ABSTRACT

Title of Thesis:	SYSTEMS MODELING AND TECHNO-ECONOMIC ANALYSIS FOR reACT NET-ZERO ENERGY HOME
	Akanksha Bhat, Master of Science, 2019
Thesis Directed By:	Dr. Raymond A. Adomaitis Professor, The Institute for Systems Research

Net-Zero Energy building designs have become ubiquitous within modern sustainable city frameworks because of their ability to minimize adverse ecological impact, through the integration of energy efficiency principles with renewable energy generation sources. This study presents the key accomplishments and research methodology for the detailed modeling and techno-economic assessment of Net Zero energy homes, conducted in collaboration between the A. James Clark School of Engineering and the U.S. Department of Energy's National Renewable Energy Laboratory (NREL). The University of Maryland's 2017 award-winning reACT virtual

system has been used as a prototype for modeling and assessment efforts. By amalgamating elements of Model-based Systems Engineering design with NREL's REopt optimization platform, the research aims to minimize system lifecycle costs for Net-Zero energy homes through the optimization of available generation resources, which will in turn proliferate and encourage the adoption of Net Zero Energy homes across global communities.

SYSTEMS MODELING AND TECHNO-ECONOMIC ANALYSIS FOR reACT NET-ZERO ENERGY HOME

by

Akanksha Bhat

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Advisory Committee:
Professor Raymond Adomaitis, Chair/Advisor
Professor David J. Lovell
Assistant Professor Huan Xu

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List of Abbreviations

BDD	Block Definition Diagram
DOE	Department of Energy
GHG	Greenhouse Gas
IBD	Internal Block Diagram
IEA	International Energy Agency
INCOSE	International Council on Systems Engineering
LCOE	Levelized Cost of Electricity
LEED	Leadership in Energy and Environment Design
MACRS	Modified Accelerated Cost Recovery System
NAHB	National Association of Home Builders
NREL	National Renewable Energy Laboratory
NZEB	Net Zero Energy Building
reACT	resilient Adaptive Climate Technology
SAM	System Advisor Model
HOMER	Hybrid Optimization of Multiple Energy Resources
IEA	International Energy Agency
SoC	State of Charge
WorldGBC	World Green Building Council

Chapter 1: Introduction

1.1. Background

Green building designs have gained traction among global communities in response to growing concern for the reduction of carbon footprint and mitigation of adverse ecological impact. This trend is supported by organizations such as the World Green Building Council (WorldGBC) and key findings from data quantification and assessments conducted by the International Energy Agency (IEA), which state that building design and construction sectors are responsible for 36% of global final energy consumption and nearly 40% of total direct and indirect CO2 emissions. [1] Within the U.S. itself, the residential and commercial sectors together account for 39% (about 38 quadrillion British thermal units) of total U.S. energy consumption, primarily attributed to building design. [2]

This has led to a proliferation in research efforts for the design and development of Net Zero energy buildings. The U.S. Department of Energy defines a Net Zero energy building as one which incorporates energy efficiency and renewable energy resources to consume only as much energy as can be produced onsite through renewable resources over a specified period of time. [3] In 2016, the Net-Zero Energy Buildings (NZEBs) market size was valued at USD 8.04 billion, indicating growing demand for Net Zero energy homes and communities across the nation, in an effort to transition to a low-carbon economy. [4] However, it is interesting to note that the adoption of Net

Zero energy design has been slow within the residential market, with Zero Energy (ZE) and Zero Energy Ready (ZER) homes making up less than 1% of the residential market. [5] The primary reason for this is the stakeholder perception of a high cost barrier associated with Net Zero energy homes. This assertion has been corroborated by the results of a 2017 survey conducted by the National Association of Home Builders (NAHB), where 81% of single-family home builders stated that they either don't know how much more it will cost to build a green home or thought that a green home building would add more than 5% to the cost. [6] With a slew of federal tax credits and incentives available to encourage the adoption of these technologies at the residential level, it then becomes an optimization problem where the upfront cost of the technologies must be balanced against revenues generated over the lifetime use of these assets.

Historically, techno-economic studies have been conducted on hybrid renewable energy systems (HRES) and individual renewable energy resources such as Solar Photo-Voltaic technology to quantify the cost impact associated with these technologies, however, no large-scale research has been conducted in assessing the techno-economic feasibility of Net Zero energy homes. This thesis research aims to analyze the techno-economic feasibility of Net Zero energy homes by addressing stakeholder end needs of cost optimization and system resiliency. This is accomplished by developing an estimate of optimal technology sizes chosen from an available renewable energy resource mix and identifying economical dispatch strategies for meeting stakeholder requirements. While modeling platforms such as EnergyPlus, HOMER and SAM are commonly used for energy efficiency assessment, the REopt tool developed by the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) has been used as the primary platform for conducting techno-economic assessment within this research.

In essence, a number of decisions need to be taken when designing a Net Zero energy home. These decisions range from optimal site selection to the selection of ideal building size, architectural design, thermal insulation, optimal sources for on-site energy generation, total costs and greenhouse gas emissions (GHG) associated with the Net Zero energy home. [7] Energy asset modeling and analysis tools such as SAM and EnergyPlus are utilized extensively by home owners and green building rating systems such as the Leadership in Energy and Environment Design (LEED) to characterize building energy performance and calculate performance of the construct with respect to sustainability metrics such as energy and resource efficiency, indoor environmental quality and waste reduction potential. However, these tools are inept at performing dynamic optimization of home resources and cannot monitor load and cost variance of the house from day to day. To address these limitations, the University of Maryland Engineering Team designed the "reACT Virtual Simulator" for real-time control and dynamic resource optimization of electrical and thermal loads within the reACT Net Zero energy home.

By utilizing elements of Systems Engineering design, this research aims to provide a detailed and modular architecture for the reACT Virtual simulation framework to understand the process flow and interdependence of the modules within the simulation. An initial assessment of the potential stakeholders and their expectations from the Net Zero home simulation tool will open new dimensions for the modification and development of the reACT simulation. Additionally, any changes and configurations to the systems architecture will be effectively monitored and controlled by the developers and maintainers of the reACT Virtual simulation software throughout the project lifecycle.

1.2. Solar Decathlon

The Solar Decathlon Competition is a collegiate competition sponsored bi-annually by the U.S. Department of Energy, that fosters the design and development of green buildings that can effectively demonstrate energy efficiency principles and an innovative design for sustainable living. This competition serves as a platform for universities across the world to design and build highly efficient and innovative buildings powered entirely by renewable energy generation sources. The designs submitted as part of the competition are required to comply with the Solar Decathlon Building Energy Codes and rules, which consist of standards akin to LEED and other green building ranking systems.[8] The competition ranks teams based on the performance of their Net Zero energy homes in key sustainability areas such architecture, market potential, water use and re-use strategies, occupant health and comfort, energy-efficiency and cost-effectiveness.

The University of Maryland, College Park has been a frequent participant in the Solar Decathlon competition. In the 2017 Solar Decathlon competition, the University of Maryland Team developed an innovative Net-Zero energy home named “reACT” which stands for resilient adaptive climate technology. This entry was ranked first within the U.S. and second internationally. Designed with influences from the Nanticoke and Maryland tribal traditions, reACT featured an innovative composting system, hydroponic garden, vegetable garden, and movable “living walls” covered in plants. To complement and support the physical model, a virtual model of the reACT home was designed by the University of Maryland Engineering team, for predicting the performance of the house design based on weather forecasts corresponding to the location of the virtual houses. Figure 1.1. shows the reACT physical model developed as part of the competition deliverables.

Figure 1.1: reACT Net Zero energy house [9]

Building on the success of the reACT Net Zero energy house design, the University of Maryland will participate in the Solar Decathlon Europe 2019 Competition which will be held in Szentendre, Hungary and will rank the designs based on effective simulation of existing buildings for enhanced interior comfort, four-season design, and architectural quality in integrating new technologies and materials. The University of Maryland has also collaborated with the Al Akhawayn University, Morocco for participating in the Solar Decathlon Africa 2019 Competition and is responsible for providing software development and support for the “DarnaSol” Net Zero Energy Home located in Morocco. To aid these endeavors, the physical and virtual model developed for the award-winning reACT Net Zero Energy Home are being leveraged to support the design and development of future Net-Zero energy homes for entry into the respective competitions.

1.3. Project Objective/ Motivation

By utilizing elements of Systems Engineering design, this research aims to provide a detailed and modular architecture for the reACT Virtual simulation framework which will help document the functionality and inter-dependence of existing software modules within the reACT Virtual model. The identified modular design framework can then be used for migrating the Python code into other optimization frameworks such as Julia and R and will allow the use of the simulation in cross-functional applications. With the steadily increasing penetration of Net Zero energy homes and constantly evolving building energy codes, it has also become imperative to identify potential stakeholders for this technology and incorporate their requirements in the design and development of energy modeling tools for performance assessment of buildings. As part of the research work, a detailed stakeholder needs assessment has been conducted for the reACT simulation software and their expectations from the simulation have been identified as potential system capabilities. This study discusses the key results of implementing Systems Engineering design principles for achieving the aforementioned goals.

Constant innovations in the renewable energy domain have led to a significant decrease in market prices of renewable resources. While solar module prices have plunged by

81% in the past decade, the LCOE of utility- scale PV and Li-Ion battery systems has decreased to USD 0.10/kWh and USD 187/MWh respectively. [10] [11] The LCOE for a technology is defined as the ratio of total lifecycle cost and total electrical energy produced over the lifetime of the energy asset. This has made it possible for the average home-owner and designer to choose from a mix of diverse clean energy technologies for supporting Net-Zero energy goals for their home designs. This raises the challenging problem of identifying an optimal energy resource mix for meeting thermal and electrical loads based on the location of the building and the geographical availability of resources within the area. The thesis builds on the use of NREL REopt tool for performing techno-economic assessment of net zero energy homes in order to identify the optimal mix of generation resources for reducing system lifecycle cost and maximizing resiliency goals.

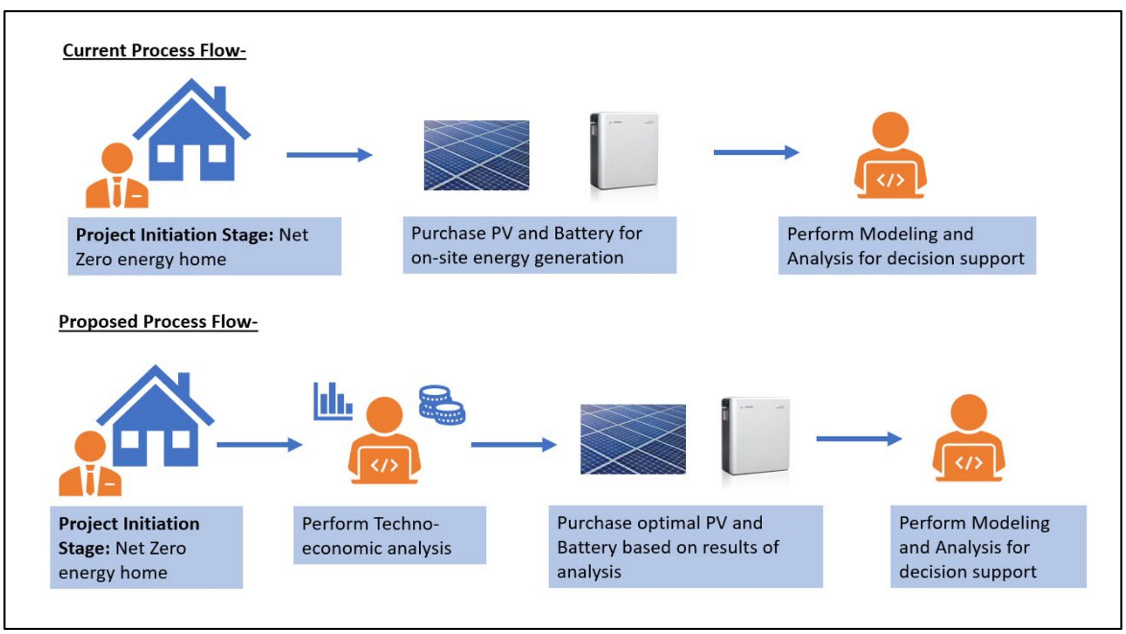

Figure 1.2: Current and proposed process flow for the design and development of Net Zero energy homes

By amalgamating elements of Model-based Systems Engineering design with NREL's REopt optimization platform, the research aims to capture the above requirements through stakeholder needs assessment, software systems modeling and the optimization of available generation resources for minimizing system lifecycle cost. This will in turn help proliferate and encourage the adoption of Net Zero Energy homes across global communities.

Chapter 2: reACT- Virtual House

2.1. Overview

The reACT Net Zero energy home is the University of Maryland's 2017 entry into the Solar Decathlon Competition. To support the design and development of the reACT physical model, the University of Maryland Engineering Team has developed a detailed simulation model that can predict the performance of the reACT house based on weather forecasts corresponding to the locations of the virtual houses. The open-source model is written entirely in the Python programming language and utilizes first-principles description of Solar Irradiance, house PV array power output, nominal house energy loads and the thermal modeling of the house and its HVAC system. [12]

