THE EVALUATION OF TRNSYS IN CREATING ADVANCED ENERGY
MANAGEMENT SYSTEMS IN BUILDINGS

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by
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ABSTRACT

In meeting the energy demands in today’s society, a number of environmental, political, economic, and societal issues, in both a local and world perspective, have emerged. Together these issues have influenced a reexamination in the way today’s energy demands should be met, with a particular look into renewable energy technologies.

A particular energy system of focus is a residential, grid-tied solar system with advanced energy management. This system incorporates energy storage into the dynamics of the system, so as to take advantage of electricity rate structures, enhancing the value of solar power, and providing grid and resident security. However, there currently does not exist any accurate or robust modeling tools to analyze the dynamics or suitability of such a system for any given situation.

This thesis examines the suitability of the energy simulation program TRNSYS (Transient Energy System Simulation Tool) in creating advanced energy system simulations. Analysis of the system and subsystem physical dynamics and economics was performed. Next, based off this analysis, a tool consisting of TRNSYS simulations and an Excel spreadsheet was created, which required custom programming of TRNSYS and which provided extensive insight into the creation of simulations using TRNSYS. Finally, a guide to creating accurate and robust advanced energy system simulations was developed and organized.
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Chapter 1

Introduction

In meeting the energy demands in today’s society, a number of environmental, political, economic, and societal issues, in both a local and world perspective, have emerged. The awareness of the environmental and rising political concerns of using fossil fuels and foreign oil to meet energy demands has increased, and the changing world and local economic conditions, particularly in the true cost of energy, has been brought to public attention.

Together these issues have influenced a reexamination in the way today’s energy demands should be met, with projection to the future. The opportunities with renewable energies in meeting today’s and tomorrow’s building, transportation, and energy needs, and the challenges in integrating them with the current infrastructure, are currently being examined.

1.1 Opportunities with renewable energy sources
Simultaneously, new technologies are coming out to meet the demands for more efficient and integrated solutions to energy-related problems. One particular technology has been advanced battery storage technologies, for integration into the grid and renewable energy technologies. The utilization and integration of energy storage allows for greater management and use of energy throughout the day, particularly due to the intermittent generation of power with solar and wind technologies. For this particular thesis, the integration of grid-integrated storage technology within a residential solar system is focused on. Knowledge and insight gained from this focus can be transferred to similar grid-integrated battery storage systems for other, related system challenges.

1.2

1.2: Grid-integrated solar system with advanced energy storage technology

With the grid-integrated battery storage system within a residential solar system, a particularly interesting challenge is the opportunity to strategically buy, sell, or keep solar or grid power throughout the day in areas with a time of use electricity rate structures. Such a system with this advanced energy management can increase the value and worth
of solar systems, can make residential solar systems more affordable due to its greater potential to pay itself back and its perceived value, and can ease the burden of peak demand times on power companies. The increased value of day-generated solar power may also increase the awareness of energy use by the homeowner, as they can essentially “day trade” energy.

1.1 Problem Statement and Motivations

As new systems and technologies arise, such as this system with advanced power management, the need for accurate and robust energy simulations becomes apparent. Currently, however, there are no readily available robust tools that allow for these types of systems to be easily simulated and analyzed, as typical simulation software is geared towards simulating the dynamics of current systems and technologies. This makes it very difficult to effectively program and simulate new technologies, especially to compare them in performance and economics with current technologies.

1.2 Proposal and Objectives

The main goal of this thesis is to analyze the process of creating accurate and robust advanced energy management system simulations with the simulation program TRNSYS (Transient Energy System Simulation Tool). TRNSYS is a commonly used and respected solar energy modeling program which also offers the opportunity to program custom technologies or components.
In the process, the barriers within the simulation development process in effectively modeling the system will be identified, and future work and research suggestions for ultimately developing proper models will be provided.

To effectively test and analyze the accuracy and robustness of the simulation model, a tool will be developed that can:

1) Analyze the physical and technical performance of the system under a wide range of operating conditions

2) Reveal the associated economic costs and gains of the system, including, but not limited to:
   a. Economic gain of the energy output
   b. Upfront system cost
   c. Anticipated maintenance costs

3) Determine if this system is more suitable than another for a given set of physical, economic, and user-specific constraints

Objectives:

1. **Review** the TRNSYS program and previous work on the subject, so as to understand the capabilities and workings of the program, to identify the best ways to approach the problems, and to review previous work on how the program has been used for similar application

2. **Analyze** the physical and economic factors of the typical photovoltaic system and the advanced energy management system, in order to identify all factors to account for when creating the tool
3. **Create** simulation models of a typical system and an advanced energy management system, so as to understand, explore, and test the procedure of creating simulations

4. **Pinpoint** three major barriers or issues that arise in the development of the simulation models, so as to provide the greatest contribution within an appropriately limited scope of research

5. **Develop** a guide that addresses and organizes these issues, so as to clearly communicate the findings for future research, and

6. **Identify** future work and research that can lead to the successful development of simulation models for advanced energy management systems within TRNSYS, so as to continue research efforts in this area of study, based on the findings of this research

### 1.3 Reader’s Guide

Chapter 1 provides an introduction to the context, problem statement, motivations, and objectives of this research.

Chapter 2 summarizes the literature review performed, which discusses computer modeling, the values of TRNSYS, and a systems-driven approach to energy and energy efficiency.

Chapter 3 discusses the methodology in completing the stated objectives.

Chapter 4 contains the breakdown of the addressed systems into subsystems, and an analysis of all physical and economic factors of each of these subsystems. These
factors are categorized and listed at the end of the chapter, along with a chart on how they are dependent upon each other.

Chapter 5 examines the development of an evaluation tool for analyzing the two systems, the process for making the two TRNSYS simulation models, the procedure for creating new components within TRNSYS, and a breakdown of how each factor listed in Chapter 4 was accounted for in the tool.

Chapter 6 has organized three approaches to creating accurate and robust advanced energy management models with TRNSYS, based off experiences in creating the aforementioned simulations and from consultation with the TRNSYS programmers.

Finally, Chapter 7 summarizes the work done, states contributions of the study, discusses limitations, and suggests future work.
Chapter 2
Literature Review

Introduction

The purpose of this literature review is to examine previous work and research that has been done which support the underlying goals and motivations of this thesis work. These include:

• The promotion of energy efficiency, energy awareness, and decreased energy use in the residential sector;
• The examination and analysis of solar energy systems through a systems-driven approach;
• The utilization of computer modeling tools to model solar energy systems; and
• The study of batteries and accurate battery models for use in computer simulations

For the first objective pertaining to residential energy use, extensive data was examined on current trends of residential energy use. This is followed by a deeper look into how and why residences use energy.

For the second objective, the benefits of taking a systems approach to photovoltaic systems is discussed, in terms of how it has benefited systems economically and technically.
For the third objective, the importance and challenges of computer modeling is discussed, as well as the details of how TRNSYS is appropriate for this type of modeling.

For the final objective, previous write ups on battery testing and model development are explored.

**Energy Efficiency & Awareness**

*Introduction*

As more and more households enjoy the modern day conveniences of energy-consuming technologies, the demand for energy grows. Residential energy use has nearly quadrupled since 1950, mostly due to the increased use of electric heat pumps, refrigerators, washers and dryers, dishwashers, lighting, and central air systems within homes. Currently, approximately thirty-seven percent (37%) of the total electricity produced is sold to the 90 million dwellings in the United States. (Energy Efficiency, 1999) Please see Figure 2.1 for total energy consumption by sector.

2.1

![Total Consumption by End-Use Sector, 1949-2006](image)

2.1: Total energy consumption by sector (Figure 2.1a, 2006)
Within residences, approximately forty-seven percent (47%) of energy is used for space heating, twenty-four percent (24%) for lighting and appliances, seventeen percent (17%) for water heating, five percent (5%) for refrigeration, and five percent (5%) for air conditioning. (Residential Energy, 2004)

2.2: Energy use within the residential sector (Residential Energy, 2004)

Energy Efficiency Measures in the United States

With the energy crisis of the 1970s, the high cost of electricity and heightened environmental concerns had states looking for ways to cut down on the growing energy demand. California was the first to pass legislation for state-wide energy efficiency standards, and a number of states, including New York, followed this path (Gillingham et al., 2006). Additionally, the United States Department of Energy (DOE) passed the Energy Policy and Conservation Act (EPCA), in which nation-wide efficiency targets for appliances were set but not required to be followed (Energy efficiency, 1999). The
efforts were overall unsuccessful due to the lack of pressure on the manufacturers and non-uniform national standards (Gillingham et al. 2006) (Energy efficiency, 1999).

In 1987 energy efficiency standards on certain appliances and lights were set nationally with the National Appliance Energy Conservation Act (NAECA). These standards have been reevaluated over the past two decades (Energy efficiency, 1999). Please see Figure 2.3 for the list of appliances that were included in this act and when the standards were revised. Figure 2.4 shows the projections, as evaluated by Meyers, et al. (2003), of energy savings due to the enactment of the efficiency standards. The large rate of growth over the next twenty years is due to the increased number of energy-efficient appliances that are expected to enter the market (Meyers et al., 2003)

2.3

<table>
<thead>
<tr>
<th>Product</th>
<th>Date effective</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>98 99 00 01 02 03 04 05 06 07</td>
</tr>
<tr>
<td>Refrigerators</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Freezers</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Room air conditioners</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Central ACs</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Stoves</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Clothes washers</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Clothes dryers</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Dishwashers</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Water heaters</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Gas furnaces</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Oil furnaces</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Ranges and stoves</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Pool heaters</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
<tr>
<td>Direct heating equipment</td>
<td>X   X   X   X   X   X   X   X   X   X</td>
</tr>
</tbody>
</table>

X, included in this study’s estimates. O, not included in this study’s estimates.

2.3: Residential appliances included in DOE efficiency standards (Meyers, 2003)
Also in 1992, the United States Environmental Protection Agency (EPA) and the DOE set up the joint initiative for the voluntary Energy Star appliance labeling program, which helped clearly identify what appliances were more energy efficient, and which helped lead the way in establishing a market for these types of appliances. Sanchez et al. (2008) states that the EPA saved 4.6 Exajoules (EJ) of energy between 1992 and 2006, and anticipates that the program will save the United States 12.8 EJ between 2007 and 2015. The 2001 Annual Report of the EPA states that the Energy Star program had saved the United States over 80 billion kWh. (Gillingham et al., 2006) Please see Figure 2.5 for the list of appliances included in the Energy Star program.
Despite the positive numbers towards the decrease in residential energy use, there are a number of criticisms. According to the Lawrence Berkley National Laboratory (LBNL) from their report on “Is Energy Efficiency Enough?” (2005), research done by...
Herring (1998, 2006) states that, from the economists’ point of views, the decrease in energy demand due to these energy efficiency measures will then decrease the price for energy. This will then make the energy more affordable and more likely to be used. As stated by Gillingham et al. (2006), researcher Khazzoom (1980) shares this view and states this effect would then cause a smaller proportion energy use decrease than energy efficiency increase, which would be evident in the data. According to “Is Energy Efficiency Enough?” (2005), Herring (2006) suggests that this “rebound effect”, as it is dubbed in economics terms, will have a 100% effect on energy use, while other sources, as stated within Gillingham et al. (2006) suggest more like 20% effect. As reported by Gillingham et al. (2006), researcher Brookes (1990) suggests that the efforts in increasing energy efficiency in appliances would be technological progress that would then increase economic growth, encourage investment, and, in turn, increase overall energy demand, outside of the residential sector.

Gillingham et al. (2006) reports from researchers Hausman & Joskow (1982) that actual energy use is determined mostly by the consumer’s behavior, which is often unpredictable and uncertain. Furthermore, with the country having such a wide array of incomes, home sizes, climates, and energy prices, it is difficult to determine the actual change in energy consumption due to efficiency standards.

Further, the resulting data will not be able to accurately represent consumer behavior in terms of location or income level, which will have a significant variation. An example given is for a resident who uses an air conditioning unit only a few times a year, either due to income level, house size, or location (climate). S/he may buy a less efficient, but less expensive, air conditioner to suit his/her needs. This factor would not
be evident within the data. Similarly, researcher Sutherland (1991, 1996) in the same report by Gillingham et al. (2006) suggests that these energy efficiency standards will have a proportionately higher negative impact on low-income families, who may not be buying new appliances or energy-efficient appliances due to upfront cost.

With this said, a deeper look into the actual energy use behavior of consumers and appliances is necessary. First details on energy use data within the home will be stated, including sources for household and appliances data, followed by studies of consumer behavior and attitudes.

*Household Energy Data*

As stated previously, actual energy use data are very dependent a number of different factors. The Energy Information Association (EIA) is the national organization that compiles national energy statistics, and which organizes the Residential Energy Consumption Survey (RECS), in order to determine energy use based on a variety of factors. Organization of their data is by factors which include climate, year of construction of the home, household income, type of home, urban versus rural location, region of the United States (Northeast, Midwest, South, West), number of household members versus demographics, the size of the home versus household demographics, household members versus usage indicators, and square feet versus usage indicators. This data is then compiled into spreadsheets based on total residential energy consumption, water heating, space heating, air conditioning, and appliances.

To obtain this data, the EIA conducted in-person, 45 minutes interviews with actual residents; mailed questionnaires, conducted in-person interviews, or held telephone
interviews with rental agents; and mailed questionnaires to energy suppliers. Twelve survey periods have been completed between 1978 and 2006, with the most recent years (1993, 1997, 2001, and 2005) available for download off their website. By far is this the most comprehensive set of data on energy use within the residential sector. (Energy Information).

Appliance Energy Use Data

When household energy use data is combined with data on individual appliance energy use and duty cycles can a better picture of appliance energy use and loads within the home be realized. A report done by Hendron (2007) from the Building America program provides detailed and comprehensive energy use data on appliances, lighting, and other electric loads on a time of use scale. This source came highly recommended by both Professor Andy Lau of Penn State, who has done appliance system modeling, and TRNSYS programmer, David Bradley, who has modeled similar systems.

Additional information from other sources include a study done by Hendron et al. (2005) which provides experimental consumption data from an Energy Star washer, dryer, and dishwasher, depending upon cycle chosen (hot, cold, etc.)

Looking deeper into specific models, obviously the amount of energy used per appliance will vary by size and manufacturer. A study done in Sweden by Swisher (1994) gives a plot of energy use versus size for various AC refrigerators (Figure 2.6).
Notton et al. (1998) compared various models of DC refrigerators in terms of energy consumption to volume (Figure 2.7), noting, however, that these models generally cost three times more than their AC equivalents, due to the lack of mass production.

