ASHRAE and EnergyPlus are assessed in the context of early courtyard designs of reACT. The overall dimensions at the time remained the same except the roof was considered to be totally flat. Although EnergyPlus also considers ground effects, these were ignored for simplicity and quicker understanding of radiative effects. Comparison of sensible, radiation, other sources are considered as according to ASHRAE fundamentals and formulas from EnergyPlus models.

The basic heat equation is

$$\Sigma Q = m * Cp * \Delta T. \tag{A.2}$$

By quantifying the amount of heat being imposed on our house through a heat balance, we can derive out expected temperatures:

$$m * Cp * \frac{\mathrm{d}T}{\mathrm{d}t} = [Q_{sens} + Q_{rad} + Q_{vent\&inf} + Q_{human} + Q_{appl}] + Q_{heater,A/C} \quad \text{(A.3)}$$

As such, a goal of this work was to figure out which heats may be significant for further refinement to help size a suitable HVAC system.

A.2.1 Plug Load Heat

A simple schedule was made based off of the requirements of the Solar Decathlon as well as common family activities. This schedule was an earlier rendition of the schedule seen in Table 2.1, in which only the first 9 of the events are represented in Figure A.1.

A.2.2 Human Heat

The phenomena of heat generation from occupancy is relatively simple of a concept. ASHRAE has a novel way in which a general design of expected accumulated body heat over a day can be modeled. Table A.1 shows typical values of W/m^2 for four different activities. The squared meters refers to the body surface area (BSA). A typical family of four, adult male, adult female, 12 year old, and 9 year old, correspond to average BSA values of 1.9, 1.6, 1.33, and 1.07 m^2 [25]. From this a quick schedule of mixed activities was made in the following manner:

- 0:00 - 7:00 - $Activity_0$
- 7:00 - 10:00 - $.5 * Activity_1 + .5 * Activity_2$

n	Activity	Heat
0	Sleeping	46
1	Standing, light activity	93
2	standing, medium activity	145
3	Calisthenics	261
4	Seated, relaxed	58

Table A.1: Select metabolic activity heat generation rates (W/m^2) [24]

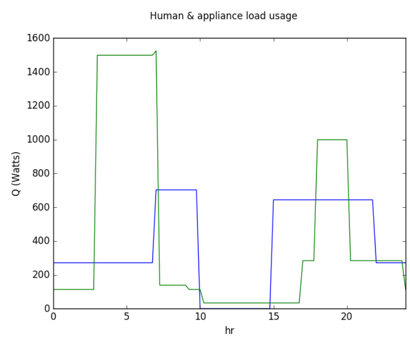

Figure A.1: Heat profile assessment of an average family of four (blue) and typical scheduled loads (green)

- 10:00 - 15:00 - 0 (not at home)
- 15:00 - 22:00 - $.3 * Activity_1 + .3 * Activity_2 + .1 * Activity_3 + .2 * Activity_4$
- 22:00 - 0:00 - $Activity_0$

Multiplication of the schedule by the combined family BSA gives rise to the projected heat generation profile based from metabolic rates as seen in Figure A.1. As a basic assessment, it was fairly intriguing to see human heat being comparable to typical scheduled heat loads.

A.2.3 Sensible heat

Sensible heat, Q_{sens}, can be simply quantified in the case of buildings:

$$Q_{sens} = \text{U-value} * \text{Area of surface} * [T_{out} - T_{in}]. \tag{A.4}$$

in which the U-value represents the amount of conductance through a specified material at a given thickness. For given parameters of the house, the amount of heat transfer attributable to the difference of temperature is quickly calculated and seen in Figure A.2 (left).

A.2.4 Long and short wave radiation

Radiative effects are much more complexly modeled. In particular, ASHRAE standard model was not used due to the fact that their model is only used for temperature data that has been corrected for radiative use [23]. As such Energy-Plus formulas were tested in the context of Solar Decathlon parameters. Empirical correlations were used for the infrared "sol-air" temperature. Sol-air temperature ($T_{sol-air}$) is a variable used to improve the estimated heat load on a building through exterior surfaces [8]. It is considered as an improvement over sensible heat because it accounts for radiative effects.

$$T_{sol-air} = T_o + \frac{\alpha * I - \Delta Q_{ir}}{h_0} \tag{A.5}$$

$$T_{sol-air} = T_o + T_{swr} + T_{lwr} \tag{A.6}$$

where parameters are noted as:

- T_o = Outdoor temperature
- α = solar irradiation absorptivity (.4 for light colored)
- I = global solar irradiance (w/ cloud cover) $[W/m^2]$
- ΔQ_{ir} = extra infrared radiation due to difference between the external air temperature and the apparent sky temperature $[W/m^2]$.
- h_o = heat transfer coefficient for radiation $[W/m^2K]$

Following through EnergyPlus's model, the heat transfer coefficient is calculated as

$$h_o = \sigma * \epsilon(T_s^2 + T_o^2)(T_s + T_o) \tag{A.7}$$

where,

- $\sigma = 5.670367 * 10^{-8}(\text{Stefan-Boltzmann const}, W/(m^2 * K^4))$
- ϵ = emissivity, .9 typically
- T_s = surface temperature (°K)
- T_o = outside temperature (°K)

The first step to estimating the ΔQ_{ir} is to calculate a sky temperature, T_{sky}. The series of formulas to calculate T_{sky} from EnergyPlus are as follows

$$Sky_{emissivity} = .787 + .764 * ln(\frac{T_{dew\_pt}}{273.15}) * (1 + .0224 * cldcvr - .0035 * cldcvr^2 + .00028 * cldcvr^3) \tag{A.8}$$

$$Overall\_Horizontal\_Q_{IR} = Sky_{emissivity} * \sigma * T_o^4 \tag{A.9}$$

$$T_{sky} = (sky_{IR}/\sigma)^{.25}(K) \tag{A.10}$$

where,

- T_{dew_pt} = Current dew point (K)
- $cldcvr$ = current cloud cover in tenths (0-10)

This estimation of T_{sky} now allows for,

$$\Delta Q_{IR,sky} = \epsilon * f_{surf} * \sigma * \beta_{surf} * (T_{sky}^4 - T_{indoor}^4) \quad \text{(A.11)}$$

- ϵ = emissivity of surface (typically .9)
- f_{surf} = form factor (1 for horizontal, .5 for vertical)
- $\beta_{surf} = (.5 * (f_{surf} * 2))^{.5}$ beta view factor

β_{surf} represents the fraction amount of heat that is split into sky radiation with the remaining transfered to surrounding air (T_{sky} vs. T_o). This adds an additional equation for emitted infrared radiation as

$$\Delta Q_{IR,air} = \epsilon * f_{surf} * \sigma * (1 - \beta_{surf}) * (T_o^4 - T_{indoor}^4) \quad \text{(A.12)}$$

Finally the calculated Q_{ir} is able to be converted to how it affects temperature change via

$$T_{lwr} = \Delta Q_{ir}/h_0 \quad \text{(A.13)}$$

Meanwhile, solar irradiation was calculated from a fundamental standpoint. The same solar irradiance the fundamental calculations were used shown in the model work in sub section 2.2.4. This overall heat profile was then influenced by weather conditions of specifically cloud cover originating from TMY3 data. Overall the calculations made directly used calculated E_{total} without tilt considerations. Instead were multiplied by form factor similar to the infrared calculations as

$$Q_{swr,surf} = [(1 - cloudcover) * E_G + cloudcover * E_F] * f_{surf} \quad \text{(A.14)}$$

and shortwave radiation effect on temperature is calculated as

$$T_{swr} = Q_{swr}/h_0 \quad \text{(A.15)}$$

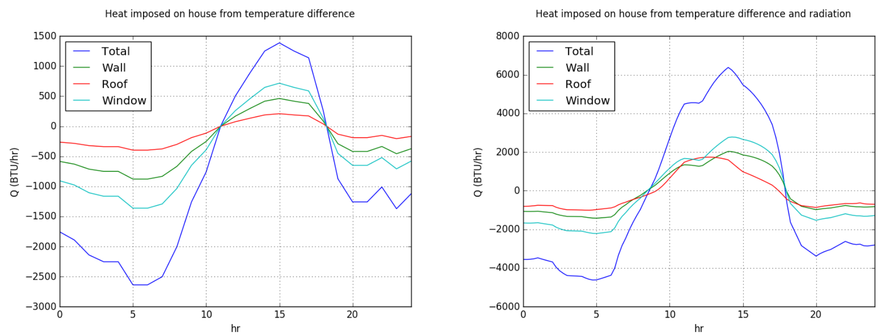

Figure A.2: Simulated heat profile due to sensible (left) and combined sensible and radiative effect (right) for College Park, MD using TMY3 Data.

Based from the calculations using equations for radiation, the amount of sensible and radiative heat was quantified together as seen in Figure A.2. The magnitude of the radiation seems to overshadow the sensible effects. There are however a few questions pertaining the origin of EnergyPlus's sky temperature formula and derivation of heat transfer coefficient. In particular this radiation heat transfer coefficient plays a big part in deciding how much radiation is converted to felt temperature.