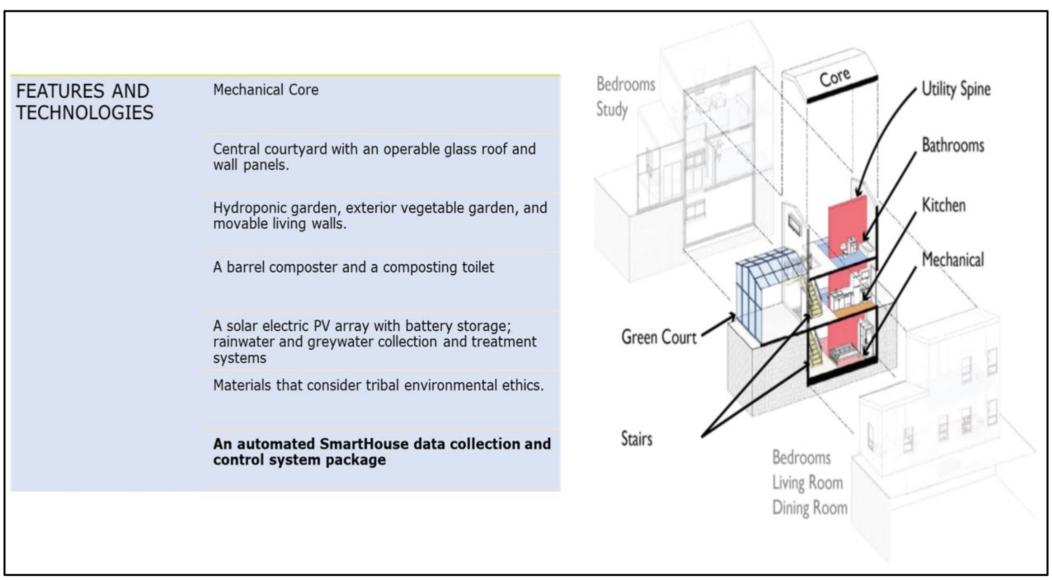

Figure 2.1: reACT Physical Model with corresponding features and technologies

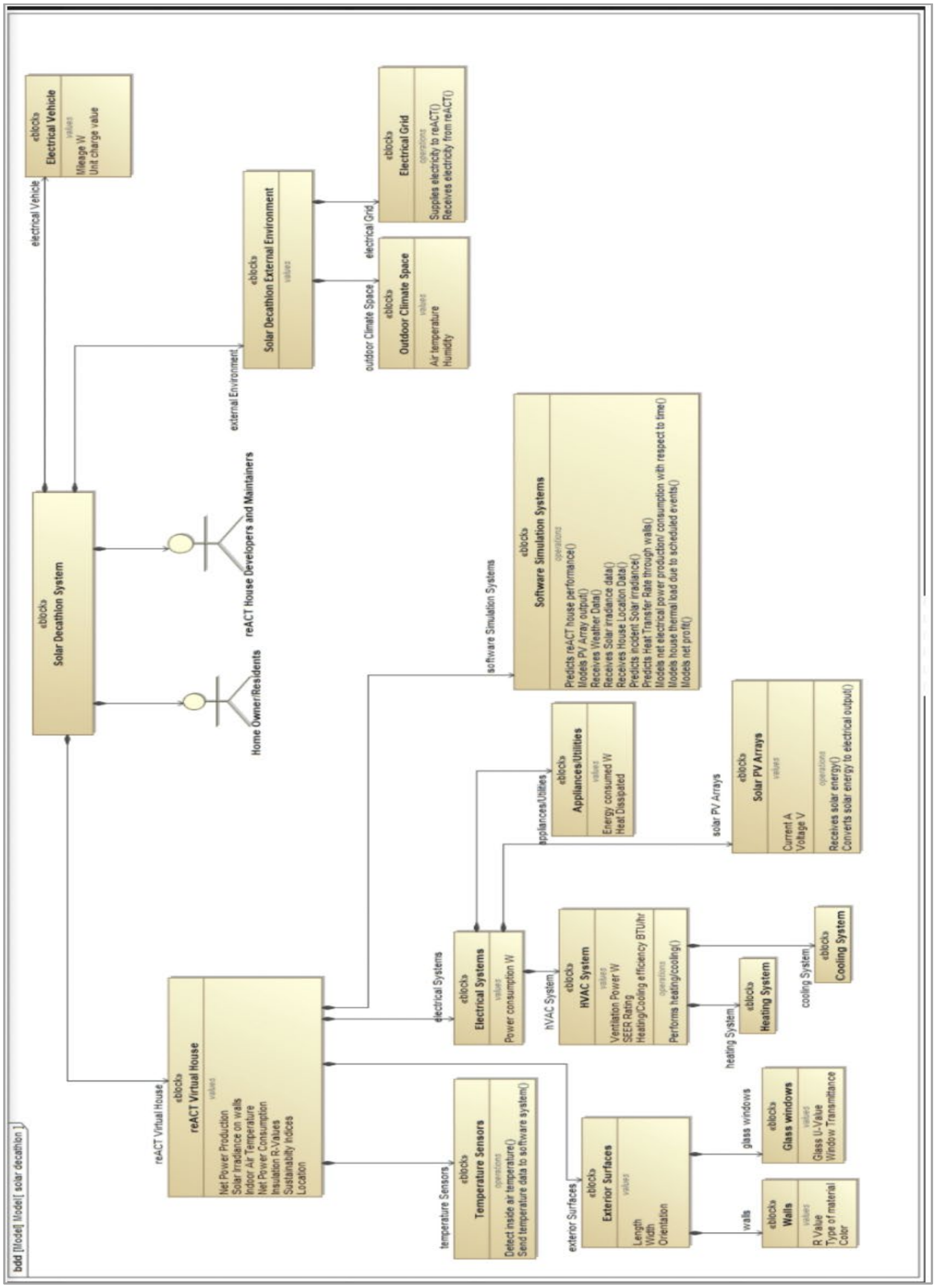

Figure 2.2: Block Definition Diagram showing components of the reACT Net Zero Energy house

2.2. Virtual Model

The generalized simulation design has been represented through a flowchart shown in Figure 2.3. The virtual model is a conglomeration of individual modules and libraries designed for characterizing the performance of the reACT house through thermal envelope balancing, power and cost profiling. The architectural properties, weather effects, solar irradiance, and load schedules are used as input into the virtual model for generating a detailed performance report for the physical model. The simulation output is generated in time steps of 15 minutes.

For the purpose of the competition, Denver, Colorado and College Park, Maryland were chosen as the primary locations for assembling the Net Zero energy home and validating the performance of the home through the Virtual Simulation Model. The model inputs, simulation modules and outputs are explained in detail in the following sections.

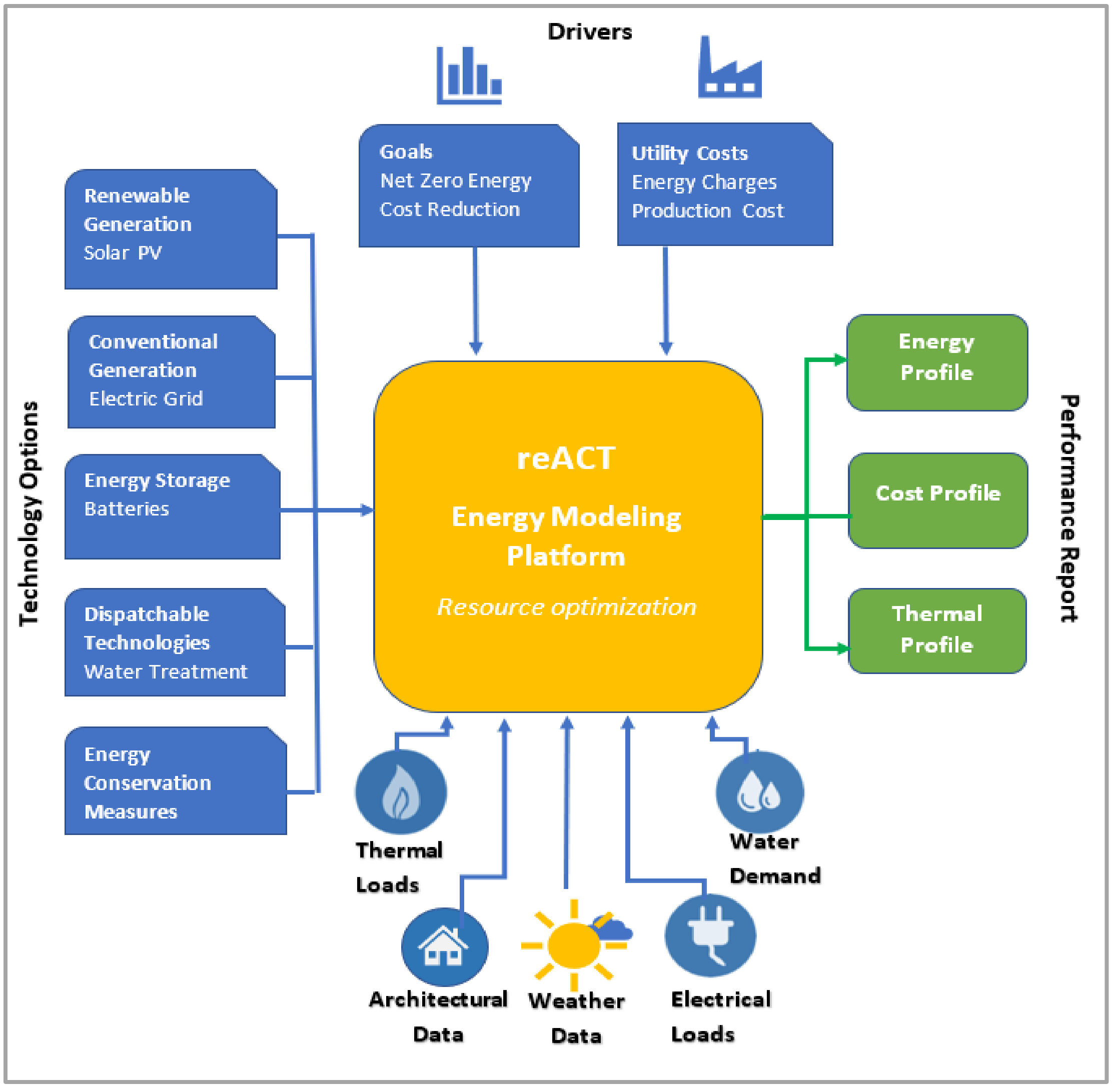

Figure 2.3: Summary of the high-level Inputs and Outputs for the reACT Simulation Software

2.2.1. Inputs

The primary inputs to the simulation are the material/architectural properties of the Net Zero energy home, the load schedule data, the site-specific weather conditions and solar irradiance. It is important to note that the reACT house is primarily designed as a courtyard style house. In order to effectively model the designed building, general architectural parameters such as the Length, color, type of materials, width, R-value, surface orientation and other material properties for each surface (walls, roofs, and windows), were extracted from the architectural design for the reACT house and stored in an XML file for input into the Simulation.

Load Schedules indicate the power consumption for the Net Zero energy home. The events that result in load consumption generally involve typical family events such as drying clothes, washing dishes and heating water. Additionally, the Solar Decathlon rules also mandate the use of an electric vehicle for commuting. The vehicle must be driven for 25 miles (40.234 km) for each day of the competition and can only be charged from the house electrical system. Therefore, in order to earn credits within the competition, the battery State of charge (SoC) for the electric vehicle must reach 100% at the end of the competition period. The power usage of the appliances used in the Net Zero energy home and the corresponding load events are described through fixed and pre-specified load schedules for the Solar Decathlon event. The nominal load schedule data is represented in Table 2.1. and is stored as an XML file for input into the simulation. The loads are specified in Watts and represent power usage throughout a 24-hour time period.

n	Event	Load (W)	Duration	Start Time
0	Refrigerator	27	1440	0:00
1	Personal Computer	36	240	17:00
2	Television	90	240	19:00
3	Laundry Machine	211	90	19:00
4	Dryer	667	90	21:00
5	Water Heater	950	90	1:00
6	Stovetop	715	120	18:00
7	Dishwasher	500	120	9:00
8	Car Charger	2656	240	18:00
9	Lighting	250	720	18:00
10	HVAC	143	1440	0:00

Table 2.1: Fixed rate and duration power load data as specified by the Solar Decathlon Competition rules [13]

In order for the reACT house to be Net Zero, it is required to generate and sell back as much energy as it consumes over a (day/year) back to the grid. The U.S. DOE specifies fixed energy consumption and sell-back (production) costs for the Net Zero energy home as part of the rules specified in the Solar Decathlon Competition. Table 2.2. shows the peak, off-peak and partial peak hours for the Net Zero energy home. Net production is achieved when the total power sent to the grid over a 15-minute period exceeds the total power drawn from the grid. Net consumption is achieved when the total power drawn from the grid over a 15-minute period exceeds the total power sent to the grid. Energy consumption costs are highest around on-peak period from 1 pm-7 pm and lowest within the off-peak period. At the same time, net energy produced on-site and sold to the grid during the peak demand period generates maximum profit while selling back energy between 12 am-7 am generates no revenue. It should be noted that these values change with a change in the location and the corresponding utility that the Net Zero energy home connects to.

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 am- 12 am
Net Consumption cost per kWh	$ 0.05	$ 0.12	$ 0.45	$ 0.15	$ 0.05
Net-production cost per kWh	$ 0.00	$ 0.05	$ 0.20	$ 0.08	$ 0.02

Table 2.2: U.S. Department of Energy Schedule of Service Cost [14]

Another important input to the reACT virtual model is the weather and solar irradiance data for the specific locations where the Net Zero energy house is assembled for final operation. Variation in climate and weather conditions can significantly impact the performance of the Net Zero energy house. In order to take these into account, a weather data source called Forecast.io has been utilized. Daily forecasts are requested from the API, and the resulting weather data is stored at midnight every day for Denver, CO and College Park, MD locations.

2.2.2. Simulation

With the above inputs specified, the simulation forecasts the expected performance of the Net Zero energy house over a 24-hour period using interdependent and cross-functional libraries and modules. The core functionality of the simulation is divided into thermal envelope balancing functions and power and cost profiling functions. Initially, the incident solar radiation and indoor/outdoor air temperature variations are used to determine the heat transfer rates through the house external walls. The heat transfer through the external walls and windows, direct radiation through the windows, and waste heat dissipated from nominal load consuming events are then used to determine the HVAC loads, indoor air temperature, and overall net power production value for the Net Zero energy house.

- The Solar Simulation modeling tool is used by the model to predict the sun's normal irradiance as a function of the location of the house and time of year. These data are combined with the cloud-cover forecast data to determine the incident global irradiance on each external surface (walls, windows, PV array) of the reACT house.
- The PV manufacturer's performance data is stored as an XML file for input into the PV performance toolbox. The PV Performance Toolbox uses this data to determine the current versus voltage characteristics of the PV arrays over a 24-

hour period using the solar irradiance forecasted using the Solar Simulation Toolbox.

- Nominal electric load schedule data is read by the simulator and used to compute the energy consumption associated with regularly scheduled events.
- Heat Profile simulation is done by the reACT Simulation module to calculate indoor and outdoor temperature, along with the temperature flux for the reACT Net Zero energy home.

2.2.3. Simulation Outputs

Once the input data is specified, the Simulation module generates a detailed performance report for the reACT Net Zero energy house. The performance report contains the power and accumulated energy profiles for the period of the day based on calculated PV performance data and thermal profiles. Once, the energy generation and consumption are calculated, the reACT Virtual simulator generates the projected profit based on DOE specified utility rates by multiplying accumulated charge (kWh) with the rate of utility cost ($/kWh) for an instantaneous profit per hour. Through this analysis, the reACT simulation meets the twin goals of dynamic resource optimization and system analysis. By ascertaining the projected performance of the reACT Net Zero energy house, critical decisions can be made regarding the choice of material, architecture and technology options.

Chapter 3: Systems Engineering based Modeling and Design

3.1. Overview

Given the complexity of modern systems, systems engineering's methodical approach for the definition and realization of systems has become highly relevant across a plethora of applications and processes. INCOSE states that “Systems Engineering helps avoid omissions and invalid assumptions, helps to manage real world changing issues, and produce the most efficient, economic and robust solution.” [15] The reACT Virtual system is, in its entirety, a sophisticated and complex system that is composed of inter-dependent and cross-functional modules and libraries. This paves the way for the implementation of system engineering principles and methods to the reACT virtual simulation system. To allow the reACT virtual simulation to evolve, it is necessary to identify potential stakeholders for this technology and address their needs through future modeling efforts. Consequently, the Systems Engineering process has been incorporated in this research to comprehend stakeholder needs and manage change and configuration effectively throughout the project lifecycle.