2.7: Energy use by volume for European DC refrigerators (Notton et al., 1998)

A more in-depth look at the energy use of specific appliances will be required for a more comprehensive modeling tool.
**Daily Load Profile**

The daily load profile is the daily energy demand by the home, as a function of the hour of the day. These profiles are useful for: understanding general energy use behavior of a resident; understanding how common energy use times translate into “peak demand” times and high energy prices for a resident; properly designing and sizing residential energy systems, such as solar energy systems, which will be discussed further in a later section; and, providing accurate data for effective computer simulation, which will also be discussed in a later section.

**Average Load Profiles**

Determining load profiles can be very difficult, due to the number of factors that goes into energy use behaviors, which can vary anywhere between the number of people in the home to the weather outside. The determination of these profiles is important, however, as it gives better insight into where and when energy is used, and what is using it. These load profiles will be necessary for effective computer modeling, as well, which will be discussed in a later section.

**Individual Load Profiles**

Several researchers have taken various paths of developing load profiles for a home that attempt to account for the number of factors involved, and with a number of different mindsets.
For the development of load profiles for water heating and miscellaneous loads, Lefebvre & Desbiens (2002) used mathematical equations to determine energy use of the water heater, based on physical factors such as voltages, temperatures, and internal resistances, and combined it with actual experimental hot water consumption data and hot water use probability functions. Please see Figure 2.8 for their sample load profile for a given winter day.

2.8

![Graph showing load profiles](image)

Fig. 2.8: Average load profiles derived for a winter weekday (Lefebvre & Desbiens, 2002)

To determine the load profile of air conditioning and lights for a home in Taiwan, Chen et al. (1995) combined normalized energy demand data from a national survey, answers to another survey on how residents used their energy, and equations on the power demand of these appliances based on voltages, and, in the case of the air
conditioning, ambient temperature. Please see Figures 2.9 and 2.10 for these generated load profiles.

2.9

2.10

2.9: Normalized usage load pattern of air conditioning (Chen et al., 1995)

2.10: Normalized usage load pattern of lighting (Chen et al., 1995)

Paatero et al. (2006) states, however, that data from the electric utilities generally does not give enough insight into the events within the households to give a proper load profile for a home. This study then suggests generating household appliance load profiles with a “bottoms-up approach”, first by rigorously analyzing and calculating a general load profile from utility-provided data, then obtaining grassroots-level information on
energy usage trends in the home, followed by using carefully crafted algorithms that included probability factors for both season and “social” uncertainty.

Further, this model was then used to show how peak demands could be shaved, with attention paid to if the altered time use of some of these appliances would cause “consumer inconvenience.”

Capasso et al. (1994) developed a novel, very technical algorithm for developing residential load profiles. This approach, which was called ARGOS, could take into detailed account a number of factors for operation of the appliances, including:

- type of activity - cooking, housework, personal hygiene, leisure, etc.
- the mode of operation – automatic (refrigerator) versus requiring human resources (hair dryer)
- within the mode of operation, a distinction between “activating and using” (hair dryer) versus “activating only” (clothes washer or dishwasher)
- typical duty cycles and power consumptions for all appliances

It even had the opportunity for usage profiles within the appliance, which included factors such as:

- unitary energy consumption
- daily probability of usage
- human resources required to use appliances – eyes, ears, hands, etc.
- “deferability” – if the appliance could be used at a different time throughout the day
- working cycle
Further research needs to be reported here on experimental acquisition of load profiles and the Benchmark Models established by Building America.

**Energy Use Decision Making**

*Research to Determining Behaviors*

With all the data given, the actual decision-making process of why residents choose to use energy, when they choose to use it, etc., in order to create the most accurate load profile, but also, more importantly, to appropriately and effectively encourage a decrease in energy consumption, is still unclear.

Palmborg (1986) conducted interviews with the man and woman of 73 households to study energy use habits within the home. Questions asked reflected research done on factors that may affect energy consumption, including: the size of the living area, amount of time present at home, personal priority of housing, if one is family-oriented, general attitude towards energy consumption, and personal priority for saving money. Results were statistically analyzed to determine general usage patterns and trends, with specific data on how each the men and women contributed to energy consumption. (Interestingly, all but four surveys were conducted in the evenings during the darkest time of the year, and percentages of bulbs on to bulbs off were calculated, with varying results.) Please see Figure 2.11 for a consumer sociological model of energy consumption.
Wilson & Dowlatabadi (2007) extensively discusses social influences on behavior and different models of how decisions are made, specifically pertaining to residential energy use, and organizes it within four perspectives: conventional and behavioral economics, technology adoption theory and attitude-based decision making, social and environmental psychology, and sociology. Please see Figure 2.12 for the table of results on what would bring about behavior change through each of these four models.
Lutzenhiser (1992) suggests that the ways energy consumption is currently thought of, in terms of psychological, sociological/anthropological, economical, and engineering factors, is incomplete, and further suggests that energy consumption must be looked at from a cultural standpoint. Though early in full model methodology development, he cites how, without looking to be stereotypical, the “retired working class
couple”, the “young suburban families” and “low-income rural families” will all have
different energy consumptions and patterns, with potential predictions on when or
why a certain group would be using energy. Looking at it from this perspective would
also help better explain why and how, for example, Japan and Western Europe are more
than twice as efficient as the United States, with a very similar quality of life. (He further
states that, one might argue it is because the United States is so spread out, which causes
inefficiencies; however, he states, the US has not exactly applied its ingenuity to fixing
the transportation issues.) Finally, he states that by looking at it from this perspective,
one can then ask, “Why are the refrigerators in the United States so large?”

Lindén et al. (2006) conducted a survey for 600 Swedish households to determine
residential energy use behaviors and suggested ways on how to effectively alter these.
Figure 2.13 shows the energy-efficient behaviors in the home and reasons why these
occurred, and Figure 2.14 shows the energy-inefficient behaviors, why they occur, and
what policies could help change them.

<table>
<thead>
<tr>
<th>Functional area</th>
<th>Behaviour</th>
<th>Grading/frequency</th>
<th>Factors that contributed/comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm and light</td>
<td>Preferences for indoor temperature</td>
<td>55% do not want more than 20°C</td>
<td>In apartment houses it is often 22°C</td>
</tr>
<tr>
<td>house</td>
<td>Bathing in the bathtub</td>
<td>60% use them less than once per week</td>
<td>Hurried lifestyles</td>
</tr>
<tr>
<td></td>
<td>Use of the iron</td>
<td>More than half use them less than once per week</td>
<td>Hurried lifestyles, product development</td>
</tr>
<tr>
<td></td>
<td>Washing textiles only when the machine is full</td>
<td>80% wash only when it is full or almost full</td>
<td>Changed standards for cleanliness, information</td>
</tr>
<tr>
<td>Cleanliness</td>
<td>Put lid on pots</td>
<td>81% do it always or almost always</td>
<td>The oil crisis, habit</td>
</tr>
<tr>
<td></td>
<td>Washing dishes only when the machine is full</td>
<td>71% wash only when the machine is full</td>
<td>Information, habit</td>
</tr>
</tbody>
</table>

Note: All behaviours chosen in this analysis are significant at the p-level 0.05 (Carlsson-Kanyama et al., 2003).

2.13: Energy-efficient behaviors (Lindén et al., 2006)
2.14 Energy-inefficient behaviors (Lindén et al., 2006)

The study also sheds light into behaviors that provide an interesting perspective on energy use, such as: leaving the television on at night when one is alone; rinsing dishes with hot water, with the perception that this would be the only way to get them clean; or the aversion to certain, more energy-efficient technologies, as was echoed in this statement:

“It does not always feel that it is quite OK to use the microwave oven, maybe it is something that I got into my mind it may hurt the food in some way, it is so strange that it is heated from the inside and it is this disgusting it gets so hot sometimes, microhot, it becomes hotter than when one cooks it, and it feels unnatural in some ways, I don’t know, I don’t like it.”

Additionally, every household surveyed stated that they wanted to receive feedback on their energy efficiency measures or changes in behavior, whether in

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### Table: Inefficient behaviours and factors promoting for changing behaviour

<table>
<thead>
<tr>
<th>Functional area</th>
<th>Behaviour</th>
<th>Grading/frequency</th>
<th>Policy instruments for change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm and light house</td>
<td>Use of energy efficient light bulbs</td>
<td>90% do not use them</td>
<td>Information, product development, rebates</td>
</tr>
<tr>
<td></td>
<td>Turning lights off when leaving a room</td>
<td>Only 17% do it all the time</td>
<td>Rebels, information, product development</td>
</tr>
<tr>
<td></td>
<td>Lowering indoor temperatures at night</td>
<td>38% of those who have the possibility do not use it, 23% can not lower temperatures at night</td>
<td>Information, product development, rebates</td>
</tr>
<tr>
<td></td>
<td>Covering windows at night</td>
<td>Half of the households never do</td>
<td>Product development, information</td>
</tr>
<tr>
<td></td>
<td>Airing during wintertime</td>
<td>40% air daily during this season</td>
<td>Product development, information</td>
</tr>
<tr>
<td></td>
<td>The frequency of washing laundry</td>
<td>Half of the households run their washing machine 4 times per week or more</td>
<td>Changed norms for cleanliness, product development</td>
</tr>
<tr>
<td></td>
<td>Removing stains instead of washing</td>
<td>70% never do</td>
<td>Product development, rebates, information</td>
</tr>
<tr>
<td></td>
<td>Airing clothes instead of washing them</td>
<td>60% never or almost never do</td>
<td>Product development, rebates, information</td>
</tr>
<tr>
<td>Food provision</td>
<td>Using a kettle when boiling water before putting in the dishwasher</td>
<td>Only 30% do this</td>
<td>Information, product development</td>
</tr>
<tr>
<td></td>
<td>Rinsing dishes in running hot water</td>
<td>37% do it often or always</td>
<td>Information, product development</td>
</tr>
<tr>
<td></td>
<td>Rinsing dishes in running water when washing dishes by hand</td>
<td>50% use this practice</td>
<td>Information</td>
</tr>
<tr>
<td>Entertainment and information</td>
<td>Using the energy saving function on the computer</td>
<td>Half do not have it or don’t know that it exists</td>
<td>Information, support</td>
</tr>
<tr>
<td></td>
<td>Turning off the TV with the on/off button</td>
<td>34% never do it</td>
<td>Information about e.g. risk of fire</td>
</tr>
</tbody>
</table>

*Note: All behaviours chosen in this analysis are significant at the p-level 0.05 (Carlsson-Kanyama et al., 2003).*
monetary savings or improved health benefits, both of which a power company does not supply.

**Systems-Driven Approach**

**Introduction**

A systems-driven approach to solar energy systems is the perspective that, by looking at how every piece interacts with another within the system, the “big picture” can be realized, and a greater understanding can be had. According to Building America (2006), “a market-driven, system-based research approach can provide valuable benefits to builders, consumers, and utilities while simultaneously resolving market and technical barriers to innovation.” Figure 2.15 shows a flowchart of how the various aspects of photovoltaic systems are interrelated.

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2.15: Interrelatedness of solar power system (Solar Energy, 2008)
To elaborate, looking at just one part of a solar energy system, for example, the upfront cost of a residential, can be daunting and an inaccurate measure of the true “cost” of the system. Indeed, this upfront cost number is what turns many away from installing a system in their home.

However, when taking a systems perspective on solar energy, the environmental and technical factors, as well as more representative economic factors, can be seen. A main environmental factor is the amount of carbon emissions and greenhouse gasses saved by switching away from coal-based power to emission-free solar power. Please see Figure 2.16 for the energy payback period for photovoltaic panels and information on its environmental benefits.

2.16

![Figure 2. Cumulative Net Clean Energy Payoff](image)

**PV systems can repay their energy investment in about 2 years. During its 28 remaining years of assumed operation, a PV system that meets half of an average household’s electrical use would eliminate half a ton of sulfur dioxide and one-third of a ton of nitrogen-oxides pollution. The carbon-dioxide emissions avoided would offset the operation of two cars for those 28 years.**

2.16: Energy payback graph of PV energy, and information on its environmental impact (PV FAQs, 2004)
Finally, once the system dynamics are studied and understood, the performance of individual components can be examined and optimized, in the context of bettering the system.

For this report, a more in-depth look at how understanding photovoltaic systems from a systems perspective has improved their economic affordability, and then how, by examining the technical dynamics of the photovoltaic system, its physical performance was improved. Finally, the value of a systems-driven approach on the design and implementation of photovoltaic systems will be discussed.

**Economic Factors**

By looking at photovoltaic systems from the economic “big picture” perspective, beyond just the totaled cost of panels, inverters, and charge controllers, the true cost of photovoltaic panels is realized, and its affordability is better attained. Also, by understanding the cause and effect each component has on the system, these components can then be optimized.

A study by Reckrodt et al. (1990) developed a comprehensive lifetime assessment of the economics of battery storage. This included quantities such as battery salvage value, tax depreciation, and the cost of loss energy due to inefficiencies.

A study by Black (2004) discusses and calculates how a region in California, through a variety of external factors, could viably install affordable solar electric systems. These factors include:

1. Government incentives
2. The opportunity for annual net metering
3. Time of use rates on electricity

4. High electricity costs

5. A decrease in PV system costs

6. High tax brackets

The government incentives helped offset the cost to the consumer through a $3.60/W rebate, as well as a 7.5% state level income tax credit, based on the after-rebate cost of the system. The annual net metering opportunity allowed for residents to receive full credit for excess energy provided to the grid, which could then be used anytime during the year, similar to a “100% efficient battery” for year-round use. This allowed for excess energy generated in the summer to be used in the winter.

Time of use rates on electricity allowed solar power system owners to receive a higher rate for their solar energy that was sold during peak demand, which is conveniently when solar power generates its energy. This period for California is noon to 6pm from May 1st to October 1st, which cost $0.31/kWh, compared to $.09/kWh off-peak. Winter peak demand yielded $0.12/kWh, with off-peak yielding $.09/kWh. These high electricity costs also helped to make photovoltaics more cost competitive with the grid, thus making it more affordable. Further, California has added rate charges for those customers using more kWh than the average usage for their region.

The decrease in PV system cost was due to the average decreases in cost from improved components and increase in demand. The high tax brackets helped make solar more affordable, as electricity bills are not tax deductible, and with the aforementioned
benefits, more money was left over after taxes for electricity bills, which are, due to the previously mentioned factors, significantly lower than a typical grid-connected home.

Additionally, the researcher assumed an increase in property value for the home and calculated the positive cash flows per month for a typical home, due to the previously mentioned cost savings (Figure 2.17)

<table>
<thead>
<tr>
<th>Pre-solar bill</th>
<th>kWh per month</th>
<th>System AC size (kW)</th>
<th>Final net cost (K)</th>
<th>Net monthly cash flow (per month)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$75</td>
<td>580</td>
<td>2.5</td>
<td>$14.5</td>
<td>+$7</td>
</tr>
<tr>
<td>$175</td>
<td>1050</td>
<td>5.0</td>
<td>$26</td>
<td>+$59</td>
</tr>
<tr>
<td>$300</td>
<td>1560</td>
<td>7.5</td>
<td>$37.5</td>
<td>+$126</td>
</tr>
</tbody>
</table>

2.17: Positive cash flow estimates per month (Black, 2004)

Conclusions from the study showed that if the resident had good exposure to the sun, had monthly electricity bills that were $75 or more, and if the resident lived in the Pacific Gas & Electric (PG&E) territory of California, then solar systems were economically viable.