A.2.5 Ventilation and Infiltration

ASHRAE 62.2-2010 was used to calculate the minimum ventilation rate required. ASHRAE standards for minimum ventilation are based on health and safety standards [23].

$$Q_v = .05 * A_{cf} + 3.5 * (N_{bedroom} + 1)(L/s) \tag{A.16}$$

Where, A_{cf} refers to conditioned floor area and $N_{bedroom}$ = # of bedrooms

Infiltration is overall calculated from an expected leakage area for which in-

	I_0	I_1	I_2
Hot	51	.35	.23
Cold	25	.38	.12

Table A.2: ASHRAE 62.2 infiltration driving force coefficients based on wind speed and pressure

ternal and external pressure forces ultimately produce unwanted infiltration of air throughout the house. An infiltration driving force variable is calculated by ASHRAE as

$$IDF = I_0 + H \mid \Delta T \mid *(I_1 + I_2 * A_{l,flue}/A_l))/1000 \ L/(s * cm^2) \tag{A.17}$$

where coefficients I_0, I_1, I_2 were taken from ASHRAE 62.2 (Table A.2), ΔT refers to difference of outdoor and indoor temperature, and A_{flue} represents flue space (assumed 0), H wall height (m). Overall leakage rate Q_i is then calculated as

$$Q_i = A_l * IDF \ (L/s) \tag{A.18}$$

- $A_l = A_{cs} * A_{ul}$ effective leakage area cm^2
- A_{cs} = building exposed surface area
- A_{ul} = unit leakage area cm^2/m^2 [Tight = .7, Good = 1.4, Avg = 2.8]

With infiltration and ventilation rates, Q_i and Q_v, calculated, this is then considered in the context of a heat or energy recovery (HRV/ERV) system. This system acts as a dedicated outdoor air unit to import necessary fresh air from outside and export stale air from within. As such it is assumed then that minimum required

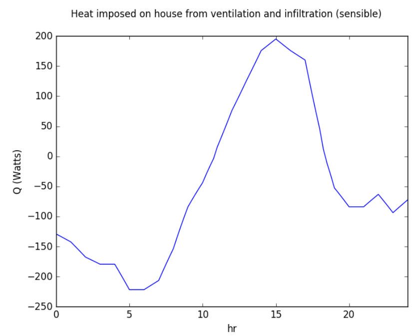

Figure A.3: Combined Ventilation and Infiltration Effects on Heat based off of ASHRAE standard 62.2

rate as the specified ventilation rates for HRV/ERV $Q_supply =$ Qv & $Q_exhaust =$ Qv

The methodology of heat calculations arising from ventilation/infiltration are listed below from ASHRAE:

- $Q_{vhc} = Q_v + Q_i$ Combined inflow
- Q_{bal} = min($Q_{supply}, Q_{exhaust}$)
- Q_{unbal} = max($Q_{supply}, Q_{exhaust}$)-Q_bal
- $Qvi = max(Q_{unbal}, Q_i + .5 * Q_{unbal})$ Maximum vent./inf. inflow

Sensible heat load from ventilation & infiltration:

- $Q_{bal,other} = 0$ other ventilation source
- $e_s = .85$ assumed HRV sensible efficiency
- $Cs = 1.23$ heat capacity of air W/(L*s*K)
- $q_{vi,sens} = [Cs * (Qvi + (1 - e_s) * Qbal + Qbal_{other}) * (T_o - T_i)$

After following through ASHRAE's model for heat losses due to infiltration and ventilation, the combination of heats associated with ventilation and infiltration results can be seen in Figure A.3. Because the infiltration driving force is assumed to only vary with temperature at an assumed constant wind speed, the profile looks similar to that seen in Figure A.2 (left).

A.3 Discussion

Comparing Figures A.1, A.2, and A.3, it seems that radiation effects result in the highest magnitude in heat load. As this a relatively quick preliminary measure for magnitude of heat, latent loads due to moisture in the air were not considered at the time. One of the key challenges found while performing calculations from EnergyPlus was that although the formulas were explained, most of the coefficients had to be derived elsewhere. As a similar point in ventilation and infiltration, wind speed was not really addressed through their formulations. Instead, the coefficients were only derived for two wind speeds. Wind speed as found in any weather data file is highly variable, and may need to be considered in a different infiltration model. Overall, the formulas used by ASHRAE standards and EnergyPlus were found to be a good starting point for understanding thermodynamic interactions for surfaces. In essence, difficulty quickly arises whenever coefficients and parameters are not so well are defined for a customized building when trying to include more effects.

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