The reACT simulator engine is currently written in the Python programming language primarily due to the ease of use of the language, user-friendly data structures and extensively available third-party modules and libraries for optimization support. However, with software languages and their syntaxes constantly evolving, it becomes imperative to envision the reACT Simulation System simplistically in terms of its core components. By modeling the functionality and dependability of modules, this research will enable the migration of the reACT Simulation system to other efficient and widely used platforms such as Julia, R, Mosel and encourage the scaling and deployment of the reACT Virtual system to new as well as existing Net Zero energy homes.

3.2. System Stakeholder Analysis

A System stakeholder analysis was performed to identify existing and potential stakeholders for the reACT Virtual system. Table 3.1. enlists the principal stakeholders identified for the reACT virtual system and informs on their respective roles.

ID	Stakeholder	Role(s)
SH1	Solar Decathlon Simulation Team	Customer, Maintainer, User
SH2	U.S. Department of Energy (DOE)	Project Sponsor
SH3	The A. James Clark School of Engineering	Project Sponsor
SH4	Net-zero energy Home Owner	Customer, User
SH5	Researchers and Educators	User
SH6	Educators	User
SH7	Students	User

Table 3.1: Stakeholder List

The University of Maryland Solar Decathlon Simulation team primarily consists of virtual simulation developers and maintainers who are responsible for managing the development, modification and maintenance of the Net-Zero energy simulation tool. As such, the Simulation team has been identified as the principal stakeholder in this analysis. The U.S. Department of Energy and the A. James Clark School of Engineering are the project sponsors and stakeholders for the research and development of efficient Net-Zero energy homes. The reACT house has been developed for a married couple living in Denver, Colorado, who remain registered members of the Nanticoke Indian Tribe, and they will be the primary customers for the Net Zero energy house.

The potential users for the reACT virtual simulation are scientists and researchers within diverse fields, who will interface with the simulation to support their research efforts. Another segment of potential users includes educators across universities who will interface with reACT Simulation for educational and teaching purposes. Finally, the students who interact with the reACT virtual software will use the software modules such as Solar Irradiance Toolbox and PV Performance Modeling in their field of study and for gaining educational exposure to energy modeling and simulation for renewable technologies. For instance, the Solar Simulation Toolbox was used in the design process, allowing for the multiscale time-based evaluation of chemical reactor systems and plant location sites across the U.S in the senior capstone CHBE design class taught by Dr. Raymond Adomaitis in spring 2018. [16]

3.3. System Capabilities

The reACT Virtual Simulation Software was primarily built to support the design and development of the reACT physical model. In the project planning, design and construction phase for the physical model, the simulation was used as a decision support tool to identify parameters such as PV array tilt based on solar irradiance, window location, thermal insulation and surface orientation, to ultimately ensure that the building is Net Zero energy. Once, the reACT physical model was developed and commissioned, the primary capability for the reACT virtual simulation system shifted to the efficient prediction of the year-round performance for the Net Zero energy house, based on weather forecasts corresponding to the locations of the virtual houses. Table 3.2 further defines this high-level goal in terms of lower level capabilities.

Priority	Capability	Rationale
1	Perform thermal envelope balancing	Defines "predictive capability"
1	Perform power profiling	Defines "predictive capability"
1	Perform cost profiling	Defines "predictive capability"
1	Generate Performance report for U.S. DOE compliance	Defines "predictive capability"
1	Provide high availability	Defines (24/7/364) home resource monitoring
2	Perform dynamic optimization of home resources (loads)	Defines "supervisory control capability"
3	Support research and development activities	Additional Mission
3	Support educational activities	Additional Mission
3	Support students in their analysis	Additional Mission

Table 3.2: reACT Virtual Simulator System Capabilities

The reACT Simulation is constantly evolving to support the design and development of Net Zero energy homes such as the “DarnaSol” Net zero energy home built by Al Akhwayn University for the Solar Decathlon 2019 Competition in Africa. The purpose of conducting a capability analysis was to identify existing and potential capabilities for the reACT simulation system in order to identify potential ways to expand its functionality through new modules.

3.4 System Capability Requirements

The system requirements can be broadly classified into system programmatic requirements and system operational requirements and have been discussed in the sections 3.4.1. and 3.4.2.

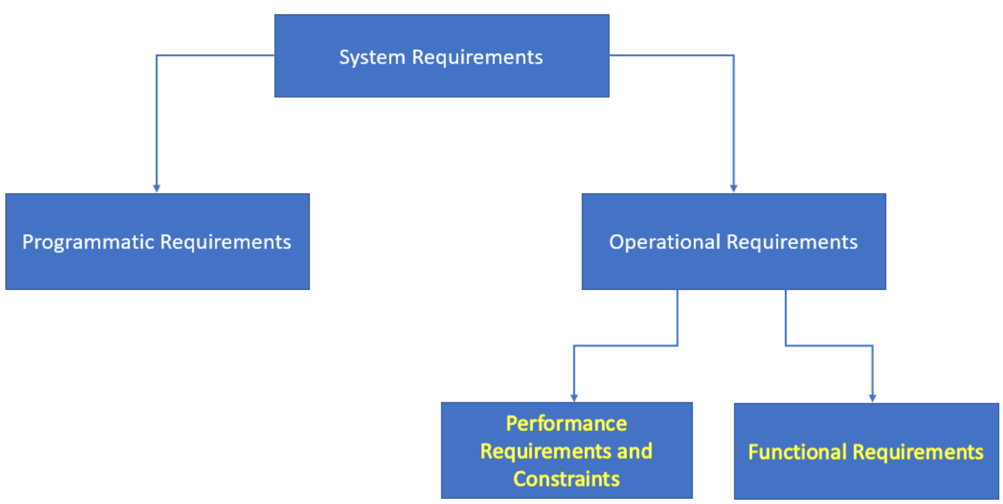

Figure 3.1: reACT System capability requirements

3.4.1. System Programmatic Requirements

The programmatic requirements for the reACT Simulator system are listed in Table 3.3. These represent stakeholder expectations in terms of cost incurred in the design and development of the reACT simulation, which depends on the cost of labor, hardware and O&M costs for the simulator engine. Other programmatic requirements for the system include the need for enhanced system reusability and portability for migration into other optimization platforms.

Stakeholder Requirement Number	Stakeholder Requirement	Description
SHR 3.4.1.1.	System Lifecycle Cost	The reACT Simulator system shall have a life cycle cost of less than $100,000. The lifecycle for the reACT simulator includes the initiation, design, development, testing and commissioning phase.
SHR 3.4.1.2.	System Portability	The reACT Simulator system shall provide flexibility by allowing for easy migration to different software platforms such as Julia, Mosel and R. Additionally, the system should be easily portable to newer Net Zero energy home designs.
SHR 3.4.1.3.	System Reusability	The reACT Simulator system shall be easily modifiable and programmable for application within different domains.
SHR 3.4.1.4.	Schedule Requirement	The reACT Simulator system shall be operational (tested and validated) before the given deadline for the Solar Decathlon Competition.

SHR 3.4.1.5.	System cross-functionality	The reACT Simulation system shall be capable of working in parallel with modules in other platforms. For instance, the Python code for the reACT house should be capable of invoking functionalities and modules developed within other platforms and languages such Modelica or R.

Table 3.3: Programmatic Requirements for the reACT Virtual Simulation System

3.4.2. System Operational Requirements

Table 3.4. details the operational requirements for the reACT Simulator engine. It should be noted that the simulator engine is considered separate from the inputs, thereby allowing its use in characterizing other buildings.

Stakeholder Requirement Number	Stakeholder Requirement	Description
SHR 3.4.2.1.	**Performance Requirements & Constraints**	
SHR 3.4.2.1.1.	Operational Availability	The reACT Virtual system shall provide a steady state operational availability of (Aoss) > = 0.95
SHR 3.4.2.1.2.	Operational Frequency	The reACT Virtual system shall provide a mean time between analysis cost and energy profile of = < 24 hour
SHR 3.4.2.1.3.	Prediction Error	The reACT Virtual system shall predict cost and energy performance for the Net Zero energy home with an accuracy > = 98%

SHR 3.4.2.1.4.	System Run Time	The reACT Simulation system code shall execute in < = 240 seconds
SHR 3.4.2.2.	**Functional Requirements**	
SHR 3.4.2.2.1	Perform dynamic profiling	The reACT virtual system shall be able to simulate and optimize the performance of the house for different virtual house locations.
SHR 3.4.2.2.1.1.	Perform weather and climate profiling	
SHR 3.4.2.2.1.1.1.	Compute solar irradiance for specified location	The reACT virtual system shall be able to compute the solar irradiance for a specific set of longitudes and latitudes
SHR 3.4.2.2.1.1.2.	Compute dry bulb temperature and cloud cover forecast for specified coordinates and days	The reACT virtual system shall be able to generate the dry bulb temperature and cloud cover forecast for a specific set of coordinates and time of day.
SHR 3.4.2.2.1.1.2.1.	Request weather data	The reACT Virtual System shall send weather data request to Forecast.io API at midnight every day
SHR 3.4.2.2.1.1.2.2.	Retrieve weather data	The reACT Virtual System shall retrieve 24-hour weather forecast data for the subsequent day.
SHR 3.4.2.2.1.2.	Perform heat profile simulation	
SHR 3.4.2.2.1.2.1.	Simulate total house thermal loads	
SHR 3.4.2.2.1.2.1.1.	Simulate total house thermal loads due to scheduled load events	The reACT Virtual System will calculate and plot the heat dissipated in the home due to scheduled load events such as cooking and/or using refrigerator.

SHR 3.4.2.2.1.2.1.2.	Simulate total house thermal loads due to heat transfer with the environment	The reACT Virtual System will calculate, and plot heat transferred into an out of the building based on weather data.
SHR 3.4.2.2.1.2.2.	Simulate outdoor/indoor temperatures with respect to time	The reACT Virtual System will forecast hourly outdoor temperatures and simulated indoor temperatures and plot them with respect to time.
SHR 3.4.2.2.1.3.	Perform power profile simulation	
SHR 3.4.2.2.1.3.1.	Model performance of solar panels	
SHR 3.4.2.2.1.3.1.1.	Calculate power generated from PV array	The reACT Virtual System will simulate and plot Power versus Voltage characteristics for the PV Array to determine maximum power point for efficient operation.
SHR 3.4.2.2.1.3.1.2.	Plot Current-Voltage characteristics for the PV Array	The reACT Virtual System will plot the Current versus Voltage characteristics for the PV array to determine maximum power point for efficient operation.
SHR 3.4.2.2.1.3.2.	Model scheduled plug loads	The reACT Virtual System will model the electrical loads based on specified nominal load schedule (in Table 2.1.)
SHR 3.4.2.2.1.4.	Perform cost profiling	
SHR 3.4.2.2.1.4.1.	Calculate and plot projected profit	The reACT Virtual System shall calculate projected profits for the Net Zero energy home. 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 fifteen-minute time steps to track the accumulation of profit profile throughout the day.

SHR 3.4.2.2.2.	External Interface Requirements	
SHR 3.4.2.2.2.1.	Provide User Interface	The reACT Virtual simulator shall provide an API interface to the home-owner that accepts user commands and displays status of load and cost profile data for the Net Zero energy home.
SHR 3.4.2.2.2.2.	Provide Maintainer and Developer Interface	The reACT Virtual simulator shall provide an API interface for the developer and maintainer that accepts maintenance commands in the event of a failure or system update and displays status of load and cost profile data for the Net Zero energy home.
SHR 3.4.2.2.2.3.	Operating Environment Interface	The reACT Virtual simulator shall gather sensory data on weather conditions such as temperature, humidity, shading effects from the operating environment.
SHR 3.4.2.2.3.	Specialty Engineering Requirements	
SHR 3.4.2.2.3.1.	RAM Requirements	
SHR 3.4.2.2.3.1.1.	Reliability	The reACT Virtual simulator shall have a mean time between critical failure (MTBCFs) >= 90,000 hrs.
SHR 3.4.2.2.3.1.2.	Maintainability	The reACT Virtual simulator shall have a mean down time (MDTs) < = 10 hrs.
SHR 3.4.2.2.3.2.	System Security Requirements	The reACT Virtual Simulator shall be secure from cyber threats.
SHR 3.4.2.2.3.3.	Training Requirements	The reACT Virtual Simulator shall have a user manual and training materials for development support.

SHR 3.4.2.2.4.	Other Operational Requirements	
SHR 3.4.2.2.4.1.	Enable Cross-functional application	The reACT Virtual Simulator shall allow for easy updating and reprogramming. This capability will be implemented through the documentation of the libraries and modules within reACT Virtual Engine, for easy comprehension and use by different stakeholders.
SHR 3.4.2.2.4.1.1.	Support research and development activities	The reACT Virtual Simulator shall support researchers and scientists in conducting analysis for Renewable Energy technologies and Net Zero energy buildings.
SHR 3.4.2.2.4.1.2.	Support educational activities	The reACT Virtual Simulation shall support educators in demonstrating the principles of energy efficiency and simulation design.
SHR 3.4.2.2.4.1.3.	Interface with students	The reACT Virtual Simulation shall have an interactive GUI for supporting students in conducting analysis for their projects and learn about Net Zero energy design.

Table 3.4: reACT Simulation System Operation Requirements.

3.5. System Measures of Effectiveness

Now that the stakeholder requirements and expectations for the reACT Virtual Simulator system are clearly defined, it is important to develop metrics that can help the stakeholder to measure the extent to which the reACT Virtual Simulation system meets the above goals. System Measures of Effectiveness (MOE) are measures designed to quantify the accomplishment of mission objectives or desired results for a system. Table 3.5. identifies the high-level measures of effectiveness for the reACT Virtual simulation system and the associated threshold values.

Attribute	Metric	Type	Definition	Threshold Value	Unit
PV performance Error	PVe	MOE	The % error in predicted power generated from the PV array based on solar irradiance modeling	< 6	%
Cost Error	Ce	MOE	The % difference in actual cost incurred and the predicted cost for the Net Zero energy home over an year	< 1	%
System Availability	Operational Availability (Ao)	MOE	The probability that the system will be able to monitor the home resources at any given time (=MTBCFs/MTBCFs+MDTs)	0.95	N/A
System Recovery Time	Mean Down Time (MDTs)	MOE	The time it takes to maintain and update the reACT virtual system after a failure event	3	hrs
Simulation Run Time	Ts	MOE	The time it takes the reACT simulation system to execute and generate performance report for the Net Zero energy house	240	s

Table 3.5: reACT Simulation system Measures of Effectiveness

3.6. System Context

The principal system users are the system operators and maintainers. They are considered external to the system. Other system users include reACT Net Zero energy home owners, researchers and educators who will interface with the reACT Simulation system.