In a study by Hoff et al. (2007), the increased value of photovoltaic systems that had battery storage was performed, with case studies in California and New York. Reasons cited were the protection against outages and minimizing the cost of using electricity throughout the day. The California case study showed higher value, due to the higher electricity rates there, as well as a capped buy-down rate in New York.

A study by Oatman et al. (2002) discusses how the components of a photovoltaic system were decreased in cost through systems-level integration. Utility Power Group, a subsidy of Xantrex inverters and Kyocera Solar Inc, developed a modular photovoltaic system for residential use. By buying materials in bulk, prefabricating installation
components and photovoltaic modules, and streamlining the installation process, the cost of material and labor for the array was reduced from approximately $7.00 per square foot to about $3.79 per square foot. Additionally, the power unit cost, which is a combination of the inverter, controllers, and protection devices, was reduced from $.67 per watt to about $.34 per watt. Approximately 80 households in Sacramento were currently benefiting from the installation of these systems.

A similar study by Strong (1999) discusses his work towards decreasing the cost of a photovoltaic system. He discusses the development of lower cost photovoltaic systems from September 1995 to June 1998 through six original main tasks:

1) Performing a system-level review of the photovoltaic systems, components, design, and installation

2) Designing innovative mounting systems

3) Enhancing modularly designed inverters

4) Pre-manufacturing the wiring systems

5) Standardizing and pre-approving these modular designs

6) Developing US-based products and systems for export

Once beginning the work, the team discovered that it would be near impossible to design the control systems to the cost and performance specifications necessary, and thus revised the work plan was revised to include: obtaining a UL listing for the photovoltaic modules as unit, achieving code and standards compliance, continuing the efforts to reduce the cost of the modular inverter, developing a mounting system for the photovoltaic modules, and developing an electrical connector system for the modules.
Technical Factors

By examining the dynamics of the physically installed system, and by examining how compatible individual components are within the systems and subsystems, the performance of a system can be increased.

A study by Palomino et al (1996) describes the development and optimization of the controls for a very similar grid-integrated battery system. Researchers are using a lead acid battery in this system, however the proper controls and optimization of the system allowed for optimal operation of the battery.

A study by Duryea et al. (2001) discusses the study and lifetime optimization of the batteries within a stand-alone photovoltaic system. By examining the typical battery cycling and concurrent battery state of charge, alterations to the system were made to best maintain the life of the battery. This source outlines testing procedures and includes hardware used to perform the system tests.

A study by Li et al. (2009) describes the physical and economic optimization of three photovoltaic systems with varying, hybrid energy storage systems. The first system was a photovoltaic system with a lead acid battery, the second system was a photovoltaic system with fuel cell energy storage, and the third system was photovoltaic system with a hybrid lead acid battery and fuel cell technology for energy storage. Through these studies, it was determined that the latter system of altered energy storage capacity of each and less photovoltaic panels than originally thought yielded a lower cost and a higher efficiency than the other systems.

A study by King et al. discusses how stand-alone photovoltaic systems were optimized through experiments and testing, with the goals of optimizing performance,
reliability, and safety. At the end of their experiments, a 30-day testing procedure was developed, from which future analysis of systems could be conducted with similar results. Further the studies on the systems allowed for informed dialogue between the researchers and system and component designers, as well as with the system owner on how his/her system most efficiency would perform.

From their experiments, a number of system inefficiencies and conflicts were discovered. For example, one point of optimization dealt with the mismatches in the maximum voltage of the solar panels and system’s operating voltage dependent upon the state of charge in the batteries. It was determined that one system that located in Albuquerque, NM had a 15-20% year loss of DC energy as a result, which would have been even higher in a colder climate.

It was also determined that the inverter manufacturer’s low-voltage disconnect voltage setting, which could not be altered, was too low for the optimal operation of the batteries, which would likely limit the lifetime of the batteries.

Additionally, current, voltage and power flows in and out of each component were measured, in order to determine the efficiencies and performance of each piece. Overall, it was suggested that, through changing the system components, altering the charge-control setpoints, and tweaking the operating strategy, the efficiency of a system would significantly increase.

Palomino et al. (1997) discusses the performance of a grid-connected, 2.4 kW PV system that had 25.2 kWh storage, which was used to provide power for residential customers during peak energy demand times, which was between 4pm and 7pm in the summer, and between 6am and 10am in the winter. While their study concluded that the
system was working well enough to achieve their design goal, it was determined that there was up to 40% electrical loss in the system, with 25% likely loss in the battery. Further studies on the system and energy flows would most likely lead to system and component alterations that would significantly improve the overall efficiency.

Hammond & Turpin (1997) discussed surveys that were sent to PV system integrators, PV charge controller manufacturers, and battery manufacturers in order to:

1. Determine the market for batteries for PV systems
2. Quantify the different types of batteries used for various PV applications
3. Characterize the charge controllers used in PV systems
4. Determine the operating conditions and environments of PV battery storage components
5. Predict the PV battery market for the year 2000

The most interesting conclusions from the surveys were that there is an obvious lack of communication among these industries when designing components for photovoltaic application.

For example, while many battery specifications ranked by system integrators yielded an “Essential” or “Useful” rating, the most common and important specification asked by the integrators to the battery manufacturer was “Cost.”

On the other hand, one battery manufacturer expressed their frustration with system integrators with the statement:
“…listen to the battery industry when we tell you that we need constant voltage regulators, higher end-voltage limits, and higher limits for low-voltage disconnects.”

Furthermore, charge controller manufacturers unanimously stated that they do not receive sufficient information from battery manufacturers on the performance of their batteries in PV systems. Finally, no battery manufacturers reported offering an “Application Guide for PV Customers” for their product, though approximately half said they would have one available by the end of the year (1996).

This study shows the lack of integration among the various manufacturers of PV system components, as well as between PV system integrators and component manufacturers. Increased communication and integration among these key players, as well as reliable data on system performance and limitations, would significantly aide in furthering PV system performance and efficiency.

This all-in-one approach is a potential work path for future iterations. This path was suggested against by TRNSYS programmers, citing “let TRNSYS do what it’s good at doing”, which was the energy simulations, and to let a program like Excel handle the economics.

An important aspect when looking at grid-connected systems is the interaction and impact that feeding local power has on it. With proper examination and equipment design, these types of issues can be resolved.

A study performed by Vallvé et al. 2007) discusses the effect that feeding photovoltaic power, and photovoltaic power from a battery storage device, has on the
grid. Suggestions in how to optimize this power deliverance with the system at hand are given.

Weiping (2008) discusses the study on the power from residential-scale photovoltaic systems and how it harmonically interacts with the grid, in order to synchronize and optimize power transfer to the grid.

A study by Salas et al. (2006) examines the transfer of power from photovoltaic systems onto the grid, with particular attention to minimizing any DC current leak by the inverters.

**Computer Modeling of PV Systems**

*Introduction*

Computer simulation models are a relatively inexpensive way to determine the performance of the components and systems of a photovoltaic system, and can provide comparable results to actual systems, given the mathematical and logical parameters are accurate, and that key assumptions are not overlooked.

Modeling does not replace physical experiments; rather, it complements them, with opportunities to validate the model components and systems for various other applications, such as system sizing, cost analysis, and future system design. With these validated computer models, determining the effects of individual variables on the system can be evaluated, which would be near impossible to physically and cost effectively do with an actual system.

Limitations in simulations generally include making inaccurate assumptions or ignoring factors that may seem irrelevant, but, ultimately, lead to a distinct outcome
differences. Additionally, physical imperfections, such as leaking pipes or broken controllers, are not anticipated for a computer simulation, which would affect the relationship between actual and simulated results over the long term. (Duffie & Beckman, 2006)

**Details of Computer Modeling PV Systems**

Any component in a photovoltaic system can be described with equations or data that numerically, mathematically, or logically explain their behavior in a given situation. Entering these either algebraic or differential equations into a computer program that can solve them, and by linking inputs and outputs of these equations with other logically expressed components in the system, also while keeping time an independent variable, a mathematical representation of the time-variant dynamics of a photovoltaic system can be created. Extensive amounts of characteristic equations for photovoltaic system components are found in Duffie & Beckman (2006)

Depending on the complexity and nonlinearity of the equations, the given solver could combine the equations algebraically, for a simpler solving technique. However, if the equations are relatively complex, or if there are a number of them, the solver can keep them separate and solve for them simultaneously. The latter procedure is beneficial for determining how an individual component performs, as the characteristic equations were not combined with other equations, thus, the performance data is not muddled among combined equations.

Additionally, as the numbers of components goes up in a system, and as the characteristic equations of these systems becomes more complex and lengthy, the desire
by the modeler to have these components already derived and expressed mathematically increases exponentially.

*TRNSYS*

With that said, the computer program TRNSYS, which stands for Transient Energy System Simulation Tool, fits as a useful and appropriate solver tool for photovoltaic systems.

TRNSYS was originally developed to model the thermal processes of photovoltaic systems, but it is currently used for a variety of both thermal and photovoltaic system modeling. With its basis in solar technology, there are many available components, such as solar panels, inverters, and batteries, which are already programmed in for the modeler.

Additionally, TRNSYS is very flexible and allows for the creation of one’s own components, which is unlike other programs which have standard, rigid components. This is possible due to TRNSYS’s inherent solving method, which does not algebraically combine the equations.

Finally, because of TRNSYS’s origins in modeling solar systems, daily solar radiation values and weather data are already built-in, based on compilations of numerous studies done that represent a typical meteorological year (TMY).
Appliance Modeling

There are a number of ways to effectively model appliance power usage within a home, whether it be through characteristic equations and functions of voltages, or empirical data based on actual load profiles. Most of these techniques were mentioned earlier when discussing load profile derivations and have been used in those studies.

For TRNSYS, the suggested way to model the appliances was to input the power demand from the appliances in a constant time step. This will require deriving the frequency of use and other factors however deemed fit; however, inputting the data in such a way will allow for easier flexibility in changing the data and requiring less work than attempting to derive characteristic equations of various residential appliances.

How Computer Modeling Fits with Systems-Driven Approach

The systems-driven approach to viewing photovoltaic systems is highly supported by computer modeling, as computer modeling tools are designed to do just that – evaluate the performance of a component by its performance in the system. TRNSYS is particularly suited to this task, due to its opportunities for creating new components, its flexibility in changing the characteristics of current components, its openness to investigation of how various components and sections of a system are performing and interacting, and to its very nature of already having photovoltaic components programmed in.

Here are example studies of how computer modeling has been complemented with the systems-driven approach, followed by studies that have used TRNSYS to evaluate their systems.
Non-TRNSYS Modeling

Celik (2007) created a computer model of a stand-alone photovoltaic system using a series of equations and algorithms, as opposed to using already programmed components or program, in order to determine the effect of various load profiles on the system. Ultimately he compared the effects of temperature, voltage changes, and currents on battery to load ratios and solar to load ratios, in order to determine performance and life cycles of the lead acid batteries.

Urbina et al. (2000) developed a simulation of a photovoltaic system that used a stochastic model for the panels and a neural network model for the batteries. All algorithms were all derived by the researchers. Their studies show that their battery would last at least one year on full capacity. Russell (1994) used photovoltaic component equations from derivations made by Sandia Laboratories. The computer model was able to show them some inverter control problems, which they then could work with the manufacturer on. Joyce et al. (2001) derived their equations and inputted them into the software ModelMaker. Results from their experiment contributed to the optimization of the inputted battery parameters. Amer & Younes (2006) used equations from Duffie & Beckman, and from work cited within that work, to model a photovoltaic water pumping system. Their work was verified with actual experiments, which helped validate the models.
TRNSYS Modeling

In a report that is similar to the project proposed here, Mehos & Mooney (2005) developed a spreadsheet with a user interface, computer model, cost input, and financial calculator that allowed the user to design a system and calculate its overall cost. The programmers used TRNSYS for parts of their system development, as TRNSYS already had a library of components and could easily integrate the solar system.

Fry (1998) discusses the development of TRNSYS simulation models and an automated .exe program for the physical and economic assessment of building-integrated photovoltaic systems. This project also required custom programming of TRNSYS components, such as a new photovoltaic module component and utility bill processors.

This all-in-one approach is a potential work path for future iterations. This path was suggested against by TRNSYS programmers, citing “let TRNSYS do what it’s good at doing”, which was the energy simulations, and to let a program like Excel handle the economics.

Hendron et al. (2005) used TRNSYS for simulations to determine the performance of the home’s solar water heater, in order to analyze a system design change. The current system provided 83% of the home’s domestic hot water and 25% of the basement space heating load. With the proposed design change, the system would provide only 77% of the domestic hot water; however, the change could provide the basement space heating with 56% of the required load.

Norton et al. (2005) compared actual to simulated electricity use data in the study of the performance the Solar Patriot home, built by Don Bradley, in Virginia. After modeling the home in DOE2.0, with some systems analyzed using TRNSYS, it was
determined that the home performed well above the benchmark standards set by Building America, however, the reduction in electrical loads would significantly improve the performance and affordability of the home. Additionally it provided a visual interpretation of the performance and output of the computer model. It also gives detailed, month by month energy use charts for various appliances and electrical loads.

*Battery Modeling*

Many studies have been performed to derive the characteristic equations for batteries, generally, in the case of photovoltaics, lead acid batteries, as these are typically used in the system. TRNSYS has several lead acid battery components already programmed in. Similar processes to developing the lead acid battery models can be used for other types of batteries.

González-Longatt (2006) presents a study on battery circuit models, with characteristic equations of dynamic battery models derived. Copetti & Chenlo (1994) tested lead-acid batteries for photovoltaic systems, with resulting characteristic equations for all sizes and types of lead-acid batteries. Sauer & Garche (2001) developed a mathematical model for lead acid batteries in photovoltaic systems. From this model, an improved battery design and utilization strategies that would work best for photovoltaic applications were explored. Guasch & Silvestre (2003) discusses a comprehensive study to develop an electrical battery model for stand-alone photovoltaic systems.

A study by Medora & Kusko discusses the process of modeling a lead acid battery with just the data provided by the manufacturer. Experimental data was verified with
existing computer models of batteries. This article also provides insight into what pertinent, mathematical details would be necessary for successful computer modeling, such as the battery’s capacity as a function of the discharge current and the discharge voltage as a function of the battery’s state of charge.