The environment consists of: 1) Net-Zero Energy House (the home for which economic and resource inventory optimization is done through the simulation software); 2) Operating Base (which includes the hardware and tools necessary for operating and maintaining the software simulation) 3) External Environment (the external environment consists of parameters such as relative humidity, temperature, incident solar irradiance etc. that impact home performance variables) 4) Electrical Vehicle (this includes an electric vehicle that needs to be driven 25 miles each day of the Solar Decathlon competition. Figure 3.2 provides a Block Definition Diagram (BDD) that indicates the structure of the reACT system domain.


bdd [Model] Model[Model]
reACT Simulation Domain
reACT Simulation Environment
Electrical Vehicle
External Environment
Net Zero Energy Home
Operating Base
electrical Vehicle
external Environment
operating Base
net Zero Energy Home
reACT Simulation Users
SD Developers & Maintainers
Home Owner
Wall Geometry Module
PVmodules.xml
Constants Module
Constants
Projected Irradiance Module
parseXML_moduleSpecs
Irradiance Library
cldySun
projected Irradiance Module
irradiance Library
irradiance Module
reACT Simulation Module
Solar Irradiance Module
simForecast Class
Irradiance Module
reACT Simulation Module
solar Irradiance Module
simForecast Class

Figure 3.2: BDD for reACT Virtual Simulation Software

3.7. System Operational Concept

The high-level user goals for the reACT Virtual system are indicated as Use Cases to understand how users interact with the Simulation to achieve end goals. Not all use cases could be listed in detail here due to the competitive nature of the Solar Decathlon Competition. Figure 3.3 shows the use case diagram for the reACT Simulation Module. For the given use cases, only the reACT system developer and researcher are considered as principal users interacting with the system, and their activities are described through different use case scenarios.

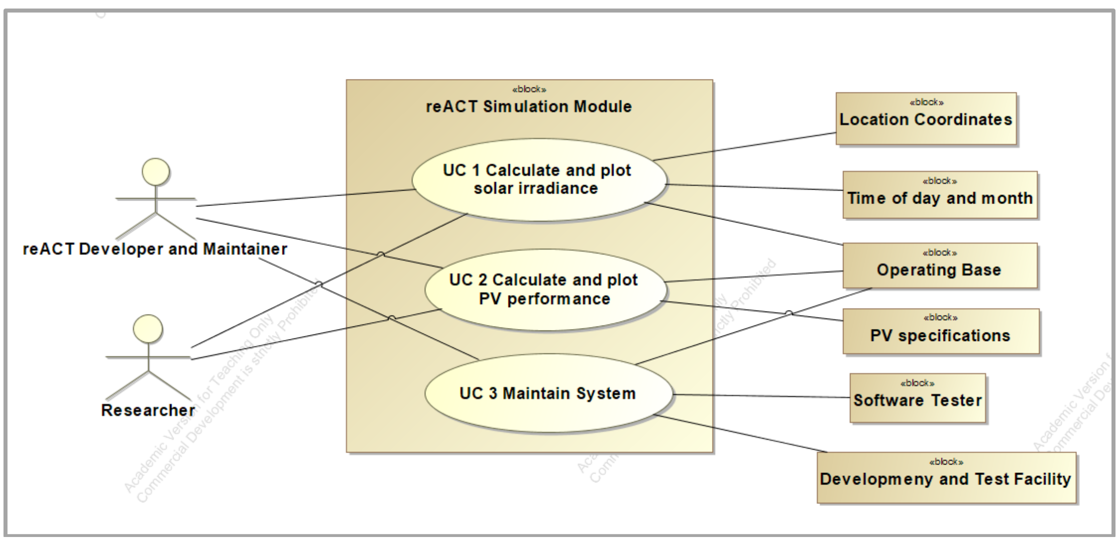

Figure 3.3: Context-Level SysML Use Case Diagram for the reACT Virtual System

Based on Figure 3.2, the following use case narratives have been identified to describe how UC 1 and UC 2 are implemented. UC 3 has been listed in Appendix C.

- **<u>Use Case Narrative: UC 1 Calculate and Plot the Solar Irradiance</u>**

Trigger: The Software developer and/or the researcher instructs the Simulation Module to execute.

Main Success Scenario:

1) The Software Developer instructs the Simulation Module to begin execution.

2) The Software Developer inputs values for Number of days after winter solstice (nd), day, month and latitude in the script interface.

3) The Simulation Module invokes the Solar Irradiance Module.

4) The Solar Irradiation Module calculates days after winter solstice (td) and returns this value to the Simulation Module.

5) The Simulation Module calls the Solar Irradiance module again with input values of latitude, number of time steps (24) and the value of td calculated in Step 4.

6) The Solar Irradiance Module returns the values for Apparent Solar Time (ast), direct Normal Irradiance (EDnorm), global flat plate (e.g., ground, flat roof) irradiance (EGflat), Air Mass equivalents (AM), Sun azimuth (sunAz) and sun altitude over horizon (sunAlt).

7) The Simulation Module plots the global flat plate irradiance (EGflat) versus apparent solar time (for a 24-hour period).

8)End

Extensions:

Extension 1: E1.1. Simulation Module Critical Failure to execute

Extension Trigger: Simulation Module fails to execute.

1.1) If the researcher is using the simulation, he/she reports the failure to the Simulation Developer.

1.2) The Developer tests and validates the performance of the simulation module.

1.3) Return to step 2.

Extension 2: E3.1. Solar Irradiation Module Failure to execute

Extension Trigger: Solar Irradiance Module fails to execute.

3.1) If the researcher is using the simulation, he/she reports the failure to the Simulation Developer.

3.2) The Developer tests and validates the performance of the solar irradiation module.

3.3) Return to step 5.

- **<u>Use Case Narrative: UC 2 Calculate and Plot the PV Performance</u>**

Trigger: The Software developer and/or the researcher instructs the Simulation Module to execute.

Main Success Scenario:

1) The Software Developer instructs the Simulation Module to begin execution.

2) The Simulation Module reads the XML data file with PV Array data in it. The XML data file returns PV array data consisting of the PV manufacturer name, short circuit current and open circuit voltage specified by the manufacturer for the PV array.

4) The Simulation Module calls the PV performance module.

5) The PV Performance Module fits the PV module parameters (Current versus Voltage diode model parameter fit (Io, Iph, Rs, Rsh, and beta) to the given performance data.

6) The Simulation Module generates a plot of the PV characteristics.

5) End

Extensions:

Extension 1: E1.1. Simulation Module Critical Failure to execute

Extension Trigger: Simulation Module fails to execute.

1.1) If the researcher is using the simulation, he/she reports the failure to the Simulation Developer.

1.2) The Developer tests and validates the performance of the simulation module.

1.3) Return to step 2.

Extension 2: E4.1. PV performance Module Failure to execute

Extension Trigger: Solar Irradiance Module fails to execute.

4.1) If the researcher is using the simulation, he/she reports the failure to the Simulation Developer/

4.2) The Developer tests and validates the performance of the solar irradiation module.

4.3) Return to step 5.

Figure 3.4 shows the activity diagram showing the sequence of activities for the reACT Simulation Module.

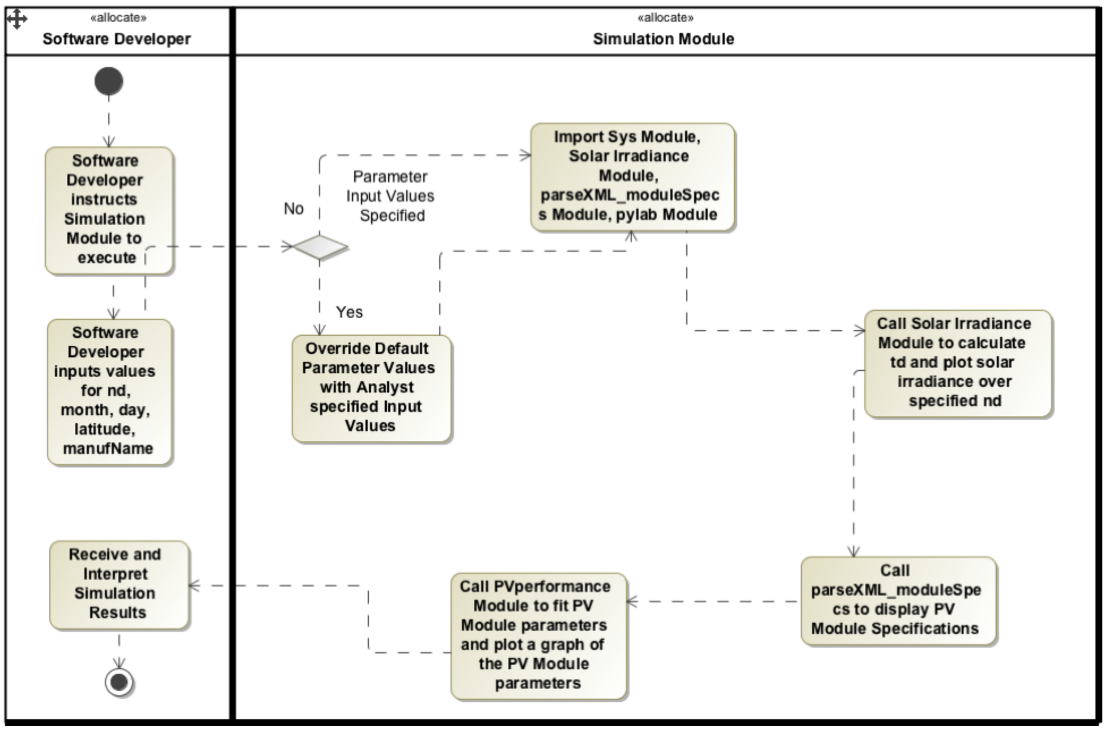

Figure 3.4: Context-Level SysML Activity Diagram for Use Cases UC 1 and UC 2

An activity diagram is a flowchart that represents the flow from one activity to another activity, where an activity can be considered as the operation of a system. The activity diagram developed for the reACT system represents a graphical workflow of stepwise activities and actions with choice, iteration and concurrency. Diagrams developed for the reACT Virtual system flow will help future developers and users to envisage the flow of activities and determine scope for optimization.

3.8. Discussion

To support the design and optimization of the reACT virtual simulation engine, the system and its associated operational activities have been identified through this research. However, detailed modeling diagrams and use cases for the entire model cannot be listed here due to the competitive nature of the Solar Decathlon competition.

By identifying potential stakeholders and their needs, the reACT simulation system can be expanded by adding new functionalities to support the identified capabilities. A detailed description of the system capabilities and associated metrics will help the University of Maryland Engineering Team to benchmark system performance against objectively defined threshold values.

As the reACT system evolves to support Solar Decathlon efforts in Europe and Africa, a modular architectural framework will prove pivotal in real-time visualization of the basic workflow and system entities within the reACT simulation. Any changes and configurations to the systems architecture will be effectively monitored and controlled by the developers and maintainers of the reACT Virtual simulation software throughout the entire project lifecycle and this will further bolster its adoption across Net Zero energy communities that are based on the reACT Net Zero energy prototype.

Chapter 4: Techno-Economic Analysis for Net Zero Energy Homes

4.1. Overview

A significant number of green building designs today incorporate some mix of renewable energy (RE) and energy efficiency (EE) technologies for on-site energy generation. Economies of scale and research and development (R&D) activities for these technologies have resulted in steadily decreasing hardware, software and O&M costs, which has further bolstered consumer demand. However, with a myriad of renewable energy generation technologies available at hand, the consumer is tasked with the arduous decision of choosing an optimal mix of RE and EE technologies to maximize cost efficiency and meet energy resiliency targets for their building design.

Most energy asset modeling tools that are utilized today to provide decision support place the onus on the home owner to specify the system/ technology size. While the user can make an educated guess to estimate the system size, the economic viability of the system can be significantly affected if the performance analysis is based on system sizes that are not optimal. Energy asset modeling tools are also limited by their inability to model multiple technologies concurrently and typically consider one technology at a time, which results in inaccurate estimations of economic viability. To address these limitations, NREL developed the REopt integration and optimization tool for renewable energy technologies which provides techno-economic decision support analysis for renewable energy projects across all stages of the development lifecycle.

The REopt tool has been utilized in this research as a platform for conducting techno-economic assessment for the reACT house. Findings and results from this research can then be used to inform decision making for Net Zero energy homes that use reACT house design as their preliminary prototype.

4.2. REopt Optimization Tool

The REopt tool was developed by the U.S. DOE NREL as a successor to the REO tool for energy system integration and optimization. [17] REO provided early estimates of sizes for renewable energy technologies during the screening and project initiation phases. Later in the project, the default estimates could be replaced by detailed site data for estimating optimal sizing. To improve the speed and accuracy of the REO solver, it was converted to a Mixed Integer Linear Program (MILP) and was named REopt.

The REopt model is a techno-economic decision support model that solves a deterministic optimization problem to determine the optimal sizing and dispatch strategy of RE and EE technologies, such that the electrical and thermal loads are met at each time step at the minimum lifecycle cost. Figure 4.1. illustrates the model inputs and outputs for the REopt model. The inputs can be classified into site-specific inputs (geospatial data, energy consumption and costs, building type and size), technology options and other drivers of the optimization such as economic considerations and client goals. The primary outputs for the technology include optimal technologies and technology sizes for a site, operations strategy and the financial and resiliency metrics for the project.

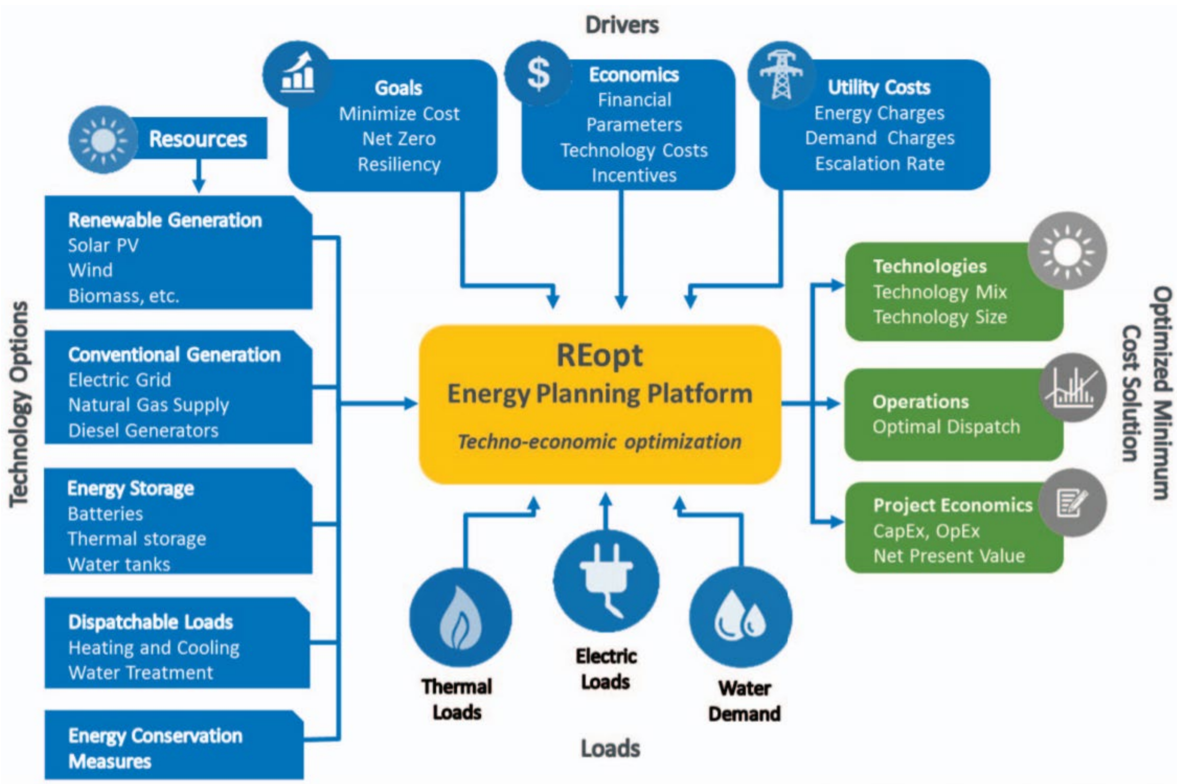

Figure 4.1: Summary of the inputs and outputs for the REopt optimization model [18]

The REopt tool performs a deterministic optimization to determine the optimal solution for the given technology mix for a site. The current code for the REopt model is written in the MOSEL programming language within FICO Xpress.