Studies have also been performed to develop models for lithium ion batteries. Gao et al. (2002) discusses the development of a dynamic model for lithium ion batteries. The model was developed from manufacturers’ data and confirmed with experimental data. Tremblay et al. (2007) discusses the development of a battery simulation model for use with hybrid electric vehicle simulations. Kroeze & Krein (2008) developed a battery model for electric vehicles by representing the batteries as equivalent electrical circuits.

In the case of the matrixed lithium ion battery technologies, a study by Cromwell discusses the number of technical factors within the design of lithium ion battery arrays. These include the temperature, voltage, and power output concerns within each cell, as well as the component needs and specifications, such as the controllers and power supply. These types of studies will help to understand the full implications in developing more advanced energy storage technology models.
Chapter 3
Methodology

1) **Review** the TRNSYS program and previous work on the subject, so as to understand the capabilities and workings of the program, to identify the best ways to approach the problems, and to review previous work on how the program has been used for similar application.

In order to do this, I will attend the available TRNSYS training program available by the software developers. Following this, I will perform research within scholarly article databases to determine how TRNSYS has been used to develop simulation models. Finally, I will contact and work with the programmers at TRNSYS to find the most appropriate ways to model this type of system, based upon their expertise and previous work.

2) **Analyze** the physical and economic factors of the typical photovoltaic system and the advanced energy management system, in order to identify all factors to account for when creating the tool.

In order to do this, I will first deconstruct the larger system into subsystems. Next, I will analyze each of these subsystems for all relevant physical and economic
factors that have a direct influence on the final outcome of the system. I will also examine the implementation and installation of an actual grid-integrated battery system, so as to reaffirm the factors that were practically relevant. I will then categorize and list all of the identified factors.

3) **Create** simulation models of a typical system and an advanced energy management system, so as to understand, explore, and test the procedure of creating simulations.

To do this, I will first research, understand, and analyze the dynamics of the systems to be modeled, so as to understand how to appropriately translate them into the program and to identify where to make appropriate assumptions. Further, I will examine and identify the number of economic factors that affect the systems, so as to properly account for all limiting factors and to determine if final simulations produce expected values.

Based upon these analyses and assumptions, I will then use the TRNSYS program to create the simulation models of both the typical PV system and the advanced energy management system. Modeling procedures from the training session, self-help guide, and TRNSYS programmers will be used to create the simulations.

4) **Pinpoint** three major barriers or issues that arise in the development of the simulation models, so as to provide the greatest contribution with an appropriately limited scope of research
During and following the creation of the simulation models, particularly with the advanced energy management system, I will identify and analyze:

- Shortcomings with TRNSYS as a program that hinder a successful simulation model
- Needed components within TRNSYS to create successful simulation models
- Assumptions made in the simulation model making process that could affect the final outcome

5) **Develop** a guide that addresses and organizes these issues, so as to clearly communicate the findings for future research

Once the simulation models are made and the barriers identified, I will organize the issues in a clear guide that can be used by future researchers.

6) **Identify** future work and research that can lead to the successful development of simulation models for advanced energy management systems within TRNSYS, so as to continue research efforts in this area of study, based on the findings of this research

Based on the findings of this research, I will identify future work and research that can contribute to the ultimate creation of robust simulation tools for an advanced energy management system.
Chapter 4
System and Economic Analysis

4.1 Introduction

The main goal of this thesis is to determine appropriate ways to model advanced energy management systems within the simulation program TRNSYS (Transient Energy System Simulation Tool).

To do this, first, the number of physical and economic factors that directly influence the final outcome of both a typical photovoltaic system and an advanced energy management system were determined. Next, a tool consisting of TRNSYS simulation models of each of these systems and an Excel spreadsheet interface was developed. Finally, with the insight gained from these processes, a guide to creating accurate and robust models for advanced energy management systems was written.

Leading up to the creation of the tool, an analysis of all relevant physical and economic factors that have a direct influence on the final outcome of the system was performed, and all factors were identified, categorized, and listed, and which are discussed in this chapter. This list of factors was then used to create the tool, as discussed in Chapter 5, and, based on how each factor was represented within the tool, suggestions for future tools are given and discussed in Chapter 6.

To determine this list of factors, the system is first deconstructed into subsystems. Next, each of these subsystems are analyzed for general physical dynamics, and the
factors that account for each of these dynamics are identified. Following this, the economic factors of each system are identified. Finally, an actual, installed system is examined, for additional realization of physical and economic factors.

4.2 Physical Dynamic Analysis

Before attempting to simulate the dynamics of the system, an analysis of what is physically occurring should be performed, so as to approach the problem from the appropriate angle, to ensure the accurate modeling of the dynamics, and, once the simulation program is created, to verify its accuracy in modeling the proposed system.

4.2.1 Typical PV System

Figure 4.1 shows the flow chart of how a typical, grid-tied photovoltaic system operates.
The four main components that affect the quantity of the power flows through this system are the solar panels, the AC loads, the battery back up, and the grid. Other contributing components are the charge controller, the inverter, and the charger.

Going through a general day, the solar panels produce DC power, which goes into the charge controller. The charge controller then sends the power through the inverter to meet the AC loads, with excess power going to the grid. In times where there is not enough solar power to meet the loads, power is supplemented with the grid.

When the grid is down, incoming solar power is used to meet the AC loads, and, if there is not enough to meet the loads, the battery backup is used. When there is not an AC load demand, solar power is used to charge the batteries.
4.2.1.1 Discussion on typical PV system

In cases where the grid is unreliable or subject to frequent weather-related outages, having such a battery backup system is a wise decision for uninterruptable power. However, in many areas, as the grid is usually operating, the batteries typically stay fully charged and untouched for most of the life of the system, thus adding to the balance of systems cost and acting essentially as an unusable and unintegrated source of power.

Furthermore, this system is operating independent of the cost of electricity from the grid. With a flat, averaged rate for electricity, which is currently the case for Pennsylvania, the cost to meet the demand will be the same no matter the time, and no strategic power management with respect to the cost of electricity is needed. However, with time of use rates, whenever there is a demand from the AC loads, it will continue to be met with either incoming solar power, power from the grid, or a combination of both, without any consideration for how much it costs to meet that demand.

Finally, as this is how the typical photovoltaic, grid-tied system operates, particularly the decisions made by the charge controller and inverter, it is these kind of dynamics that TRNSYS will simulate. Modeling the dynamics of a system that would account for time-dependent dynamics, or for any other new factor, would then require custom programming of the system.
4.2.2 Advanced Energy Management System

The advanced energy management system, which seeks to more effectively integrate energy storage into the dynamics of the system, is discussed in this section. Figure 2 shows how the fundamental concept of having integrated energy storage in the system differs from the typical photovoltaic system.

By integrating this technology into the system, strategic buying and selling of power based on grid economics throughout the day can occur. Compared to the typical photovoltaic system, keeping the loads and incoming solar power a constant, a controls system of the energy storage technology that effectively takes advantage of these time of use rates with the integrated energy storage can now be implemented.

4.2

4.1: Power source and dynamic comparison of typical system versus advanced energy management system
First, a system that illustrates advanced energy storage is discussed, followed by the analysis of the dynamics of the system. Finally, the factors that affect its economic viability are examined.

4.2.2.1 Commercially available system

A large motivating factor for this thesis is a grid-integrated battery system that uses a commercially-available Integrated Circuits of Electric Lithium (iCeL) intelligent energy storage technology. Figure 4.3 shows an illustration of the storage technology in a residential, grid-tied, solar system.

4.3: Commercially available iCeL technology in residential, grid-tied solar system
The goal of this system, which differentiates it from a typical, residential photovoltaic system, is to capitalize on electricity price differentials throughout the day, while also meeting the incoming load demand in the most cost effective way possible. To do this, a grid- and system-integrated battery storage technology is employed, which, at its simplest, can act as a reservoir of inexpensive energy throughout the day for loads and a valuable energy source for the grid during expensive, high demand times. Energy “decisions” of a combined unit of two time-programmable inverters and one charge controller are then made throughout the day, based upon incoming solar power, state of charge of the batteries, the cost of electricity, the time of day, and the loads on the system.

Furthermore, with the integration of DC energy storage and with solar power being a second source of DC power, the addition of DC loads becomes a viable option. This system has both an AC and DC bus for loads.

Thus, the ideal outcome is a system that will cycle power daily at appropriate low buying and high selling rates; appropriately keep, use, or sell incoming solar power; and use stored power to cut down on the use of expensive daytime power from the grid.

4.2.2.2 The Energy Storage Technology

The major component to the system, the energy storage, is an intelligent energy storage technology consisting of lithium ion battery cells. These cells are wired together in a matrix configuration within the battery pack and connected to a computer chip, which monitors and controls the state of charge and temperature of each cell. This type
of architecture is representative of what is currently used in laptop batteries, as well as in naval and marine environments, where lifetime and performance are crucial. This specific company, however, is among the first to employ such a battery technology into a residential system.

As a result of this type of battery architecture, these battery packs are better equipped to handle frequent cycling than typical batteries used in residential, solar applications (typically lead acid batteries) and have lasted longer than in typical parallel or series configuration in systems with frequent cycling. Further, battery packs can effectively charge and discharge at the same time.

4.4

4.4: Internal views of iCeL battery pack

Because of this type of battery architecture, its cycling capabilities, and long lifecycle, these technologies can be well integrated into the system discussed in Chapter 1
for building energy management, transportation, and grid security. This thesis is the first step towards modeling these systems.

4.2.3 Analysis of Subsystems

With the power flows of the commercially-available system in mind, the first step towards understanding and effectively modeling this system was the analysis of the dynamics and subsystems within this system.

To most effectively discuss the physical dynamics of the system, in order to verify that the simulation is modeling the proper dynamics, the system will be explained through the breakdown of subsystems, starting with the fundamental concept of a grid-integrated battery, followed by the addition of AC loads, solar power, and finally DC loads.

4.2.3.1 Grid-integrated battery system

Figure 4.5 shows the flow chart of a grid-integrated battery system.

4.5: Grid-integrated battery system

At the most basic level, a grid-integrated battery system would include a battery pack, an inverter, a charger, and a connection to the grid. The inverter would be
programmed to charge the battery with grid power when the buying price of electricity is low, and discharge the battery to the grid when the selling price of electricity is high. This is under the assumption that there is an electricity rate price differential and the agreement of the power generator and distributor to sell power back to the grid. This is discussed more in the Economic Factors section.

In terms of the physical dynamics of the system, the battery would cycle once per day, and the amount of power transferred between the battery and the grid would be limited to the amount of power that keeps the battery at a safe depth of discharge, for example, 75-80% DOD.

### 4.2.3.2 Addition of AC Loads

Figure 4.6 shows the flow chart of the grid-integrated battery system with the addition of AC loads.

![Grid-integrated battery + AC Loads](image)

4.6: Grid-integrated battery + AC Loads

Similar to the dynamics of having a grid-integrated battery system, the inverters would still allow the charging of the battery during a low cost buying time and discharge
of the battery during a high cost selling time. However, with the addition of AC loads, the battery pack can act as a reservoir of low cost power during the high cost buying time.

Ideally, the inverters and charge controller would be programmed to fill the battery with low cost power during off-peak times and use the battery power to supply power to the AC loads during peak times, when the buying rate for electricity is high. If the AC loads use all of the available battery power, then the system will supplement the loads with the grid power. If the AC loads do not use all of the battery power, remaining battery power will be sold back to the grid at the end of the day during the high selling price time. At night, all AC loads would be met with low-cost power from the grid.

Physically, the battery would cycle once per day, and the amount of power distributed between the battery, the AC loads, and the grid would be limited by the storage capacity of the battery, while keeping the battery from not cycling below a physically detrimental depth of discharge, for example, below 75-80% DOD.

4.2.3.3 Grid-Integrated Battery System + Solar Power

Figure 4.7 shows the flowchart of the grid-integrated battery system with the addition of solar power.
4.7: Grid-integrated battery system + Solar Panels

This system is two independently functioning systems: the previously introduced grid-integrated battery system and a grid-tied solar system. As there are no loads, the battery cycles the same way, and all generated solar power goes straight to the grid.

4.2.3.4 Grid-Integrated Battery System + Solar Power + AC Loads

Figure 4.8 shows the flowchart of the grid-integrated battery system with the addition of solar power and AC loads.
4.8: Grid-integrated battery system + AC loads + Solar Power

By adding AC loads into the grid-integrated battery system that also has a second source of power (solar power), a number of new power dynamics to the system are created.

Here are the ideal dynamics of a typical day: at the beginning of the day, the battery will be charged by low-cost power from the grid. As the day continues, solar power will be generated, and there will be demand from the AC loads. The battery pack now acts as a supplement to the solar power to meet any demands. Thus, the solar power will be the first to meet the demand, supplemented with the low-cost power in the battery pack. Any extra solar power after the load is met will go to the grid during the high selling rate.

If the incoming solar power is not enough to meet the demand, and if the battery pack power has been depleted to 75%-80% DOD, then the system will meet the demand with the high buying rate grid power. If there is any power left in the battery pack at the
end of the day, it will be sold to the grid at the high selling rate. At night, all AC load demand is met by the grid.

For this system, the time at which the AC power is being demanded plays a greater role in the economics of the system, as the “free” solar power is only available during the day, and this total power varies throughout the day, depending on the weather. Thus, overall, the less power used during the day, the more incoming solar power can go directly to the grid. Concurrently, the less total AC power consumed during the day, the less reservoir power from the battery will need to be used. Remaining battery power at the end of the day can then be sold back to the grid.

Furthermore, as the user can control this aspect of the dynamics of the system, this creates the opportunity for strategic energy use decisions throughout the day, theoretically altering the energy use patterns of a user to match the economics of grid electricity and solar power throughout the day.

Physically, the battery is still cycling only once per day, and the amount of power distributed between the battery, the AC loads, and the grid would continue to be limited by the storage capacity of the battery, while keeping the battery from not cycling below a physically detrimental depth of discharge, for example, below 75-80% DOD.

### 4.2.3.5 Grid-Integrated Battery System + Solar Power + DC loads

Figure 4.9 shows a flowchart of the grid-integrated battery system with solar power and DC loads.
The presence of two sources of DC power, as well as the battery being more integral to the system, creates the greater opportunity for DC loads. As there are a number of very efficient DC appliances, this would significantly decrease the overall loads.

Similar to the last system with AC loads, the time at which the DC power is being demanded plays a greater role in the economics of the system. The less power used during the day, the more power can be sold to the grid. This may also lead to the user demanding less power throughout the day, to greater capitalize on the solar power and cycling battery power.

Further, a new and interesting dynamic in the system is the idea for strategic storing of DC power from the solar array in the battery throughout the day. This strategy would avoid inverter and charger inefficiencies going between AC and DC power, thus providing a shorter path to meeting the DC loads than AC power from the grid.
Therefore, a number of decisions by the system would need to be made throughout the day on where power should go. At the beginning of the day, the battery would still be charged with low-cost electricity from the grid. As the day progresses, solar power would be used to meet the DC loads, with the low-cost electricity from the battery supplementing the demand. However, if there is excess solar power generated, some could go to the grid, while some goes to the battery. At night, power to the loads would be met either by the grid, or by the battery pack, depending upon the cycling effects on the battery.

Physically, the battery could effectively be cycling more than once per day, due to the incoming and outgoing solar power. The amount of power distributed throughout the battery and the grid is now a function of the amount of incoming solar power, the magnitude of the DC loads, the time at which there is power demand, and the storage capacity of the battery, while keeping the battery from not cycling below a physically detrimental depth of discharge.

### 4.2.3.6 Grid-Integrated Battery System + Solar Power + AC Loads + DC loads

Combining the two previous systems allows for the final system, a grid-integrated battery system that has solar power, AC loads, and DC loads. Figure 4.10 reintroduces the flowchart for this system.
As with all the systems, the grid-integrated battery starts the day by filling with low-cost electricity from the grid. As the day progresses, solar power comes in, and power demands by the AC and DC loads will occur. Just like the system with just DC loads, the opportunity for strategic use of low-cost battery power and strategic storing of solar power throughout the day, for use by both the AC and DC loads throughout the day, is created.

Physically, the battery could effectively be cycling more than once per day, due to the incoming and outgoing solar power. The amount of power distributed throughout the battery and the grid is a function of the amount of incoming solar power, the magnitude of the DC loads, the magnitude of the AC loads, the time at which there is power demand by either the AC or DC loads, and the storage capacity of the battery, while keeping the battery from not cycling below a physically detrimental depth of discharge.
4.3 Economic Factors of the Systems

In order for any of these systems to be economically viable, there are a number of factors that come into play. The three main categories are: the costs of the physical system; the quantity, quality and time of use of the loads on the system; and the electricity costs and power purchasing agreements by the local utility company.

For each of these systems, there are costs of the physical system that contribute to its economic viability. The first of these costs is the upfront cost of the system components (solar panels, inverter, charger, battery, load equipment, appliances, etc.) The second of these costs is the installation costs, as new, more complicated, or unfamiliar systems may result in a much higher installation cost than anticipated. Finally, the maintenance of the system, including the lifetime of the battery and other system components, will contribute to its overall economic viability.

As for the loads, the magnitude of loads on the system, the efficiency of the loads on the system, and the time at which the power is demanded all play a significant part in the economic viability of the system.

Additionally, time of use rates and rate differential between low cost and high cost power will play a significant role in the viability of the system. If the money earned by selling the power cannot offset the wear and tear costs on the battery, then the system may not be economically worth installing.

Further, the individual agreements by power companies to buy and sell power from a system of this nature, as well as net metering agreements, will affect the economic viability of the system.
Finally, the existence of state or federal incentives to reduce the upfront cost of the system significantly contributes to the economic viability of the system.

### 4.4 Case Study

With the implementation and installation of these systems, more information on the factors that affect it can be gathered and documented. Because of this need, a residential, grid-integrated, photovoltaic-integrated battery system was installed for evaluation purposes in Gettysburg, Pennsylvania.

A retrofit to an existing residential, grid-tied 2.5 kW photovoltaic system, six iCeL battery packs have replaced the previous eight sealed lead acid battery backup packs. With this retrofit, the addition of a DC panel, as well as noteworthy rewiring of the system, was required, which, for a typical installation, would add to the installation time and costs. The system already incorporated a combination unit of two MPPT inverters and a charge controller, which decreased the potentially higher cost of the retrofit.

Recently the option to choose time of use billing rates has been presented, instead of the previous billing method of a flat rate. This offers the opportunity for economic payback of the system.

Additionally, the home is already extremely energy efficient and designed for energy performance. It is modularly constructed, for a tightly constructed building envelope; it incorporates passive solar strategies, such as thermal mass, southern-facing glass, and a roof overhang; Energy Star appliances, efficient mechanical equipment, and
compact fluorescent lights; and energy-conscious and energy-responsible occupants. Currently the homeowner owns no DC appliances, but anticipates exploring this option.

4.5 List of Factors

From the analysis of the physical dynamics, economic factors, and installation of an actual system, it was shown that there exist a number of factors that influence the design and final outcome of the system. These factors are compiled into the following list, as a checklist of things to use within the creation of the tool that consists of TRNSYS simulation models and an Excel spreadsheet.

Following the creation of the tool, as explained in Chapter 5, this list is reorganized by where each factor should be considered in the simulation creation process.

This section offers the preliminary list, followed by explanations of each item.

4.1 Preliminary Factor List

<table>
<thead>
<tr>
<th>Number</th>
<th>Factor Description</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Number of solar panels</td>
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<tr>
<td>2</td>
<td>Amount of energy storage</td>
</tr>
<tr>
<td>3</td>
<td>Number of cycles battery can handle in a lifetime</td>
</tr>
<tr>
<td>4</td>
<td>Time it takes for charging / discharging</td>
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<tr>
<td>5</td>
<td>Charge/discharge efficiency of battery technology</td>
</tr>
<tr>
<td>6</td>
<td>Storage capacity per battery</td>
</tr>
<tr>
<td>7</td>
<td>Incoming PV Power / Weather</td>
</tr>
<tr>
<td>8</td>
<td>Peak demand time(s)</td>
</tr>
<tr>
<td>9</td>
<td>Off-peak demand time(s)</td>
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<td></td>
<td></td>
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<tr>
<td>10</td>
<td>AC load profile</td>
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<tr>
<td>11</td>
<td>DC load profile</td>
</tr>
<tr>
<td>12</td>
<td>DOD of batteries</td>
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<tr>
<td>13</td>
<td>Number of battery cycles allowed per day</td>
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<tr>
<td>14</td>
<td>AC load quantity</td>
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<td>15</td>
<td>AC load time</td>
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<td>16</td>
<td>AC load magnitude</td>
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<td>17</td>
<td>AC load efficiency</td>
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<td>18</td>
<td>DC load quantity</td>
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<td>19</td>
<td>DC load time</td>
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<tr>
<td>20</td>
<td>DC load magnitude</td>
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<tr>
<td>21</td>
<td>DC load efficiency</td>
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<tr>
<td>22</td>
<td>User usage characteristics</td>
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<tr>
<td>23</td>
<td>User affordability</td>
</tr>
<tr>
<td>24</td>
<td>Site-specific characteristics (climate, orientation, etc.)</td>
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<tr>
<td>25</td>
<td>Electricity cost differential(s)</td>
</tr>
<tr>
<td>26</td>
<td>Cost of solar panels</td>
</tr>
<tr>
<td>27</td>
<td>Cost of appliances / load equipment</td>
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<tr>
<td>28</td>
<td>Cost of battery storage</td>
</tr>
<tr>
<td>29</td>
<td>Cost of remaining BOS components (inverters, charge controller, wires, etc.)</td>
</tr>
<tr>
<td>30</td>
<td>Cost of installation</td>
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<tr>
<td>31</td>
<td>User usage profile</td>
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<td>32</td>
<td>Incentives</td>
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<td>Peak demand charges</td>
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<td>Electricity prices</td>
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<td>36</td>
<td>Grid-Cycling Battery + Solar (no loads)</td>
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<tr>
<td>37</td>
<td>Grid-Cycling Battery + AC loads (no solar, no DC loads)</td>
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<tr>
<td>38</td>
<td>Grid-Cycling Battery + DC loads (no solar, no AC loads)</td>
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<tr>
<td>39</td>
<td>Grid-Cycling Battery + Solar + DC loads (no AC loads)</td>
</tr>
<tr>
<td>40</td>
<td>Grid-Cycling Battery + Solar + AC loads (no DC loads)</td>
</tr>
<tr>
<td>41</td>
<td>Grid-Cycling Battery + Solar + DC loads + AC loads</td>
</tr>
</tbody>
</table>
4.5.1 List explanation

The list of factors has been organized into six categories: inter-system design characteristics, factors affecting controls or decisions, load characteristics, outer-system design characteristics, economics, and subsystems. Each of these categories and factors are described below.

**Inter-System Design Characteristics**

The inter-system design characteristics section identifies the factors within the physical system that will affect the final outcome of the system.

1. *Number of Solar Panels* – the number of solar panels will affect the anticipated power output, which will be a factor in the overall design of the system.

2. *Amount of Energy Storage* – in order to achieve the return on investment, there will be a target design goal of a certain amount of energy storage (kWh) within the grid-integrated battery system.

3. *Number of Cycles Battery Can Handle in a Lifetime* – under a number of varying conditions, a battery has a cycling lifetime. Under these specific cycling conditions, the life of the battery must be considered, which will then affect how the system is designed.

4. *Time Battery Takes for Charging/Discharging* – in order to achieve the maximum energy exchange between the battery and the grid, while still considering the lifetime of the battery, the time designated for full charging and discharging of the battery needs to be taken into account.
5. **Charge/Discharge Efficiency of Battery Technology** – depending on the chosen time for charging and discharging, and depending on the specific battery technology, the energy lost in charging and discharging will vary.

6. **Storage Capacity Per Battery** – depending on the charging and discharging parameters set, each battery will have a certain amount of energy storage. Further, if faster or slower charging or discharging parameters are set, this will affect how many batteries will be needed. This factor will also affect how the energy storage system design goal is met.

### Factors Affecting Controls or Decisions

This section identifies the number of factors that can potentially affect how the system’s energy management decisions are made.

7. **Incoming PV Power / Weather** – the amount of incoming PV power will affect when/if power goes to the grid, meets the load, or charges the battery.

8. **Peak demand time(s)** – during peak demand times, the price for electricity from the grid may cost more to buy, and may offer a higher selling rate for solar or stored energy. This factor will affect how the system strategizes its energy management.

9. **Off-peak demand time(s)** – during off-peak times, the price for electricity from the grid may cost less to buy, and may offer a lower selling rate for solar or stored energy. This factor will affect how the system strategizes its energy management.

10. **AC load profile** – the AC load profile is AC energy use by the occupant throughout the day. Depending on when and how much energy is used at given times throughout the day, the energy management decisions will vary.
11. *DC load profile* - the DC load profile is DC energy use by the occupant throughout the day. Depending on when and how much energy is used at given times throughout the day, the energy management decisions will vary.

12. *DOD of batteries* – depending on how much energy is left in the batteries, and in order to maintain the lifespan of the batteries, the energy management decisions will be affected by how much energy is in the battery, and how much needs to remain.

13. *Number of Battery Cycles Allowed Per Day* – depending on the lifecycle of the batteries, the amount of solar energy coming in, the amount of AC and DC load demands of the occupant, and the buying and selling rates of electricity throughout the day, a safe and cost-effective amount of battery cycles will be allowed per day. This will then affect how energy management decisions are made.

**Load Characteristics**

This section identifies the factors within the loads that affect system design and economics.

14. *AC load quantity* – the AC load quantity is the typical total amount of AC loads throughout the day or the year (kWh), which will affect the sizing of the solar array and battery storage.

15. *AC load time* – the AC load time is the time or hour at which there is a demand by AC loads. This will affect the energy management decision of the system, as well as affect the long-term payback of the system.
16. *AC load magnitude* – the AC load magnitude is the instantaneous magnitude of an AC load at a given time. This will affect the energy management decision of the system, as well as affect the long-term payback of the system.

17. *AC load efficiency* – depending on how efficient the AC load is, this will use more or less energy than might otherwise be needed. This will affect the AC load magnitude and overall AC load quantity.

18. *DC load quantity* – the DC load quantity is the typical total amount of DC loads throughout the day or the year (kWh), which will affect the sizing of the solar array and battery storage.

19. *DC load time* – the DC load time is the time or hour at which there is a demand by DC loads. This will affect the energy management decision of the system, as well as affect the long-term payback of the system.

20. *DC load magnitude* – the DC load magnitude is the instantaneous magnitude of an DC load at a given time. This will affect the energy management decision of the system, as well as affect the long-term payback of the system.

21. *DC load efficiency* – depending on how efficient the DC load is, this will use more or less energy than might otherwise be needed. This will affect the DC load magnitude and overall DC load quantity.

Outer-System Design Criteria

These factors, tied in with the economics, are the outer forces on the design of the system, which contribute to the system as a final product.
22. **User usage characteristics** – depending on when and how much energy the occupant consumes the system may need to be upsized or downsized. Further, the payback of the system will be directly affected by this factor.

23. **User affordability** – depending on the upfront cost of the system, the system may need to be downsized for affordability. This will then affect the full design of the system.

24. **Site-specific characteristics (climate, orientation, etc.)** - depending on the orientation, operating conditions, shading, seasonal changes, etc. that affect the panels, the amount of solar energy coming in will vary, as well as the overall cost of installing the system.

25. **Electricity cost differential(s)** – depending on the price differential between high and low buying and selling rates of the grid, the overall economic viability of the system will be affected. This will also affect the target energy storage goal within the grid-cycling battery system.

**Economics**

This section identifies the number of economic considerations that go into the total cost of implementing a system at a specific location. For any of these purchases, the trade-off or balance in purchasing energy efficient equipment versus a less expensive, less efficient equipment is to be noted.

26. **Cost of solar panels** – the upfront cost to purchase the solar panels

27. **Cost of appliances / load equipment** - the upfront cost to purchase new appliances or mechanical equipment
28. **Cost of battery storage** – the upfront cost to purchase the battery storage technology

29. **Cost of remaining BOS components** – the upfront cost to purchase the inverters, charge controller, wires, etc.

30. **Cost of installation** – the upfront cost to install this system. This amount can vary significantly, based on electrician’s previous experience with such systems, if it is a retrofit or new construction, the available space to install necessary additions, etc.

31. **User usage profile** – the combined AC and DC load profile of when the occupant is using power. If the occupant uses a lot of power during peak demand or a lot of power overall, then it will be a longer time to pay back the system.

32. **Electricity prices** – the buying and selling rates of electricity throughout the day. These varying rates and buying and selling opportunities will significantly affect the economic viability of the system.

33. **Incentives** – any decrease in cost due to state or federal solar incentives

34. **Peak demand charges** – extra costs of electricity due to using electricity during peak times

**Subsystems**

This section, many of which were elaborated on earlier in the chapter, identifies the number of subsystems within the greater system, for the purpose of:

1) Identifying and breaking down the complex and intricate dynamics of this system

2) Evaluating if the greater system is properly simulated

3) Testing the final simulations for fundamental functionality and robustness
35. **Grid-Cycling Battery System (no solar, no loads)** - fundamental subsystem; battery pack that buys and sells power at economically advantageous times

36. **Grid-Cycling Battery + Solar (no loads)** - fundamental subsystem + solar power; actually two separate systems – all solar power goes straight onto the grid while the battery cycles

37. **Grid-Cycling Battery + AC Loads (no solar, no DC loads)** – AC loads connected to the grid-cycling battery; battery power is used as a cheap reservoir of power throughout the day

38. **Grid-Cycling Battery + DC loads (no solar, no AC loads)** – DC loads connected to the grid-cycling battery; battery power is used as a cheap reservoir of power throughout the day

39. **Grid-Cycling Battery + Solar + DC loads (no AC loads)** – solar power is used to meet the DC loads (‘free’ power), followed by battery power (cheap power), followed by the grid (expensive power) throughout the day

40. **Grid-Cycling Battery + Solar + AC loads (no DC loads)** – solar power is used to meet the DC loads (‘free’ power), followed by battery power (cheap power), followed by the grid (expensive power) throughout the day. All solar power would need to go through the inverter (DC to AC) to meet the load and/or charge the battery.