The objective function of the MILP minimizes the present value of the lifecycle cost over the entire analysis period. The costs considered include capital costs, O&M costs, revenues generated through net metering and wholesale electricity sales and federal, state and utility incentives. [18]

The constraints for the optimization of the objective function include load constraints, resource constraints, operating constraints, sizing constraints, policy constraints, emissions constraints and scenario constraints. It should be noted that REopt is a time-series integration model that combines energy production from all concurrently operating technologies. The typical time step is 1 hour, resulting in 8,760-time steps in a typical N-year analysis.

4.3. System Lifecycle Cost Optimization

4.3.1. Overview

One of the most common analysis scenarios for REopt modeling involves Economic Dispatch Analysis. The objective of this scenario is to determine optimal system sizes from a mix of conventional and renewable energy, and energy storage technologies to minimize system lifecycle energy costs for the consumer over an N year period. REopt estimates the net present value associated with implementing those technologies and provides a cost-optimal dispatch strategy for operating them at maximum economic efficiency.

4.3.2. Inputs

The inputs to the REopt model were tailored for the reACT Net Zero Energy house. The inputs include site-specific data for the College Park, MD and Denver, CO locations, due to their relevance to the Solar Decathlon competition. The corresponding latitudes and longitudes for the specific locations were entered to account for the incident solar irradiation at the two locations. The area and roof size for reACT house were specified to implement sizing constraints in the selection of renewable energy technologies. To conform with the Solar Decathlon rules, only PV and storage technologies were considered for the optimization. Another important site-specific input to the simulation included the monthly utility data which included electric consumption in kWh and the corresponding cost in dollars for all 12 months of the year.

The nominal load schedule data from Table 2.1. was converted to an 8760 hourly (365 days * 24 hour) load profile data for the reACT Net Zero energy house and was subsequently input into the REopt model. Figure 4.2. shows the load profile characteristics for the reACT house over a 24-hour period.

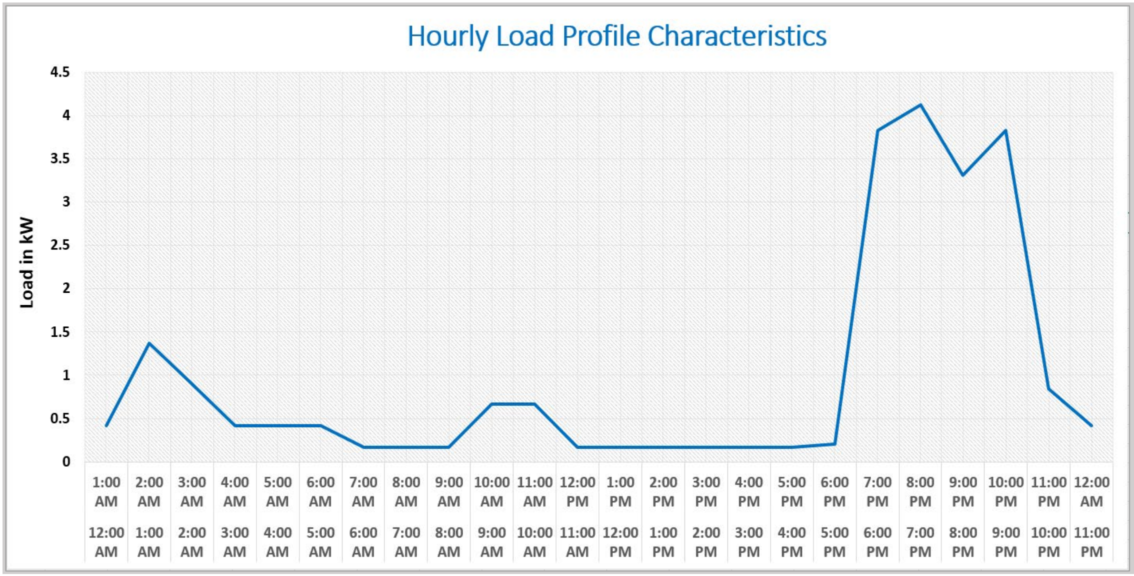

Figure 4.2: Nominal Load Schedule Data

Finally, the utility cost data for net production cost in $/kWh from Table 2.2 was converted in an 8,760 cost profile data and the production value over a day is shown in Figure 4.3. The Net Production Value is the U.S. DOE specified revenue to the user for selling excess electricity back to the grid. This cost data is then used for specifying the wholesale rate for selling excess electricity generated on-site back to the grid. For the reACT house based in College Park, MD, Potomac Electric Power Company (Pepco) has been used as the utility and for the reACT house based in Denver, CO, Public Service Company of Colorado (subsidiary of Xcel Energy) has been used for calculating energy data.

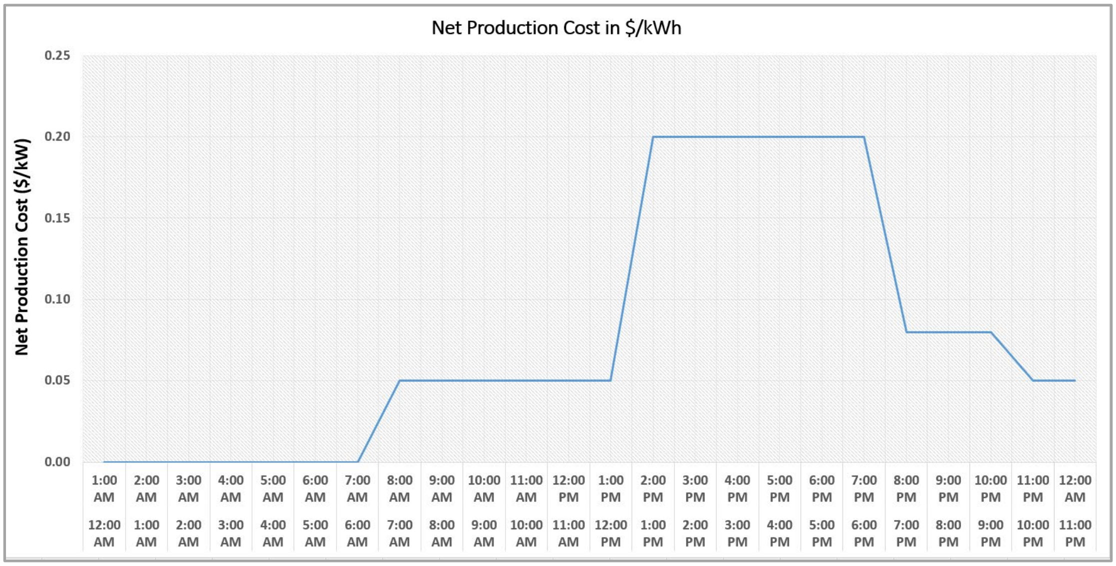

Figure 4.3: Net Production Value in $/kWh

In order to estimate the performance of the PV panel in the reACT house, REopt queried the PVWatts calculator with the location-specific coordinates to determine the energy production and cost of energy of grid-connected PV energy system. [19] The weather and climate data for the reACT house were retrieved using Typical Meteorological Year (TMY3) dataset developed by NREL. The TMY data set is composed of 12 typical meteorological months (January through December) with monthly data sets containing actual time-series meteorological measurements and modeled solar values. [20] For this analysis, the weather and load data correspond to year 2017. The detailed inputs for the optimization are listed in Appendices A and B.

4.3.3. Outputs

Based on the site specific and technology inputs, REopt generated an optimal size for the PV array and the Storage system to minimize system lifecycle cost over a 20-year time period. It should be noted that REopt solves a single-year optimization to determine N-year cash flows, assuming constant production and consumption over all N years of the desired analysis period. The Storage system considered for the purpose of this analysis is a Lithium Ion Battery with a Round Trip efficiency of 98%.

Currently, the federal government offers two key tax incentives based on how the battery is being charged and its ownership, in order to encourage the adoption of solar PV technologies. These are the Investment Tax Credit (ITC) and the Modified Accelerated Cost Recovery System (MACRS) depreciation deduction for energy storage systems. Figure 4.4 provides an overview of the tax incentives and MACRS for a Solar PV and battery system.

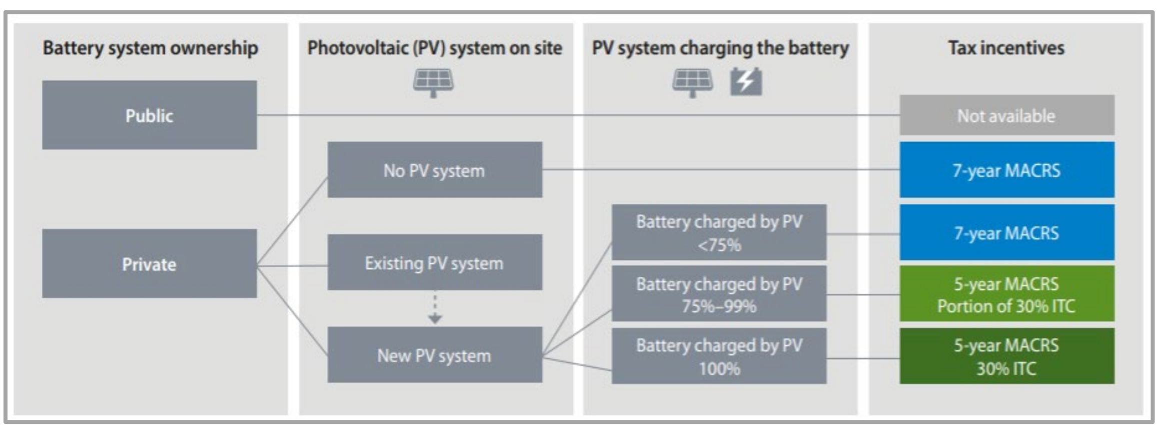

Figure 4.4: Federal Tax Incentives for Energy Storage Systems, NREL. [21]

Without a renewable energy system installed, battery systems may be eligible for the 7-year MACRS depreciation schedule, which is equivalent in capital cost of about 20% [21]. If the battery system is charged by renewable energy technology more than 75%

of the time on an annual basis, the battery can qualify for the 5-year MACRS schedule and the ITC, which corresponds to a 21% capital cost reduction. To account for the difference in MACRS and ITC available for battery systems based on whether it is charged by a renewable technology or the grid, the analysis was done for the following scenarios:

- **Scenario 1:** 30% Federal Incentive for Battery Storage with a 5-year MACRS period for Li-Ion Battery charged only from PV array
- **Scenario 2:** 0% Federal Incentive for Battery Storage with a 7-year MACRS period for Li-Ion Battery which can be charged from Grid in addition with PV array

Figures 4.5. to 4.12. show the REopt optimization results for the reACT Net Zero energy house for these two scenarios. The results are generated for the College Park, MD and Denver, CO location coordinates. It should be noted that if x% of the battery is charged from the PV system, the owner qualifies for x% of the 30% Investment Tax Credit made available by the federal government. For instance, if the battery is charged 80% of the time, the owner is eligible for 24% of the ITC (80% of the 30% ITC credit).

Scenario 1: 30% Tax Incentive and 5-year MACRS

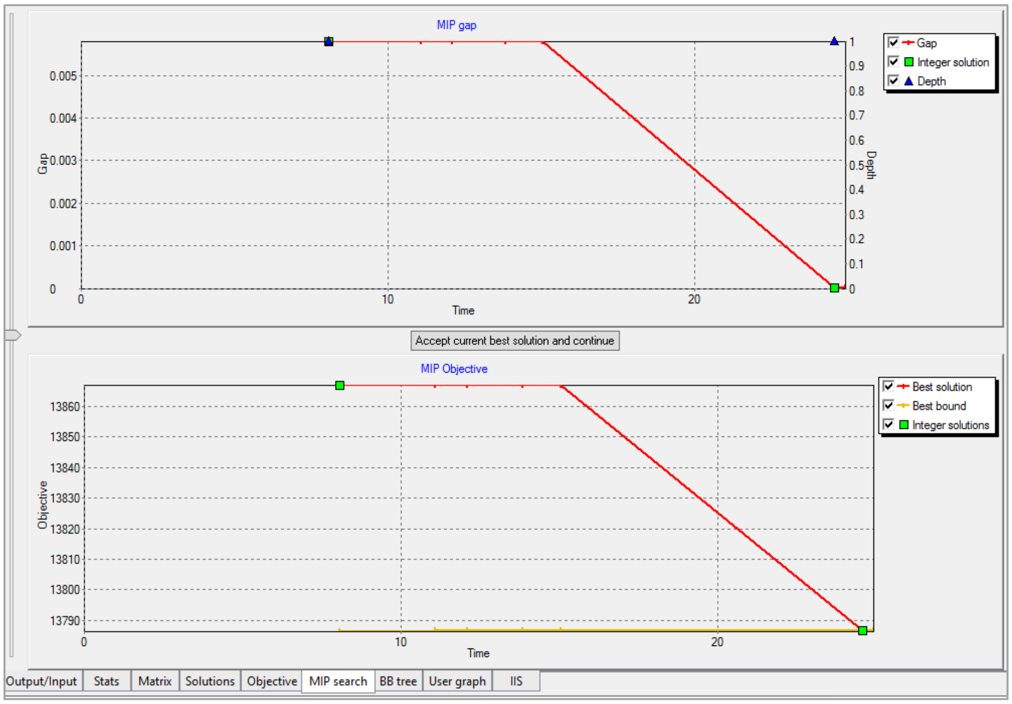

Figure 4.5: MILP optimization in FICO Xpress for College Park, MD

Problem status	Optimum found
RECosts ($)	13,786.70
Time (s)	36.778
MOSRev	738
MOSRevDate	2014/04/04 13:00:48
VBARev	759
VBARevDate	2014/05/13 14:39:58
BattSize (kWh)	6.18718
Inverter (kW)	3.80198
PV Size (kW)	8.49156

Figure 4.6: Optimal PV array size (kW) and battery size (kWh) for College Park, MD

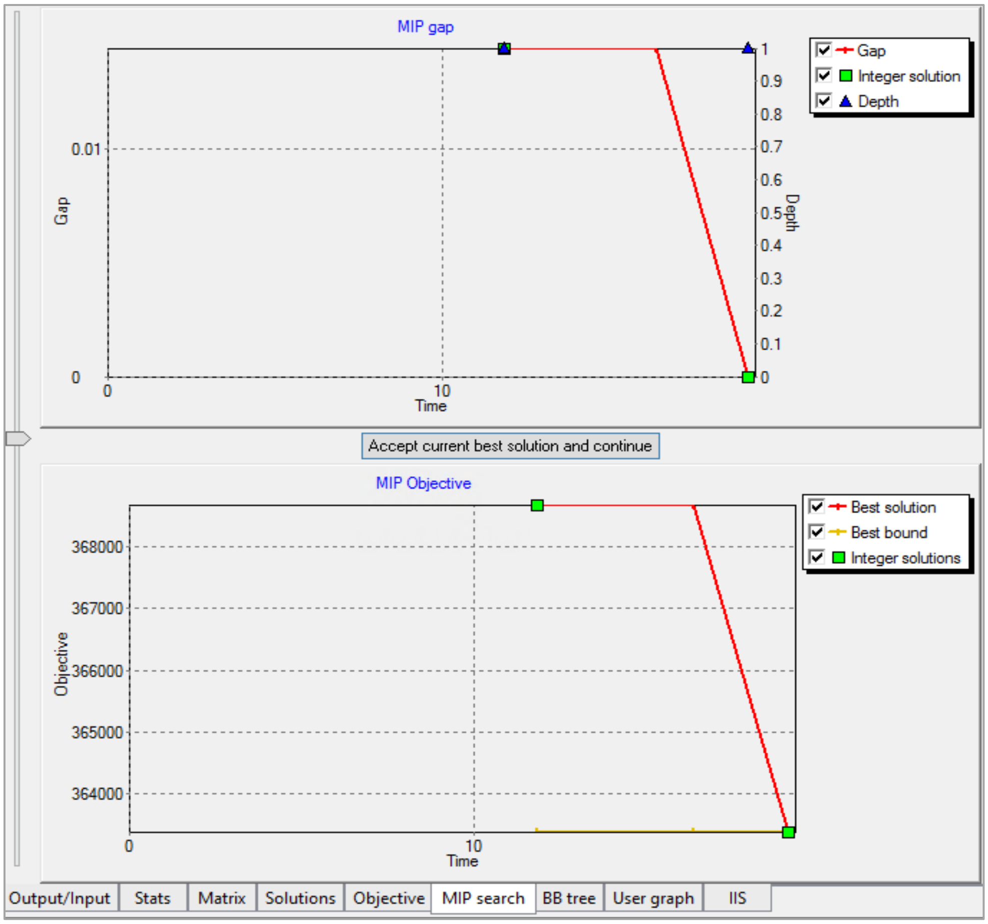

Figure 4.7: MILP optimization in FICO Xpress for Denver, CO

Problem status	Optimum found
RECosts ($)	12484.7
Time (s)	34.754
MOSRev	738
MOSRevDate	2014/04/04 13:00:48
VBARev	759
VBARevDate	2014/05/13 14:39:58
BattSize (kWh)	6.22413
Inverter Size (kW)	3.83
PV (kW)	6.99835

Figure 4.8: Optimal PV array size (kW) and battery size (kWh) for Denver, CO

From Figure 4.6 and 4.8, it can be seen that REopt recommends a PV array size of 8.49 kW for the College Park, MD location and 6.99 kW for the Denver, CO location, each considering a 5-year MACRS and 30% Federal Tax incentive for the battery system. Since, the 8,760-load data and building area is kept same for the two locations, the difference in PV size can be primarily accounted to differences in incident solar irradiance and cloud cover for the two locations. The battery size for both locations is calculated to be approximately around 6 kWh which is natural given that most residential systems deploy battery systems less than or equal to 10 kWh.

Scenario 2: 0% Tax Incentive and 7-year MACRS

If no federal tax incentive is considered for the battery system, the REopt analysis tends to shift towards a higher PV array and battery system size than for the 30% tax incentive to maximize lifecycle cost over a 20-year period as seen in Figure 4.10 and Figure 4.12. The non-convergence of the optimization runs is indicated in a high gap for the simulation optimization in Figures 4.9 and 4.11. The gap for an optimization is the difference between the true value of the optimal solution and the generated optimal solution for the optimization. Ideally, the gap for an optimization should be zero. However, the simulation does not close the gap even after 500 seconds of the simulation run time. At this point, the current best solution is accepted, and optimal PV and battery sizes are generated. It should be noted that the optimal PV and battery system sizes for the reACT Net Zero energy home should be less than 10 kW and 10 kWh respectively to comply with the Solar Decathlon rules. Since the optimization has been terminated before the ideal optimum is found, it is concluded that increasing the simulation run time will eventually generate final system sizes closer to the desired value.

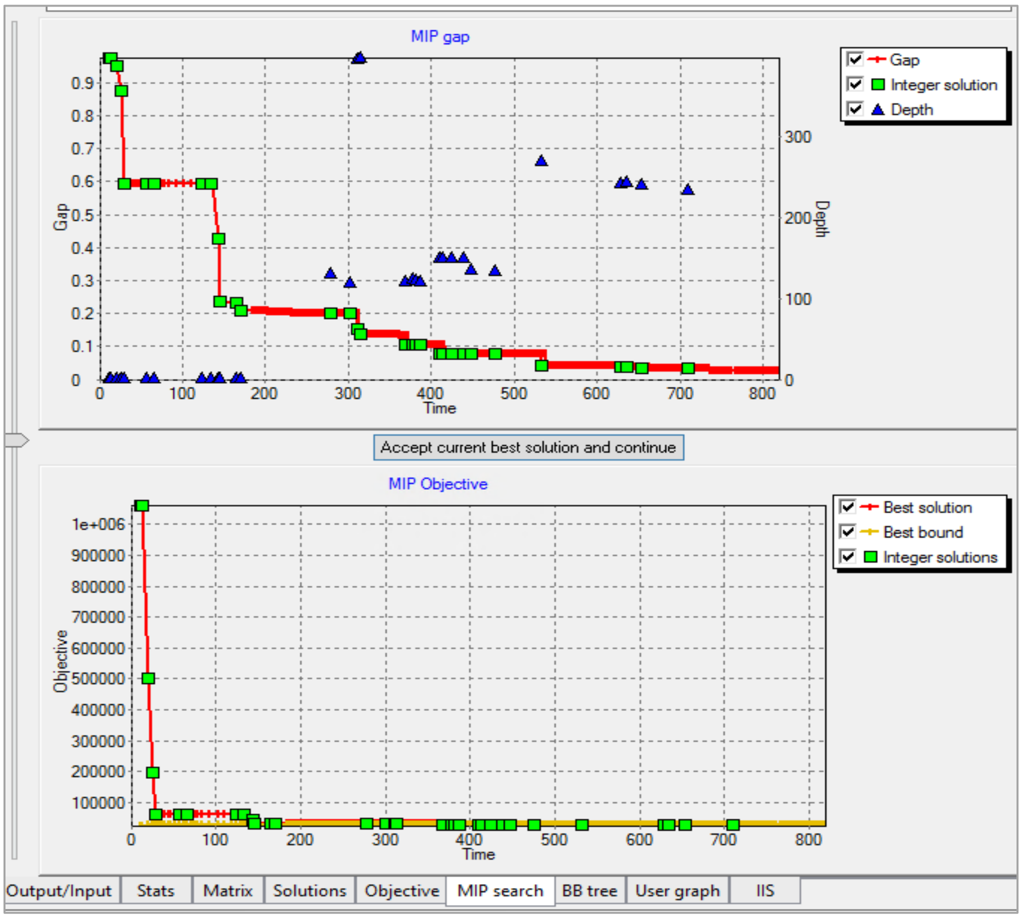

Figure 4.9: MILP optimization in FICO Xpress for College Park, MD

Problem status	Unfinished
RECosts ($)	33,297.10
Time (sec)	400.839
MOSRev	738
MOSRevDate	2014/04/04 13:00:48
VBARev	759
VBARevDate	2014/05/13 14:39:58
Battery Size (kWh)	27.6672
Inverter Size (kW)	4.13
PV Size (kW)	19.5402

Figure 4.10: Optimal PV array size (kW) and battery size (kWh) for College Park, MD

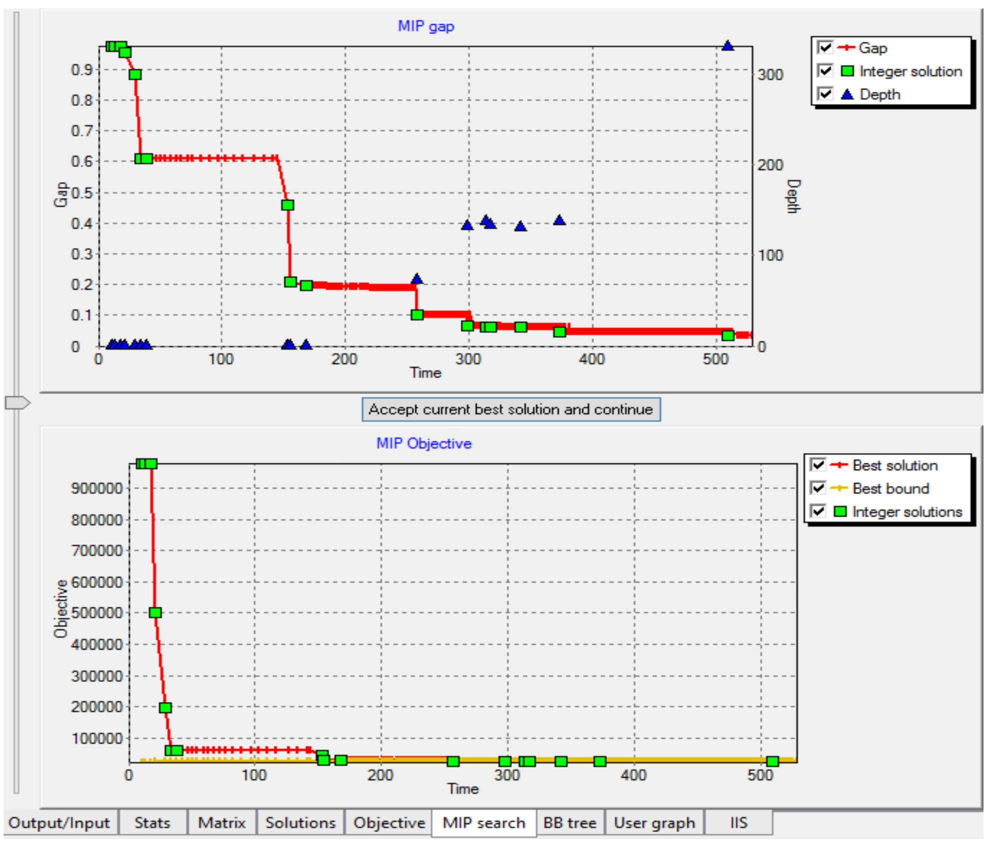

Figure 4.11: MILP optimization in FICO Xpress for Denver, CO. (The gap has not closed even after 500 seconds of the optimization.)

Problem status	Unfinished
RECosts ($)	24,266.40
Time (sec)	540.287
MOSRev	738
MOSRevDate	2014/04/04 13:00:48
VBARev	759
VBARevDate	2014/05/13 14:39:58
Battery Size (kWh)	27.7317
Inverter Size (kW)	4.13
PV Size (kW)	9.82659

Figure 4.12: Optimal PV array size (kW) and battery size (kWh) for Denver, CO

4.3.4. Economic Dispatch

Figure 4.13. and 4.14. show the hourly dispatch strategy for a single day (24-hour period with the apparent solar time) based on the results generated by the REopt model. Economic dispatch is defined as the determination of the optimal strategy for operating available electricity generation facilities, to meet the system load at the lowest possible cost, subject to transmission and operational constraints.[22] REopt solves the Economic Dispatch Problem for the reACT Net Zero energy home with Solar PV and battery as the generation sources, such that the operational and system constraints of the available resources and corresponding transmission capabilities are satisfied at all time intervals. The graphical figures below show the amount of load served by the utility, load served by the PV array and the load served by the battery for minimizing energy costs over a single day for the lifecycle period.