41. **Grid-Cycling Battery + Solar + DC Loads + AC Loads** - the final, complete system

**Dependency Matrix**

The dependency matrix shows how each factor is related to each other. An “x” is given if the item in the first column is dependent upon the item in the first row.
For example, the Incoming PV Power is dependent upon the Number of Solar Panels, so an “x” is marked in second column, eighth row.

### 4.2

#### 4.2: Dependency Matrix

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<td>Charge/discharge efficiency of different technologies</td>
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### 4.6 Conclusions

The main goal of this thesis is to determine appropriate ways to model advanced energy management systems within the simulation program TRNSYS (Transient Energy System Simulation Tool).
To do this, first, the number of physical and economic factors that directly influence the final outcome of both a typical photovoltaic system and an advanced energy management system were identified, categorized, and listed, and which are discussed in this chapter. This list of factors was then used to create the tool, as discussed in Chapter 5, and, based on how each factor was represented within the tool, suggestions for future tools are given and discussed in Chapter 6.

To determine this list of factors, the system was first deconstructed into subsystems. Next, each of these subsystems are analyzed for general physical dynamics, and the factors that account for each of these dynamics are identified. Following this, the economic factors of each system are identified. Finally, an actual, installed system is examined, for additional realization of physical and economic factors.

A dependency matrix was created to show the interrelations of each factor, and Chapter 5 discusses how each factor was accounted for within the tool, as well as reorganizes the list to show where each factor is accounted for in the simulation development process.
Chapter 5

Tool Creation

The main goal of this thesis is to determine appropriate ways to model advanced energy management systems within the simulation program TRNSYS (Transient Energy System Simulation Tool).

To do this, first, the number of physical and economic factors that directly influence the final outcome of both a typical photovoltaic system and an advanced energy management system were determined. Next, a tool consisting of TRNSYS simulation models of each of these systems and an Excel spreadsheet interface was developed. Finally, with the insight gained from these processes, a guide to creating accurate and robust models for advanced energy management systems was written.

This chapter discusses the creation of the tool, which consists of two TRNSYS simulation models and the Excel spreadsheet. The goals of this tool are to:

1) Properly account for all user-and system-specific inputs for the simulation models, as identified in Chapter 4

2) Provide the context of comparing the performance of the advanced energy management system with the typical system under the same user- and system-specific set of constraints

3) Allow for easy and flexible input and output of data to and from the simulation models
The tool consists of an Excel spreadsheet interface that contains load profile data on residential energy use throughout the day, electricity costs, and system costs. Data from this interface is then inputted by the user into two TRNSYS simulation models: one of a typical PV system and one of the advanced energy management system. Outputted data from the TRNSYS models is then inputted into another sheet on the Excel spreadsheet that calculates the yearly economics of each system.

The insight gained from creating the typical photovoltaic system simulation was used in the creation of the advanced energy management system simulation. While the former simulation could use all pre-programmed components that were included in the software package, the latter simulation required custom programming of components and additional software to complete.

The capabilities of TRNSYS, barriers to robust models, and future work suggestions in the modeling of advanced energy management systems are then identified based on the researcher’s experiences in the creation of the TRNSYS simulation models for this tool and off of the use of the tool in evaluating the performances of simulation models. These observations are organized and discussed in Chapter 6.

This chapter explains the development of the two components of the tool: the simulation models and the Excel spreadsheets.
5.1 TRNSYS Simulations Development

With the physical dynamics of each system in mind, and with the information on how TRNSYS works, simulation models of both the typical photovoltaic system and the advanced energy management system were developed.

This section describes the history and appropriateness of TRNSYS, how TRNSYS works, how to create new components for the program, the approach taken to model these simulations, and finally an explanation of the final models.

5.1.1 Introduction to TRNSYS

TRNSYS, which stands for Transient Energy System Simulation Tool, is a modular, open-source, Fortran-based energy modeling program. It began in 1975 at the Solar Energy Laboratory of the University of Wisconsin, Madison, in conjunction with the University of Colorado Solar Energy Applications Laboratory as a way to more flexibly and nimbly analyze the dynamics of various components within solar thermal systems.

As the changes to a complete system Fortran code took an excessive amount of time to alter and to complete, a modular framework that made each component its own Fortran subroutine, with the capability to then link each component through inputs and outputs, was developed. The code stayed open-source, so as to have the option to modify or create new components for the system as necessary.

Twenty five years later, the program continues to function modularly and with open-source Fortran code, but has expanded to include components for many different
types of energy systems (solar electric, wind, hydrogen, etc.) and has a visual user interface for greater user-friendliness and understanding.

This program is particularly suited for the modeling of new systems, as new technologies can be written as new components and can be made compatible with the existing solar system components.

5.1.1.1 Overview of how it works

As previously mentioned, TRNSYS is an open-source, Fortran-based program that modularizes each component as subroutines within the complete system. Once a complete system is designed, a simulation can be performed, in which the user defines a time step (15 minutes, 1 hour, etc.) and the number of time steps to analyze (96, 15-minute time steps for an individual day; 8760, 1-hour time steps for a year, etc.)

Transient data, such as the amount of power generated by the solar array within the time step, is quantified, values are transferred through the input and output connections of the virtual system, and the processes are iterated until all time steps have been gone through.

Within TRNSYS, components of a system are called TYPEs, and each TYPE has a set of parameters, inputs, and outputs that describe and set how it will link and relate to other TYPEs. Parameters are defined as any time-independent characteristics of the TYPE, such as the size of an array. Inputs are defined as any time-varying value from another TYPE, such as incoming solar radiation on a solar panel. Outputs are defined as time-varying values that can be linked as inputs to other TYPEs, such as the power produced by the solar panels at a given time step.
Each TYPE can be broken down into two parts:

1) The source code, which is the Fortran code that contains the mathematical equations and processes of the technology, and defines the function of the component

2) The proforma, which is the user interface that outlines the parameters, inputs, and outputs of the mathematical processes, and provides the framework for effectively linking the inputs and outputs of the TYPES within the system

For example, a crystalline silicon panel is defined as TYPE 94a within TRNSYS, and has: nineteen parameters, including module area, number of modules, and maximum voltage at the maximum power point; eight inputs, including beam radiation, slope of the array, and ambient temperature; and eleven outputs, including power at the maximum power point, current at the maximum power point, and temperature of the array. Please see Figure 5.1 as the display of the proforma for this TYPE.

5.1: Proforma for TYPE 94a (crystalline silicon solar panel)
The source code for each component can be found by clicking on the blue “i” icon on the left hand side of the proforma and by clicking on the “Files” tab. This allows the user to view, modify, or swap out source codes within the given proforma. Modifying source code will require recompiling of the code, which is discussed later in this chapter. Please see Figure 2 for the display on how to access the source code.

### 5.2

To create a full system, one inserts the desired TYPEs into a new Project, defines the parameters for each TYPE, and makes the appropriate connections to the inputs and outputs of each. Please see Figure 5.3 for an example solar hot water system Project within TRNSYS, as well as a list of available, pre-programmed TYPEs on the right hand side.
5.3: TRNSYS Project interface and pre-programmed TYPEs

Figure 5.4 shows an example interface on how to make the connections between the inputs and outputs of TYPEs in the system. By clicking on the Connections icon on the far left hand side, one can then click on the outputting TYPE and link it to the inputting TYPE. This interface will then appear to for the user to make the appropriate links, which is made by clicking and dragging to the respective Input variable.
Each pre-programmed TYPE has been individually compiled, and the appropriate links have been included within the program to make them compatible and functional. Therefore, all existing TYPEs can be inserted into a program and linked to other existing TYPEs without needing to edit any Fortran code or to have a Fortran compiler.

5.1.1.2 Creating New Components

While pre-programmed TYPEs can simply be inserted and linked to other pre-programmed types, new, custom-programmed TYPEs need Fortran code written, a compatible Fortran compiler installed, and for a series of steps to be taken to make this new TYPE readable, compatible, and functional within TRNSYS. Once these new
TYPEs are created and the appropriate steps performed, the TYPE can be just as accessible as the TYPEs that are included with the purchase of the program.

To create a new TYPE, the programmer needs to go through these steps:

1) Write the characteristic equations of the component’s dynamics in Fortran code

2) Create the proforma, or framework, for the component, which labels and defines the parameters, inputs, and outputs for linking among the other TYPEs

3) Export the proforma as a Fortran file, and insert the characteristic equations into the appropriate parts of the code

4) Compile the code with a compiler that can create Dynamic Link Library (.dll) files (preferably with the combination of Microsoft Visual Studio 2005 and the Intel Visual Fortran compiler)

5) Insert the source code and proforma into the appropriate folders for TRNSYS to read

6) Refresh TRNSYS “Direct Access” list to have newly created TYPEs appear like any other TYPE

Once these steps are complete, the TYPE can be accessed like any other pre-programmed TYPE, and the user will no longer need to write Fortran code or use the compiler.
5.1.2 Creating the Models

With the knowledge of how TRNSYS works, and with the dynamics of each system analyzed, simulation models of each system were created.

To create the respective models of the typical photovoltaic system and the newly proposed photovoltaic system, a combination of pre-programmed TYPEs and custom programmed and compiled TYPEs were needed.

Knowledge obtained from modeling the typical photovoltaic system was used to create the simulation model for the advanced energy management system.

5.1.2.1 Typical PV System

The typical photovoltaic system was created using completely pre-programmed TYPEs that were included in the purchase of the program. Please see Figure 5.5 for the TRNSYS schematic and Figure 5.6 for the flowchart relationship among the components.

5.5

![TRNSYS schematic of the typical PV system](image-url)
These TYPEs, descriptions, and rationales are as follows:

**TYPE15-TMY2: Typical Meteorological Year Weather Data**

This TYPE reads TMY2 weather data for a typical meteorological year and translates it into solar radiation values for the given collector. Among the parameters needed are the slope and azimuth of the collector. This data format is used by the National Solar Radiation Data Base, and TMY2 data for locations across the United States are available online free of charge. Major US city weather data is included as part of the software package.
**TYPE94a: Crystalline Module Photovoltaic Panels**

This TYPE represents the mathematical behavior of either single crystalline or polycrystalline solar electric modules, depending on the user-inputted parameters. Users can also define the number of modules, slope of the collector, and module areas. A number of other electrical parameters can be inputted to better characterize specific commercially-available panels, however default values are provided to model a “typical” array.

This TYPE was chosen, as it is closest to a photovoltaic module that a typical customer might buy. TRNSYS also has a TYPE to represent thin-film/amorphous silicon photovoltaic collectors.

**TYPE48b: MPP Tracking Power Regulator / Inverter**

This TYPE represents both a maximum power point tracking regulator and inverter. This specific TYPE48 is implemented if the system has battery storage, and is monitoring only the battery’s state of charge, not the state of voltage. An input for loads, an output to the battery, and an output to the grid are already included in this TYPE. Inputting the conversion efficiencies from AC to DC power and from DC to AC power help to characterize commercially-available regulators and inverters within the TYPE.

**TYPE185: Lead Acid Battery**

TYPE185 is a typical lead acid battery, which was the most commonly used lead acid battery by the TRNSYS programmers. This TYPE accepts a current value as an input, so the Power Manager code is programmed accordingly.
The user can define the number of cells in series and the total nominal capacity of the battery.

**TYPE9c: Generic Data Reader**

This TYPE stores the power values for the AC loads of the home. These load profiles are developed by the user within the Excel spreadsheet, which is explained in more detail later in the chapter. The spreadsheet is designed to output data into the correct format, and the user, after choosing the loads for the home, exports the file for each season as a tab delimited text file. The user then sets these files to be the input files for the data readers.

### 5.1.2.2 Advanced Energy Management System

With the dynamics of the system analyzed, the knowledge of how TRNSYS works, and experience gained from modeling the typical photovoltaic system, the newly proposed photovoltaic system was created using a combination of pre-programmed TYPEs that were included in the purchase of the program and a custom programmed TYPE.

The section discusses the approach to modeling this system, how this system was translated into a new TRNSYS component, and the component choice explanations.
5.1.2.2.1 Discussion on the approach to modeling the system

Recognizing the modular style of TRNSYS, an initial approach to modeling the system was to create components of each new component of the system, which would include the battery storage technology, a time-programmable inverter, and a time-programmable charger.

However, after reexamining the architecture of the battery, the Fortran source code for existing battery components within TRNSYS, scholarly research on obtaining characteristic equations for batteries, and available information on this specific battery technology, it was determined that there is currently a lack of needed information to properly model this type of battery in TRNSYS.

Thus, an alternative approach was taken, based on the recommendations of a TRNSYS programmer, to develop a “Power Manager” component. This component looks at all incoming factors and makes energy flow “decisions” as if it were the time-programmable inverter and charger. To keep with having some sort of battery to represent a dynamic energy storage process, while recognizing its limitations, a lead-acid battery component is inserted into the model to simulate the general dynamics of energy storage in a system. As the cycling effects and lifetime of the batteries are not simulated within the TRNSYS program, this type of assumption can be made for these purposes. The Power Manager component then internally takes into account the simultaneous charging and discharging, as well as the respective flow efficiencies, for the advanced energy storage technology when distributing power, in order to better simulate the determined energy flows of the advanced energy management system.
The lead acid battery component was chosen, as it was a readily-available TYPE within TRNSYS, the advising programmer had had good experiences when working with it, and its characteristic equations are established and documented. Had a lithium ion battery been available, that component would have been chosen. However, that is current future work of the advising programmer for later editions of TRNSYS.

5.1.2.2.2 Power Manager Development

With previous work done by the advising programmer, the insertion of a specific lead acid battery TYPE, and the analyzed power flow dynamics of the system, a single Power Manager component was written. Physically this component would represent a combination of a time-programmable inverter and charge controller, and within the simulation, it is accounting for the shortcomings of the lead acid battery TYPE compared to the dynamics of the smart battery technology.

At its most basic level, this component looks at all incoming power and load demands, and sends or takes appropriate power to and from the battery and the grid, based upon the internally programmed decision structure. The decisions and assumptions made are described in this section.