Scenario 1: 30% Tax Incentive and 5-year MACRS

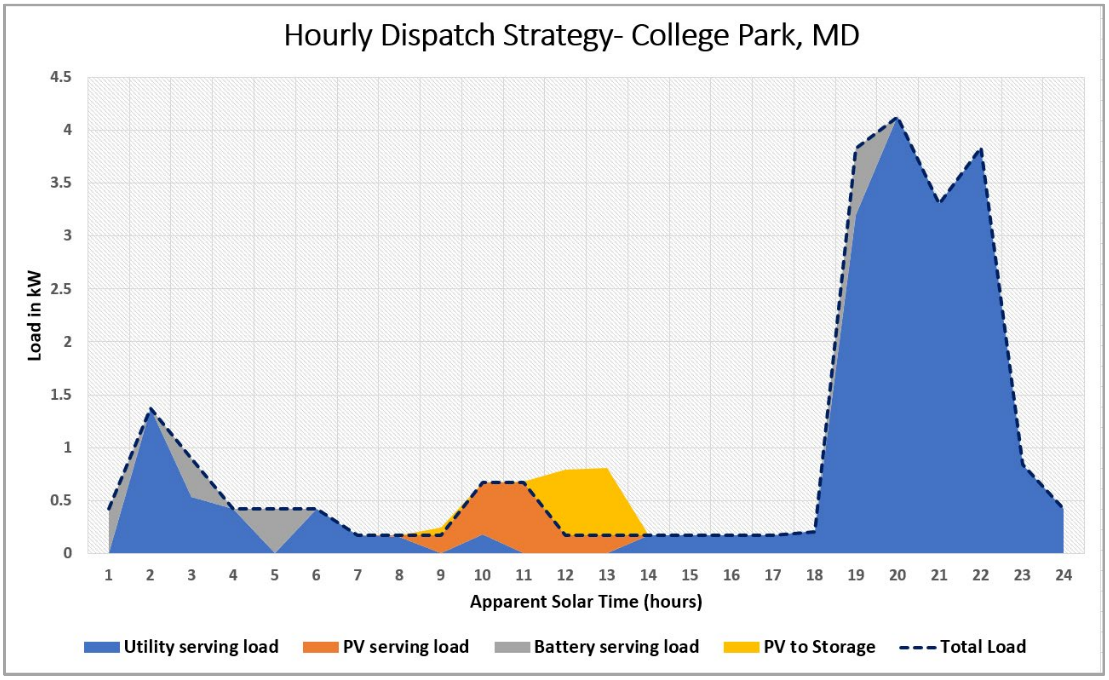

Figure 4.13: Hourly dispatch Strategy for the College Park, MD location

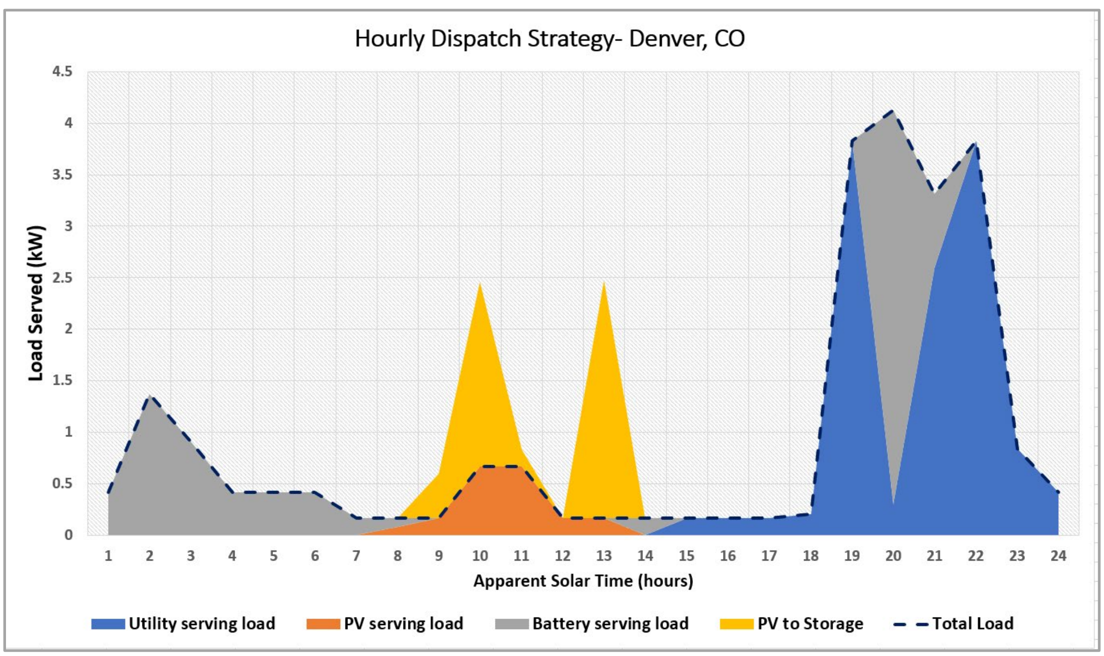

Figure 4.14: Hourly dispatch Strategy for the Denver, CO location

Scenario 2: 0% Tax Incentive and 7-year MACRS

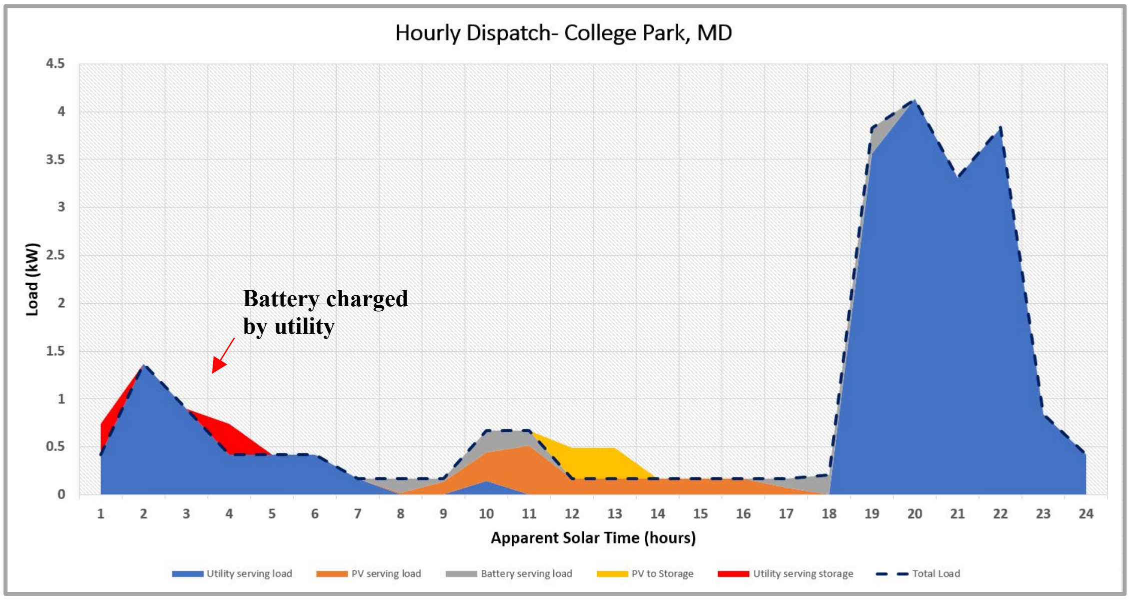

Figure 4.15: Hourly Dispatch for the College Park, MD location for 0% ITC and 7-year MACRS

The PV charges the battery and caters to the load when the solar irradiance is at its peak and the utility and battery system supply the load demand at night, when output from the PV fades. With a 0% ITC and 7-year MACRS, the only difference is that the utility is allowed to charge the battery system which is highlighted in Figure 4.15.

4.4. Maximizing Resiliency

4.4.1. Overview

Extreme weather events and natural disasters have increased the risk of grid outages in recent times. As such, modern day energy efficient buildings must also be equipped to mitigate the adverse impact of such events on their electrical and thermal load systems.

Resiliency is defined as the system's ability to serve critical load during a multi-day outage. The REopt modeling tool allows the consumer to determine the optimal sizing and dispatch strategy for meeting energy resiliency targets for their Net Zero energy homes. The PV and battery system size for the reACT house is currently chosen based on developer/user estimates and is not designed to address resiliency goals. As such, REopt resiliency analysis has been applied to the reACT Net Zero energy house to determine the optimal technology sizing and dispatch strategy for maximizing energy resiliency in the event of a grid outage.

4.4.2. Inputs

Similar to the inputs for the analysis conducted in Section 4.3., site-specific and technological input data files were generated for REopt runs. During a utility grid outage, only a certain fraction of the nominal load known as critical load is served. The critical load data for the reACT house was generated for an 8760-hourly period, assuming that the grid outage continues for an year. Only critical loads such as Refrigerator, Stovetop and Water Heater were included to calculate the hourly load in kW. The list of appliances and loads served, and their corresponding load data has been illustrated in Appendix A. Figure 4.16. shows the nominal and critical load profile characteristics for the reACT Net Zero energy house.

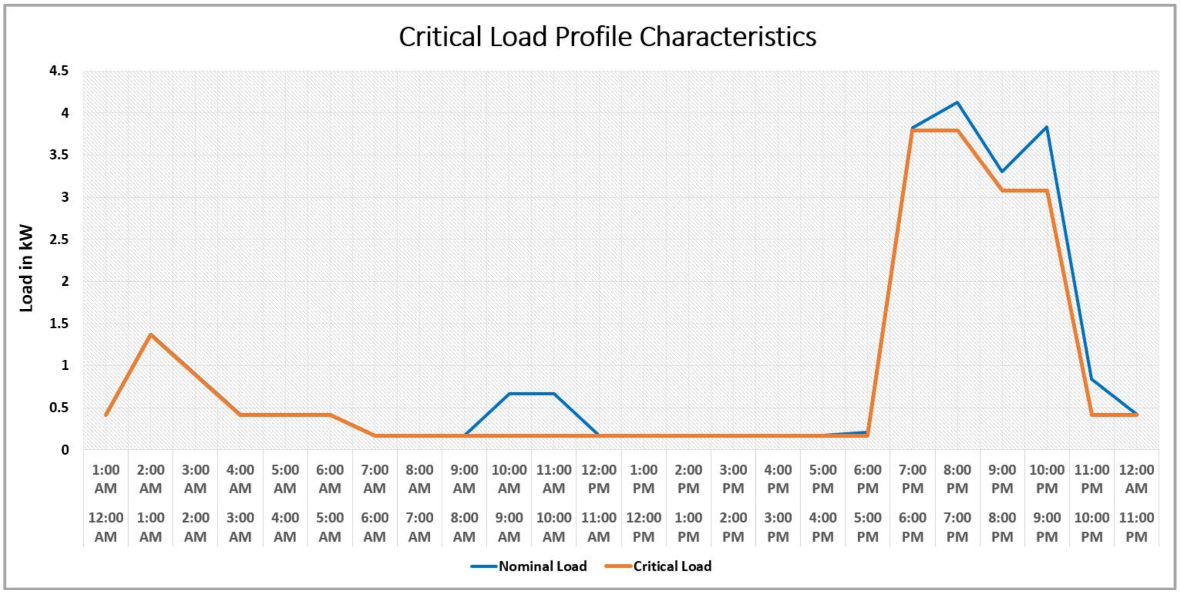

Figure 4.16: Critical load profile characteristics for the reACT Net Zero energy house

4.4.3. Outputs

	College Park, MD	Denver, CO
Problem Status	Optimum Found	Optimum Found
RECosts ($)	337955	331,346
Time (s)	36.93	36.013
Battery Size (kWh)	915.505	915.505
PV Size (kW)	7.5186	6.16219

Figure 4.17: A comparison of system sizes and technology costs for maximizing resiliency during a grid outage

From the above Figure 4.17, it can be seen that the size of the battery system is exceptionally large compared to our analysis for maximizing system lifecycle cost, while the PV size has been kept fairly small. This seems natural for a system that is designed to withstand outage for an entire year.

4.4.4. Economic Dispatch

Figure 4.18. and 4.19. show the hourly dispatch strategy to sustain grid outage for the reACT house. Since the utility does not meet any load demand, the entire load is met primarily by a combination of battery storage and PV. During the day, when the PV output peaks, most of the energy generated by the PV array is diverted towards charging the battery system for meeting load demand when it peaks at night. It can be seen that the electrical and thermal loads are met at each time step solely by the combination of on-site energy generation resources.

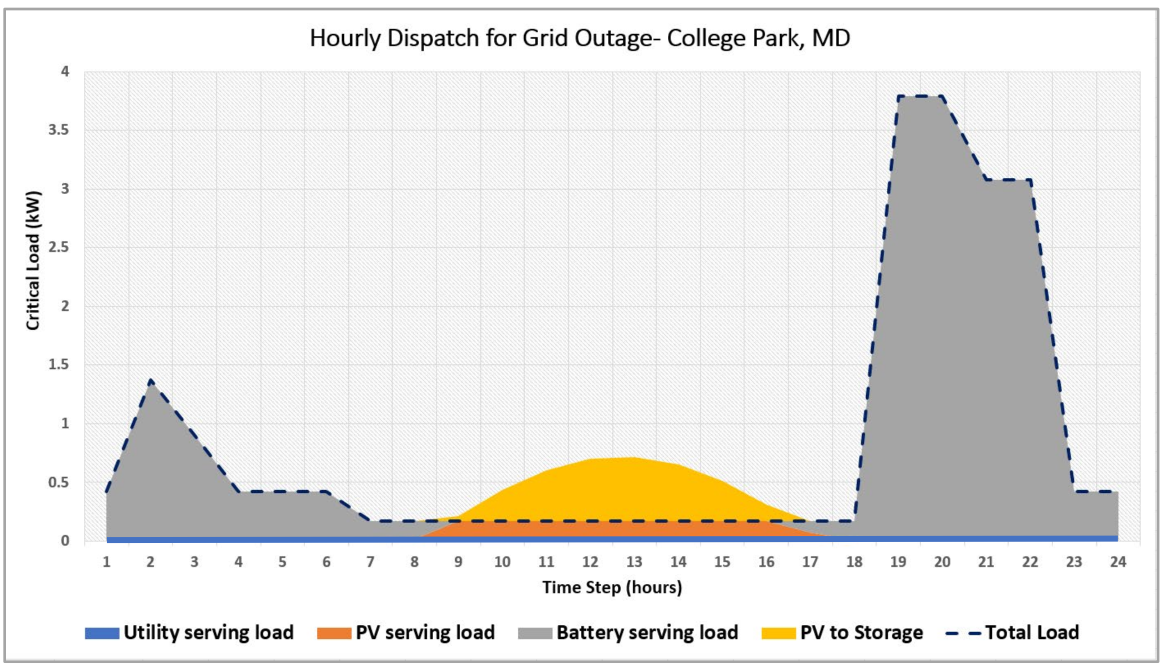

Figure 4.18: Hourly dispatch Strategy during grid outage for the College Park, MD location

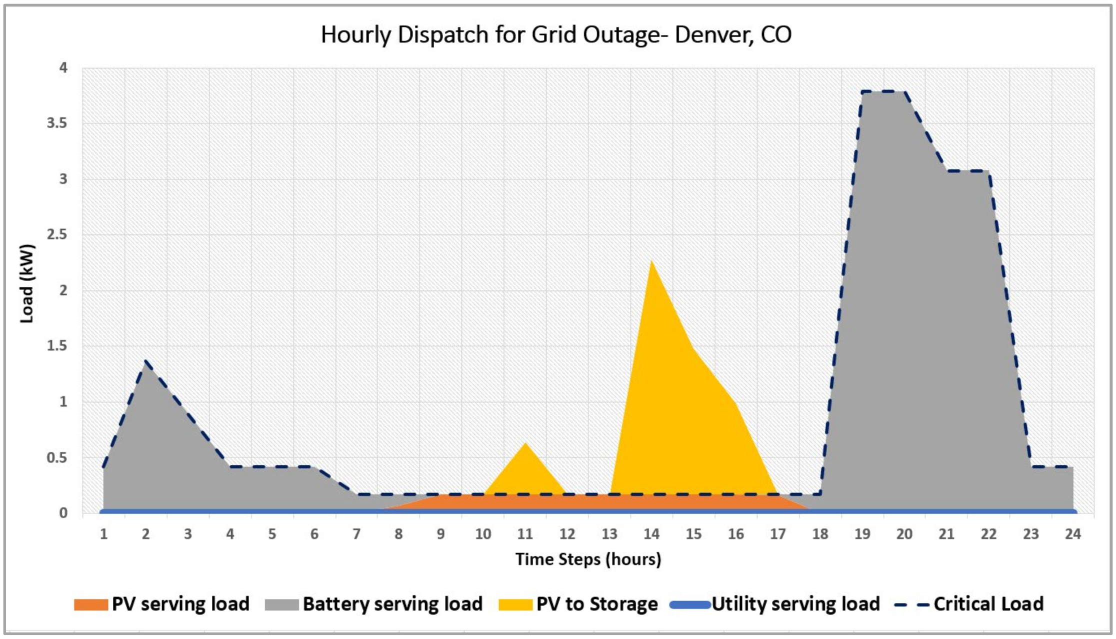

Figure 4.19: Hourly dispatch Strategy during grid outage for the Denver, CO location

4.5. Conclusion

The results generated from the techno-economic analysis have been classified into optimal size selection and economic dispatch analysis for the available resource mix within the reACT Net Zero energy home. It should be noted that these results are specific to the reACT home and consider static values of load and energy costs as specified by the Solar Decathlon competition. In order to expand the analysis for new Net Zero energy homes based on the reACT system prototype, the load and energy costs for the specific location and utility will need to be considered to factor in the variability in day to day loads and energy production and consumption costs. For instance, the value of load and corresponding peak and off-peak costs of selling and procuring energy will vary for weekends as compared to weekdays and will show seasonal variation.

The techno-economic analysis compares two tax incentives listed in Scenario 1 and Scenario 2 to identify optimal PV and battery system sizes for minimizing system lifecycle cost. The comparison of solar PV Sizes and Battery sizes for the 7-year MACRS and 5-year MACRS shows that it is profitable for the home owner to charge the battery system entirely from the solar PV array in order to qualify for the 5-year MACRS and 30% Federal ITC credits. However, since the result for the 0% ITC has been generated at non-zero gap, the optimal solution at zero gap would need to be considered to ultimately validate the system sizes generated from REopt.

The economic dispatch analysis shows the ideal operating strategy for the Solar PV and battery system in order to meet electrical and thermal loads at each time step. These results allow the home owner to determine the optimal strategy for achieving specific financial and resiliency goals from the Net Zero energy system. It should be noted that the analysis done in Section 4.3. and 4.4. does not have the Net Zero energy constraint implemented. In order for the home to continue being Net Zero, this constraint must be added to the REopt model for the specified locations. This will be addressed in ongoing research efforts for energy optimization as part of the collaboration between NREL and the A. James Clark School of Engineering.

Chapter 5: Future Work

The research efforts for this thesis primarily focus on systems engineering based modeling and techno-economic analysis for the reACT Net Zero energy home. Since the reACT Virtual model is constantly evolving to address design efforts for new Net-Zero energy constructs, the systems modeling effort will be a concurrent process that will run parallel with the modeling effort for the forthcoming months. At the same time, lessons learnt from the techno-economic modeling for the reACT Net Zero energy home will shape future modeling efforts for client specific constraints such as the Net Zero energy constraint. It should be noted that while the majority of the research efforts have been directed with the reACT home as the test case, lessons from this research can also be used to guide design and development of new and existing Net Zero energy homes.

5.1. Proposal

The reACT virtual model has been written entirely using the Python programming language to support the development and operation of the reACT Net Zero energy home. A critical step in scaling the reACT Virtual model in the design and development of Net Zero energy communities, chemical plants and industries that aim to achieve their energy goals, is to envision a web-based interface for the code. This will enable users across different domains will be able to interact with the code in real-time and gain critical insights for their buildings in the early stages of project development.

The system engineering efforts for the reACT model will be a continuous effort. Since the reACT virtual model is evolving continuously to meet specific needs for the Solar Decathlon competitions in Africa and Europe, the Systems Modeling and documentation will evolve simultaneously to reflect changes to the simulation modules. To enhance the predictive capabilities of the reACT Virtual model, the model is also being upgraded to incorporate a model-based (the virtual house) supervisory control architecture that interfaces with the virtual model to optimally control the time of use and duration of operation of home electrical and thermal loads. The control objective is to 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. By optimizing the house resources automatically, the simulation will eliminate the need for the user to micromanage all house functions. Paired with concurrent efforts of making the reACT software scalable, the control architecture can then be used to optimize the shared resources of a community of houses, both in terms of controlling common and individual household resources.

Another area of ongoing research for the reACT software is the integration of techno-economic decision support capabilities with the virtual model. As part of the ongoing collaboration with the National Renewable Energy Laboratory, new constraints such as the Net Zero energy constraint will be enforced within the REopt optimization framework to identify optimal sizes of PV array and battery system to achieve financial and resiliency goals for the user. By achieving early estimates of technology sizes and optimal dispatch strategies, the design and development of future Net Zero energy homes will be achieved in a cost optimal manner.

5.2. Risks

There are three potential risks associated with modeling new buildings based on reACT Net Zero home prototype. The primary risk arises from the distinct design for new and existing Net Zero energy constructs for which we aim to develop the web-based interface. The API needs to be able to address differences in the design of homes and the skill level of the end user in interpreting and giving inputs to the simulation interface. By using REopt Lite web-based interface for the REopt tool as a baseline, the team can develop the interface to best incorporate differences in design and user-knowledge of house resource complexities.

Another potential risk is associated with undetected changes to the house environment (e.g., the growth of a shade tree) that can introduce significant model error within the reACT system. It should be noted that the model currently does not account for the effects of shading or dirt accumulation on the PV array, and efforts are underway to acknowledge possible effects of shading on the power output of the PV array.

The final risk arises from continuous modification of the reACT virtual modules. As the base code and the list of potential stakeholders for the virtual simulation design evolve, the Systems engineering based documentation and models will need to be upgraded concurrently by a dedicated software developer and maintainer at all times.

By using Machine Learning techniques, all three of the above risks can be mitigated effectively by automating functionalities for updating the model, shading effect calculations and distinct design features for different Net Zero energy constructs.

5.3. Conclusions

Integrating renewable energy and distributed energy resources (DERs) into existing utility grids is a technological challenge because of the dynamic nature of most renewable resources and the mismatch between peak production and consumption periods. These problems will only grow with increasing reliance on renewables. Model-based resource allocation strategies, such as the one being developed by the UMD Solar Decathlon Engineering Team, will enable control of resource supply and demand at different levels of granularity: from single households to communities and more, directly addressing the challenge posed by an increasing dependence on renewable resources. Likewise, the ability to determine optimal system sizes and dispatch strategies for achieving a Net zero energy home while having a minimum lifecycle cost can have positive implications in the adoption of Net Zero energy homes and renewable technologies that can support a low carbon economy at the residential level. Lessons learnt from the systems engineering based design and techno-economic modeling will be vital in determining the future direction for modeling efforts and actively identify scope of constant improvement for the reACT Virtual software.

Appendix A: Load Data for REopt Simulation

A.1. Nominal Load Data

In order to generate the 8760 load profile data for the reACT net zero energy house, nominal load data was generated for the scheduled loads specified in Table 2.1. as part of the Solar Decathlon competition. The data for a day was generated for hourly time steps and then extrapolated for the duration of the entire year to estimate net hourly load for a total of 8760 hours in an year. Figure A.1. shows the detailed hourly load in Watts for electrical and thermal loads within the reACT Net Zero energy house.

Time			Load in Watts											Nominal Load (kW)
Start Time	End Time	Time Step	Refrigerator	Personal Computer	Television	Laundry Machine	Dryer	Water Heater	Stovetop	Dishwasher	Car charger	Lighting	Ventilation	
12:00 AM	1:00 AM	1	27	0	0	0	0	0	0	0	0	250	143	0.42
1:00 AM	2:00 AM	2	27	0	0	0	0	950	0	0	0	250	143	1.37
2:00 AM	3:00 AM	3	27	0	0	0	0	475	0	0	0	250	143	0.895
3:00 AM	4:00 AM	4	27	0	0	0	0	0	0	0	0	250	143	0.42
4:00 AM	5:00 AM	5	27	0	0	0	0	0	0	0	0	250	143	0.42
5:00 AM	6:00 AM	6	27	0	0	0	0	0	0	0	0	250	143	0.42
6:00 AM	7:00 AM	7	27	0	0	0	0	0	0	0	0	0	143	0.17
7:00 AM	8:00 AM	8	27	0	0	0	0	0	0	0	0	0	143	0.17
8:00 AM	9:00 AM	9	27	0	0	0	0	0	0	0	0	0	143	0.17
9:00 AM	10:00 AM	10	27	0	0	0	0	0	0	500	0	0	143	0.67
10:00 AM	11:00 AM	11	27	0	0	0	0	0	0	500	0	0	143	0.67
11:00 AM	12:00 PM	12	27	0	0	0	0	0	0	0	0	0	143	0.17
12:00 PM	1:00 PM	13	27	0	0	0	0	0	0	0	0	0	143	0.17
1:00 PM	2:00 PM	14	27	0	0	0	0	0	0	0	0	0	143	0.17
2:00 PM	3:00 PM	15	27	0	0	0	0	0	0	0	0	0	143	0.17
3:00 PM	4:00 PM	16	27	0	0	0	0	0	0	0	0	0	143	0.17
4:00 PM	5:00 PM	17	27	0	0	0	0	0	0	0	0	0	143	0.17
5:00 PM	6:00 PM	18	27	36	0	0	0	0	0	0	0	0	143	0.206
6:00 PM	7:00 PM	19	27	36	0	0	0	0	715	0	2656	250	143	3.827
7:00 PM	8:00 PM	20	27	36	90	211	0	0	715	0	2656	250	143	4.128
8:00 PM	9:00 PM	21	27	36	90	105.5	0	0	0	0	2656	250	143	3.3075
9:00 PM	10:00 PM	22	27	0	90	0	667	0	0	0	2656	250	143	3.833
10:00 PM	11:00 PM	23	27	0	90	0	333.5	0	0	0	0	250	143	0.8435
11:00 PM	12:00 AM	24	27	0	0	0	0	0	0	0	0	250	143	0.42

Figure A.1: Nominal Load Generation Data for reACT Net Zero energy house.

A.2. Critical Load Data

The critical load is the minimum load from operating schedules that are cost-critical to the user and need to be sustained in the event of a grid outage. These consist of electrical loads such as refrigerator and electric vehicle that are required by the user to continue operation at all times of the day. For the purpose of this analysis, non-critical schedules involving the use of Television, Personal Computer, Laundry Machine, Dryer and Dishwasher have been eliminated to generate a critical load profile. Figure A.2. shows the data for the critical load profile that has been used over an 8760 hourly time period to determine optimal dispatch strategy during a grid outage.

Time			Load in Watts											Critical Load (kW)
Start Time	End Time	Time Step	Refrigerator	Personal Computer	Television	Laundry Machine	Dryer	Water Heater	Stovetop	Dishwasher	Car charger	Lighting	Ventilation	
12:00 AM	1:00 AM	1	27	0	0	0	0	0	0	0	0	250	143	0.42
1:00 AM	2:00 AM	2	27	0	0	0	0	950	0	0	0	250	143	1.37
2:00 AM	3:00 AM	3	27	0	0	0	0	475	0	0	0	250	143	0.895
3:00 AM	4:00 AM	4	27	0	0	0	0	0	0	0	0	250	143	0.42
4:00 AM	5:00 AM	5	27	0	0	0	0	0	0	0	0	250	143	0.42
5:00 AM	6:00 AM	6	27	0	0	0	0	0	0	0	0	250	143	0.42
6:00 AM	7:00 AM	7	27	0	0	0	0	0	0	0	0	0	143	0.17
7:00 AM	8:00 AM	8	27	0	0	0	0	0	0	0	0	0	143	0.17
8:00 AM	9:00 AM	9	27	0	0	0	0	0	0	0	0	0	143	0.17
9:00 AM	10:00 AM	10	27	0	0	0	0	0	0	0	0	0	143	0.17
10:00 AM	11:00 AM	11	27	0	0	0	0	0	0	0	0	0	143	0.17
11:00 AM	12:00 PM	12	27	0	0	0	0	0	0	0	0	0	143	0.17
12:00 PM	1:00 PM	13	27	0	0	0	0	0	0	0	0	0	143	0.17
1:00 PM	2:00 PM	14	27	0	0	0	0	0	0	0	0	0	143	0.17
2:00 PM	3:00 PM	15	27	0	0	0	0	0	0	0	0	0	143	0.17
3:00 PM	4:00 PM	16	27	0	0	0	0	0	0	0	0	0	143	0.17
4:00 PM	5:00 PM	17	27	0	0	0	0	0	0	0	0	0	143	0.17
5:00 PM	6:00 PM	18	27	0	0	0	0	0	0	0	0	0	143	0.17
6:00 PM	7:00 PM	19	27	0	0	0	0	0	715	0	2656	250	143	3.791
7:00 PM	8:00 PM	20	27	0	0	0	0	0	715	0	2656	250	143	3.791
8:00 PM	9:00 PM	21	27	0	0	0	0	0	0	0	2656	250	143	3.076
9:00 PM	10:00 PM	22	27	0	0	0	0	0	0	0	2656	250	143	3.076
10:00 PM	11:00 PM	23	27	0	0	0	0	0	0	0	0	250	143	0.42
11:00 PM	12:00 AM	24	27	0	0	0	0	0	0	0	0	250	143	0.42

Figure A.2: Critical Load Schedule Data for reACT Net Zero energy house.

Appendix B: Analysis Assumptions

B.1. Minimize System Lifecycle Cost

	ASSUMPTION
Technology	Solar PV and Battery Storage
Objective	1. Minimize Lifecycle Cost 2. Maximize Resiliency
Location	1. Denver, Colorado (39.86°, -104.67 °) 2. College Park, Maryland (38.99 °, -76.97 °)
Load Profiles	1. Nominal Load Profile 2. Critical Load Profile
Roof Space available per household	10,000 sq ft (10 kW max PV)
Analysis Period	20 years
Ownership Model & Discount Rates	Single-Party Ownership- 6.2%
Incentives and Depreciation	Federal ITC: 30% for PV and battery Federal depreciation: 5-year MACRS for PV and battery Or Federal ITC: 0% for PV and battery Federal depreciation: 7-year MACRS for PV and battery Utility Rebate: $0.005/kWh SREC for PV
Grid can charge battery?	1. Yes for 30% ITC and 5-year MACRS 2. No for 0% ITC and 7-year MACRS
Net Metering Limit	None- Savings can roll over from year to year or paid at blended rate
Battery Round Trip Efficiency	Composite AC-AC RTE of 89.9% RTE of 98%

Minimum Battery Charge	20%
Inverter Efficiency	98%
Electricity cost escalation rate (nominal)	2.6% per EIA Annual Energy Outlook 2017
O&M Cost escalation rate (inflation)	2.5% per NREL ATB
Technology Costs	PV Capex: \$2.03/W for PV≤100 kW; per Q1 benchmark PV O&M: \$21/kW/yr per NREL ATB Battery CAPEX: \$548.5/kWh, \$1,097/kW Battery Replacement (yr 10): \$230/kWh, \$460/kW
PV azimuth	180° (south-facing)
PV Tilt	30 ° for 7/12 roof-pitch
Utility Considered	1. Public Service Company of Colorado 2. Potomac Electric Power Company (Pepco)

Table B.1: Analysis Assumptions for minimizing System Lifecycle Cost

Appendix C: Use Case Narrative

- **Use Case Narrative: Maintain reACT Virtual Simulation System**

Trigger: The Software Tester receives a failure event notification

Main Success Scenario:

1) The Software Tester instructs the Simulation Module to begin execution.

2) The Simulation Module invokes the Solar Irradiance Module.

3) The Solar Irradiance Module reports an error in execution.

4) The Software Tester manually tests maintenance test cases and debugs the Solar Irradiance Module.

5) The Simulation Module invokes the PV Performance Module.

6) The PV Performance Module reports an error in execution.

7) The Software Tester manually tests maintenance test cases and debugs the PV Performance Module.

8)The Software Tester re-runs the Simulation Module.

9) The Simulation Module generates desired outputs for solar irradiance and PV performance parameters.

10) End

Extensions:

Extension 1: E1.1. Simulation Module Critical Boot Failure

Extension Trigger: Simulation Module fails to boot

1.1) The Simulation Tester reports the critical failure to the Operating Base and Solar Decathlon Engineering Team.

1.2) The Developer invokes backup module script and validates the performance of the backup simulation module.

1.3) Return to step 2.

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