5.1.2.2.3 Power Manager Pseudocode

Upon examination of reports on the power flows within the advanced energy management system, and in order to best translate these decisions into Fortran code, a
pseudocode of the Power Manager was first written. This is then followed up by the assumptions of the code.

If it’s during the day and not charging/discharging (6am to 7pm):

And, the batteries are full (.9-1 Fractional SOC), then:

1. Meet AC and DC loads with solar power
2. Sell excess solar power to the grid
3. If there’s not enough solar power, meet the load with the battery
4. If there’s not enough battery power, meet remaining load with the grid

Or, if the batteries are between .25 and .9 Fractional SOC, then:

1. Meet AC and DC loads with solar power
2. Give excess solar power to the batteries
3. Sell excess solar power to the grid
4. If there’s not enough solar power, meet some of the load with the battery
5. If there’s not enough battery power, meet remaining load with the grid

Or, if the batteries are below .25 Fractional SOC, then:

1. Meet AC and DC loads with solar power
2. Give excess solar power to the batteries
3. If there’s not enough solar power, meet the load with the grid

Else, if it’s during the discharge time (7pm to midnight):

1. Discharge all power to the grid
2. Meet AC and DC loads with grid

Else, if it’s during the charging time (midnight to 6am):
1. *Charge batteries fully from grid*

2. *Meet AC and DC loads with the grid*

### 5.1.2.2.4 Assumptions and simplifications of the Power Manager

While keeping in mind the number of factors that contribute to the systems’ economic viability, but also to simplify the decisions to be made by the program, a number of assumptions and simplifications were made about the system.

Firstly, this code is written for one low buying/low selling time, which is from midnight to 5:59am, or ‘nighttime’, and one high buying/high selling time, which is from 6:00am to 11:59pm, or ‘daytime.’ The major reason for this assumption is for the simplification of the code and time-of-use rate representations. The code can be relatively easily restructured for a greater number of buying and selling times. Future work could reformat the code to make decisions during different, subjective buying or selling times. The scope of this thesis, however, is to demonstrate the basic concept of a low cost buying time and a high cost selling time.

Secondly, due to the charging and discharging characteristics of the lead acid battery, a defined, five hour time frame for full charging and full discharging was programmed. During this time, all loads are then said to be met by the grid. This assumption and simplification was made so as to best interact with the given energy storage component. However, it may add to the final system operating costs, as power that could have been taken from the battery to meet the load is now being met with potentially more expensive energy from the grid.
Finally, to account for the energy losses while going through an inverter or charger, the user inputs an efficiency factor for both inverters (DC to AC and AC to DC) which are set as parameters of the TYPE. Power flows are then multiplied or divided by this factor to represent these losses or extra needed power to meet the load. The simulation is not taking into account losses through wiring or losses due to voltage mismatches.

5.1.2.2.5 Creating the Finished Component

In order to create the component, the steps described in the previous section on creating a new component were taken.

First, the pseudocode was translated and organized into Fortran code, which is available in Appendix A. Next, the proforma of the component was created, which named the Parameters, Inputs, and Outputs of the code.

Parameters of the component are: “Number of Battery Packs”, “Battery Capacity”, “Time Step” (to convert between W and Wh, to be kept at “1 hr”), “Efficiency of Inverter, DC to AC”, and “Efficiency of Inverter, AC to DC”.

Inputs of the component, for use internally within the code and which link it to other components, are: “Hour” (hour of the day), “Power from PV”, “DC Load”, “AC Load”, “Battery Fractional SOC”, “Battery Voltage”, “Battery Current”, “Wh at 25% SOC”, and “Wh Available in the Battery”.

Outputs of the component, which can be linked for other components and/or which are used internally, and which can lead to graphical and data output, are: “Excess PV Power”, “Power to the Grid from PV”, “Power to the Grid from the Battery”, “Power from the Grid to Load”, “Power from the Grid to the Battery”, “Final Grid Counter”, “Power to the Battery from PV or Grid”, “Power from the Battery”, “Initial Power Output to the Battery” (before buying/selling), and “Final Power Output to the Battery” (after buying/selling).

This proforma was then exported as Fortran, and the previously created Fortran code that represents the dynamics of the Power Manager was appropriately placed within the proforma’s code. This was followed by typical debugging procedures while compiling the code.

Finally, the code was compiled, and a .dll file was created. The proforma and source code were placed in the appropriate folders. The “Direct Access” list was then refreshed, which showed the newly created folder of components (appropriately titled “Sarah’s Awesome Components”).

### 5.1.2.2.6 Creation of Full Simulation

With the Power Manager written and compiled, the final components were linked together for the full simulation. Figure 5.7 shows the final simulation within TRNSYS, and Figure 5.8 shows the flow diagram. This is followed by the rationale for each component.
5.7: Final advanced power management system TRNSYS simulation

5.8: Final advanced power management system TRNSYS simulation flowchart
The TYPE choice rationales are as follows:

**TYPE15: TMY2 Typical Meteorological Year Weather Data**

This TYPE reads TMY2 weather data for a typical meteorological year and translates it into solar radiation values for the given collector. Among the parameters needed are the slope and azimuth of the collector. This data format is used by the National Solar Radiation Data Base, and TMY2 data for locations across the United States are available online free of charge. Major US city weather data is included as part of the software package.

This TYPE was also chosen, as it can output an “hour of the day”, which can be used as an input into the Power Manager.

**TYPE94a: Crystalline Module Photovoltaic Panels**

This TYPE represents the mathematical behavior of either single crystalline or polycrystalline solar electric modules, depending on the user-inputted parameters. Users can also define the number of modules, slope of the collector, and module areas. A number of other electrical parameters can be inputted to better characterize specific commercially-available panels, however default values are provided to model a “typical” array.

This TYPE was chosen, as it is closest to a photovoltaic module that a typical customer might buy.
**TYPE185: Lead Acid Battery**

TYPE185 is a typical lead acid battery, which was the most commonly used lead acid battery by the TRNSYS programmers. This TYPE accepts a current value as an input, so the Power Manager code is programmed accordingly.

The user can define the number of cells in series and the total nominal capacity of the battery.

**TYPE9c: Generic Data Reader**

This TYPE stores the power values for the AC and DC loads of the home. These load profiles are developed by the user within the Excel spreadsheet, which is explained in more detail later in the chapter. The spreadsheet is designed to output data into the correct format, and the user, after choosing the loads for the home, exports the file for each season as a tab delimited text file. The user then sets these files to be the input files for the data readers.

5.2 Load / Spreadsheet Development

In order to provide properly formatted data for the TRNSYS simulation models, analyze outputted data from the models, and calculate the economics of the systems, an Excel spreadsheet was developed as part of the tool.

These TRNSYS simulation models were set up with four data readers for the typical PV system (a typical AC load profile for each season) and eight data readers for the advanced energy management system (a typical AC load profile for each season and a
typical DC load profile for each season). They were created in this way, as it allows for a significant reduction in data (instead of 365 individual days, there are now 4 “typical” days, one for each season), while still allowing for the general load differences of the various seasons. This said, now appropriate heating, cooling, and lighting loads can have representation in the model, which are seasonally-dependent. Furthermore, the AC load profiles are used for both the typical system and the newly proposed system, thus keeping them consistent for both simulations.

To create baseline profiles, data gathered from the EIA (2001) and Building America (2001) on appliances, miscellaneous electric loads (MELs) and lighting was embedded in the spreadsheet, and an initial interface was developed to allow for inputting of these particular loads. These particular sources were used within this spreadsheet, due to the data’s accessibility and open format, the amount of data available, and their reference within a number of articles.

Collected data from the home with the installed system would provide the most accurate load profiles, particularly as heating and cooling loads and load profiles are very specific to the home, the climate, and the resident. The purpose of this portion of the spreadsheet, however, is to set up an initial interface that properly formats the four seasonal AC load profiles and four seasonal DC load profiles for this TRNSYS simulation model set up, and provides baseline “typical” data for use in the simulations.

Final data sheets are automatically created in the respective tabs of the spreadsheet and are formatted for use in TRNSYS. The user then manually saves each of the respective spreadsheets as “tab delimited text files.” These files are then manually linked by the user to the respective data readers in the simulation models. After the
When simulations are completed, the user can input the data back into Excel, for yearly electricity cost calculations.

The second purpose of the spreadsheet is to allow for the input of the system and electricity costs. This allows for the calculation of the upfront cost of the system, and, with the data after the simulations have run, can calculate yearly electricity bills. The calculation of yearly electricity bills could be performed within the TRNSYS simulation. However, for easier data access and to keep all non-technical data together, these aspects were accounted for in Excel. Developing this spreadsheet in future work can include a greater analysis and lifetime assessment of the economics of the system, however, for these purposes, the initial baseline of upfront cost and electricity bill calculations were sufficient.

The following sections describe the data in the spreadsheets, and the assumptions made for each set of loads.

### 5.2.1 System and Electricity Information

To calculate the total cost of the systems and the paybacks for each, users can input the system and electricity costs into the spreadsheet. Figure 5.9 shows a snapshot of the system and electricity information interface with example numbers.
5.9

**System Information**

<table>
<thead>
<tr>
<th>Solar panels</th>
<th>12</th>
<th>$1,000.00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inverter (Typical PV system)</td>
<td>1</td>
<td>$4,500.00</td>
</tr>
<tr>
<td>Charge Controller (Typical PV system + Advanced System)</td>
<td>1</td>
<td>$600.00</td>
</tr>
<tr>
<td>Time-programmable Inverter (AC to DC)</td>
<td>1</td>
<td>$2,000.00</td>
</tr>
<tr>
<td>Time-programmable Inverter (DC to AC)</td>
<td>1</td>
<td>$2,000.00</td>
</tr>
<tr>
<td>Lead Acid Batteries (Typical PV system)</td>
<td>8</td>
<td>$40.00</td>
</tr>
<tr>
<td>Cost of 1 kWh of battery storage for Advanced System</td>
<td>6</td>
<td>$1,000.00</td>
</tr>
<tr>
<td>Installation cost of Typical PV System</td>
<td></td>
<td>$1,000.00</td>
</tr>
<tr>
<td>Installation cost of Advanced Battery System</td>
<td></td>
<td>1,000.00</td>
</tr>
<tr>
<td>Incentives / rebates</td>
<td></td>
<td>-$3,000</td>
</tr>
</tbody>
</table>

**Electricity Information**

| Low buying/selling rate per kWh | $0.06 |
| High buying/selling rate per kWh | $0.30 |

5.9: System and Electricity Information interface in Microsoft Excel

Grayed out areas imply that this number is a constant and does not need to be changed. They can, however, still be altered by the user.

These inputs are meant only for use within the spreadsheet and are not directly connected to the simulation model. This said, appropriate technical details will need to be manually inputted into the simulation model, and representations of the system here will not necessarily be represented in the same way in the simulation.

For example, the spreadsheet asks for the number of batteries in the system and cost per battery, for the purpose of calculating the initial cost of each system. However, the simulation tool will need these batteries represented by their capacity and voltage characteristics, independent of the number of physical battery packs sitting in the system.
A later tab in the spreadsheet will then total these numbers for each system.

5.2.2 Appliance Data and Load Profiles

As the time of use of the appliances in the home, as well as the magnitude of power used at each of these time steps, are critical factors in the systems’ payback times, “actual” load profiles are needed to effectively model the system.

As actual energy use varies significantly, depending on the user, characteristics of the home, region, season, culture, etc., “typical” load profiles are difficult to develop. However, a number of studies have been done that attempt to quantify when appliances are used and the magnitude of power for each of those time steps. The data is based upon the power draw characteristics of the appliance, the habits of the users, and the season of the year, with information on where the data is collected. Most data is from Building America (2001) and the EIA (2001), due to the data’s accessibility, amount of data, and reference within a number of articles.

For this spreadsheet, the representation of different appliances and plug loads is split into two parts: the normalized usage profile of when power is used daily by the specific appliance, and the total amount of energy that the appliance consumes in a given time period. Multiplying the appropriate fraction of total power by the normalized usage profile gives the magnitude of power for each time step.

To better characterize specific appliances, the opportunity to put in the final kilowatt-hours per year, based upon the Energy Guide provided by EnergyStar appliances, can be inputted in the interface. Appliances such as the stove vary
significantly user to user, so a default value based upon EIA data is provided as a guideline. For any non-EnergyStar appliance, average numbers were included as defaults. Figure 5.10 shows the Appliance Information interface of the spreadsheet.

5.10

### Appliance Information

<table>
<thead>
<tr>
<th>AC APPLIANCES</th>
<th>if using a DC appliance, type in '0' for those fields</th>
<th>Refrigerator</th>
<th># in Home</th>
<th>Cost of Appliance</th>
<th>kWh / year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Refrigerator</td>
<td>1</td>
<td>$1,200.00</td>
<td>900</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clothes Washer</td>
<td>1</td>
<td>$600.00</td>
<td>330</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dishwasher</td>
<td>1</td>
<td>$450.00</td>
<td>250</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Clothes Dryer</td>
<td>1</td>
<td>$450.00</td>
<td>1079</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stove</td>
<td>1</td>
<td>$800.00</td>
<td>976</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DC APPLIANCES</th>
<th>if using AC appliance, or if using new model, type in '0' for those fields</th>
<th>Refrigerator</th>
<th># in Home</th>
<th>Cost of Appliance</th>
<th>kWh / year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Refrigerator</td>
<td>1</td>
<td>$1,500.00</td>
<td>300</td>
</tr>
</tbody>
</table>

5.10: Appliance Information interface

The normalized usage profiles of the appliances from Building America (2001) have been used in this spreadsheet. Figure 5.11 shows when these appliances are typically used.

5.11

5.11: Normalized usage profiles of major household appliances (data based off EIA (2001))
Appliance use can be considered as season-independent, so load profiles for the appliances are represented equally in each season. Furthermore, the load profile for the refrigerator is assumed to be the same for either the AC or the DC refrigerator, with the appliance energy use data linked to its respective load profile (AC or DC).

5.2.3 Miscellaneous Electric Loads

The category of miscellaneous electric loads (MELs) includes a number of various plug loads, including, but not limited to, televisions, video game systems, cell phone chargers, small kitchen appliances, hairdryers, aquariums, and hot tubs. MELs can account for nearly 40% of a building’s total load, that an accurate representation of their magnitude and time of use would help to better model the dynamics of the system.

Hendron (2006) of Building America quantified the typical kilowatt-hours per year for an extensive list of miscellaneous electric loads (MELs), most of which are included in the spreadsheet.

Figure 5.12 shows a presented normalized load profile for MELs.
All MELs are considered to be AC, however alterations to the spreadsheet would allow them to be linked to the DC load profile, if desired. MELs are also considered to be season-independent, so the load is distributed equally over the four seasons.

5.2.4 Lighting data

As with the Appliance data, appropriate lighting load profiles can be split into two parts: the normalized usage profile of when power is used daily by the lighting fixtures, and the total amount of energy that the lighting fixtures consume in a given time period. Multiplying the appropriate fraction of total power by the normalized usage profile gives the magnitude of power for each time step.
5.2.4.1 Normalized load profiles

For the normalized load profiles, seasonally-dependent data was used from Building America (2001). Data is organized in many ways in this source, so as to be used for a number of various applications. For this specific application, “weekday”-, “dayuse”-, and “season”-organized normalized load profiles were used. The data is also split into Living Area lighting and Bedroom lighting.

Please see Figures 5.13 to 5.16 for Winter, Spring, Summer, and Fall normalized lighting profiles for the Living Area and Bedrooms.

5.13

5:13: Winter normalized load profiles for Living Area and Bedrooms
If the user would like to use normalized load profiles for weekends or holidays, data is available from Building America (2001) for these days, as well. Alterations to the
To account for DC lighting, the user can input the percentage of lights that are DC in the home on the Interface tab. To account for the percentage efficiency difference, users can also input this fraction. Figure 5.17 shows an example load profile that demonstrates the amount of AC vs. DC lighting, with the comparison of if it were all AC.
Numbers reflect 50% DC lighting in the home, with the DC lighting being 30% more efficient than the AC lighting.

5.17

5.17: Example load profile with all AC, fraction AC, and fraction DC lighting loads

5.3 Using the Tool

To properly use the tool, a number of steps need to be taken to ensure a proper model.

The broad process is to develop the load profiles for the given system, input these files into the simulation model, insert the proper parameters of each component of the system in TRNSYS, run each simulation, and insert the respective results back into the original spreadsheet for analysis.

The steps to complete this are:

1) Type in the respective costs of the system components, installation, and grid electricity
2) Choose the appropriate loads in the Interface tab of the spreadsheet for use in
the TRNSYS simulation models

3) Save the appropriate load tabs as “tab delimited text files”

4) Open the typical PV or new system TRNSYS simulation model

5) Double click the load data readers on the left hand side, click on the “Files”
tab, and locate the appropriate load data file (then exit out)

6) Double click each component in the simulation to ensure proper
characteristics of the components are included, such as number of solar
panels, etc. (then exit out)

7) Go to “Assembly” → “Control Cards” to ensure that the simulation is running
for 8760 time steps (1 year) (then exit out)

8) Hit F8 for the simulation to run

9) Exit out of the Online Plotter

10) Double click the “Grid Output” data reader on the right hand side

11) Click on the “External Files” tab, and then click “Edit”

12) Copy and paste the entire text file into the “INSERT TYPICAL GRID
HERE”, or for the integrated system, into the “INSERT NEW GRID HERE”

13) Repeat these steps for both simulation models

14) Click on “FINAL CALCULATIONS” tab to see the comparison interface
5.4 Preliminary List confirmation

In the process of creating the advanced energy management system simulation, the previously derived list of factors influencing the system was used. The following provides the list, whether it was accounted for in TRNSYS and/or Excel, and a brief description of how it was translated.

Error! Reference source not found.

5.1: Preliminary Factor Checklist

<table>
<thead>
<tr>
<th>Factors Affecting Controls/Decisions</th>
<th>Accounted for in TRNSYS</th>
<th>Accounted for in Excel</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Number of solar panels</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2. Amount of energy storage</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>3. Number of cycles battery can handle in a lifetime</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>4. Time it takes for charging / discharging</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>5. Charge/discharge efficiency of battery technology</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>6. Storage capacity per battery</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>7. Incoming PV Power / Weather</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>8. Peak demand time(s)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>9. Off-peak demand time(s)</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>10. AC load profile</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>11. DC load profile</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>12. DOD of batteries</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>13. Number of battery cycles allowed per day</td>
<td>x</td>
<td></td>
</tr>
</tbody>
</table>
### Inter-System Design Characteristics

1. **Number of Solar Panels** – the number of solar panels was represented and accounted for in both TRNSYS and Excel. In TRNSYS, one can input the number of solar panels.
into the TYPE94a proforma of the simulation. In Excel, the number of panels is inputed for final system cost calculation.

2. *Amount of Energy Storage* – the amount of energy storage was represented and accounted for in both TRNSYS and Excel. In TRNSYS, the target amount of storage is empirically formed and represented within the Fortran code through the physical battery capacity while keeping the battery above 25% SOC and the reasonable, programmer-defined charge and discharge rates. In Excel, the target energy storage amount can be inputted, for cycling cost and profit calculations.

3. *Number of Cycles Battery Can Handle in a Lifetime* – the number of cycles the battery can handle in a lifetime is currently only represented in the Excel spreadsheet. This information is used to calculate payback time and cost per cycle, as TRNSYS does not simulate the degradation of components over time. With more system studies and experiments, this information can be integrated into the Power Manager Fortran code, to more accurately account for this degradation.

4. *Time Battery Takes for Charging/Discharging* – this factor is accounted for and set by the programmer within the Fortran code of the Power Manager within TRNSYS. Certain time steps are designated as charging and discharging times. These time spans can be altered within the code, based upon system experimentation and optimization studies.

5. *Charge/Discharge Efficiency of Battery Technology* – this factor is currently accounted for in TRNSYS as a function of the charge and discharge time spans and the physical characteristics of the pre-programmed battery components. With the programming of a new battery technology component the charging and discharging efficiencies can be better accounted for for that specific product or technology.
6. **Storage Capacity Per Battery** – this factor is accounted for in TRNSYS in the proforma of the battery component. The user can input the number of battery packs and capacity of each pack within the proforma.

**Factors Affecting Controls or Decisions**

7. **Incoming PV Power / Weather** – this factor is within the TRNSYS simulation. TMY2 weather data is fed to the TYPE94a solar panel component, which outputs the amount of power of the panels for that location and with the other user-specified constraints. Within the Power Manager component, incoming PV power is linearly distributed to the load, battery, or grid, as appropriate for the instantaneous load demand, DOD of battery, and time of day/cost of electricity.

8. **Peak demand time(s)** – this factor is accounted for in both TRNSYS and Excel. In TRNSYS a time span of when to both prioritize using stored energy, to sell back as much excess PV power as possible, and to empty remaining energy from the battery for high economic return is set within the code. The subsequent cost of buying and selling power at this time is then entered into Excel, and the energy use data from the simulation is then multiplied by these buying and selling rates. For this specific simulation, there is only one high buying/selling time and one low buying/selling time. Code alterations can be made, however, to include many different buying and selling scenarios for specific regions.

9. **Off-peak demand time(s)** – this factor is accounted for in both TRNSYS and Excel. In TRNSYS a time span of when to use grid power and fill to the top the grid-cycling battery is set within the code. The subsequent cost of buying and selling power at this
time is then entered into Excel, and the energy use data from the simulation is then multiplied by these buying and selling rates. For this specific simulation, there is only one high buying/selling time and one low buying/selling time. Code alterations can be made, however, to include many different buying and selling scenarios for specific regions.

10. **AC load profile** – the AC load profile is accounted for in Excel. Using national data, the user can input the load characteristics of their residential system, which translates into load data for import into TRNSYS.

11. **DC load profile** - the DC load profile is accounted for in Excel. Using national data, the user can input the load characteristics of their residential system, which translates into load data for import into TRNSYS.

12. **DOD of batteries** – this factor is accounted for in the Power Manager component of TRNSYS. The code fixes the DOD of discharge of the batteries to the programmer-defined value of 25%.

13. **Number of Battery Cycles Allowed Per Day** – this factor is currently accounted for within the code of the Power Manager. For just the grid-cycled battery subsystem, the battery will cycle once per day. With the full system (solar, AC and DC loads), the battery will effectively be cycling more than once per day. With more system experimentation and optimization, an economical, fixed number of cycles per day can be determined and integrated into the Power Manager.
**Load Characteristics**

14. *AC load quantity* – the AC load quantity is accounted for in Excel. The interface allows users to input typical load data, and the open format allows users to add in any additional load quantities.

15. *AC load time* – this factor is accounted for in both TRNSYS and Excel. In Excel, the data is divided into one hour time steps. In TRNSYS, one can run the simulation in smaller time intervals, while defining that the supplied load data is in one hour intervals.

16. *AC load magnitude* – this factor is accounted for in Excel. The interface allows users to input typical load data, and the open format allows users to add in any additional load quantities.

17. *AC load efficiency* – this factor is accounted for by the user in Excel. The less the efficiency (among other factors), the greater the kWh usage will be per year.

18. *DC load quantity* – the DC load quantity is accounted for in Excel. The interface allows users to input typical load data, and the open format allows users to add in their specific load quantities.

19. *DC load time* – this factor is accounted for in both TRNSYS and Excel. In Excel, the data is divided into one hour time steps. In TRNSYS, one can run the simulation in smaller time intervals, while defining that the supplied load data is in one hour intervals.

20. *DC load magnitude* – this factor is accounted for in Excel. The interface allows users to input typical load data, and the open format allows users to add in any additional load quantities.

21. *DC load efficiency* – this factor is accounted for by the user in Excel. The less the efficiency (among other factors), the greater the kWh usage will be per year.
**Outer-System Design Criteria**

22. *User usage characteristics* – this factor is accounted for by the user in Excel. Average normalized load profiles of when occupants use energy is provided within Excel. These can easily be altered for more user-specific information.

23. *User affordability* – this factor is accounted for in Excel. Users input the cost of each component and aspect of the installation, which is then totaled.

24. *Site-specific characteristics (climate, orientation, etc.)* - this factor is accounted for in both TRNSYS and Excel. In TRNSYS, one can alter the weather data, slope of the panels, orientation of the panels, etc. for power output variations. In Excel, the varying aspects of the system will be represented within the installation costs.

25. *Electricity cost differential(s)* – this factor is accounted for in Excel. After the simulation is run, the resulting energy values over time can be inserted into the spreadsheet, at which point the electricity costs are calculated.

**Economics**

26. *Cost of solar panels* – this factor is accounted for in Excel. Users input the number of panels and the cost per panel.

27. *Cost of appliances / load equipment* – this factor is accounted for in Excel. Users input each component, the cost for each, and the number of each.

28. *Cost of battery storage* – this factor is accounted for in Excel. Users input the cost per battery and the number of batteries.

29. *Cost of remaining BOS components* – this factor is accounted for in Excel. Users input each component and the cost for each
30. Cost of installation – this factor is accounted for in Excel. This will vary significantly installation to installation, so the user will need to input their specific costs.

31. User usage profile – this factor is accounted for in Excel. Using national data, the user can input the load characteristics of their residential system, which translates into load data for import into TRNSYS. Users can alter these profiles to better reflect their own personal usage profiles.

32. Electricity prices – this factor is accounted for in Excel. Currently there is one high buying/high selling rate, and one low buying/low selling rate. This can be altered for area-specific electricity rates and structure.

Subsystems

33. Grid-Cycling Battery System (no solar, no loads) – this system is accounted for in TRNSYS. One inputs zero solar panels and zeros for load data, and the appropriate values for all other components.

34. Grid-Cycling Battery + Solar (no loads) - this system is accounted for in TRNSYS. One inputs zeros for load data, and the appropriate values for all other components.

35. Grid-Cycling Battery + AC Loads (no solar, no DC loads) – this system is accounted for in TRNSYS. One inputs zero solar panels and zeros for the DC load data, and the appropriate values for all other components.

36. Grid-Cycling Battery + DC loads (no solar, no AC loads) – this system is accounted for in TRNSYS. One inputs zero solar panels and zeros for AC load data, and the appropriate values for all other components.
37. *Grid-Cycling Battery + Solar + DC loads (no AC loads)* – this system is accounted for in TRNSYS. One inputs zeros for the AC load data, and the appropriate values for all other components.

38. *Grid-Cycling Battery + Solar + AC loads (no DC loads)* – this system is accounted for in TRNSYS. One inputs zeros for the DC load data, and the appropriate values for all other components.

39. *Grid-Cycling Battery + Solar + DC Loads + AC Loads* - this system is accounted for in TRNSYS. One inputs the appropriate values for all components.

### 5.5 Simulation development factor list

Following the development of the tool, the preliminary factor list was reorganized to describe when each factor was needed to be accounted for within each stage of the simulation development process.

These four stages are:

1. Preliminary System Design – this stage consists of the fundamental idea of the advanced energy management system, which is a grid-cycling battery with an electricity price differential.

2. System Design – based off of the fundamental idea of the advanced energy management system, and based off of site- and user-specific characteristics, the remaining system components are added and designed, including the solar panels and the loads, while taking into account the economics of the full system.
3. TRNSYS Model Development – once the system is designed, it is translated into TRNSYS and its components

4. Simulation Model Dynamics – the dynamics of this system are custom programmed within TRNSYS, and certain factors must be taken into particular account while doing this programming

Figure 5.18 shows the simulation development flow diagram of how and when these factors should be taken into account, with the following table stating in specific each factor at each stage.

5.18: Simulation development flow diagram

5.2: Simulation development factors list

<table>
<thead>
<tr>
<th>STAGE 1: Preliminary System Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amount of Energy Storage (2)</td>
</tr>
<tr>
<td>Electricity cost differential(s) (25)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>STAGE 2: System Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Solar Panels (1)</td>
</tr>
<tr>
<td>Incoming PV Power / Weather (7)</td>
</tr>
<tr>
<td>Load Characteristics (14-21)</td>
</tr>
<tr>
<td>User usage characteristics (22)</td>
</tr>
<tr>
<td>User affordability (23)</td>
</tr>
<tr>
<td>Site-specific characteristics (climate, orientation, etc.) (24)</td>
</tr>
</tbody>
</table>
5.6 Tool Development Conclusions

The main goal of this thesis is to explore and assess the abilities of the simulation program TRNSYS (Transient Energy System Simulation Tool) in modeling an advanced energy management system. To do this, a tool consisting of TRNSYS simulation models and an Excel spreadsheet interface was developed.

This tool consists of an Excel spreadsheet and two TRNSYS simulation models, and allows for appropriate data to be inserted into the simulation models, calculates costs of the systems, and compares the systems.

Using this tool will be one way of evaluating the simulation model creation process. Further, the process of creating this tool provided valuable information on how to create models and insight into how TRNSYS works for future models.
The creation of the typical photovoltaic system was made using completely pre-programmed components provided by the TRNSYS program, while the advanced energy management system was a combination of pre-programmed components and a custom-programmed component.

The following chapters provide information on the evaluation of the advanced energy simulation model based on insight from creating the tool and from using the tool, as well as an organized guide into how to create more accurate and robust models in the future with TRNSYS.
Chapter 6
Guide to Creating Accurate and Robust Models

Through the process of creating and debugging the TRNSYS simulation models for the typical photovoltaic system and the advanced energy management system, a number of barriers were identified that hindered the creation of accurate and robust models. Additionally, two alternate approaches to modeling this system, which could lead to more accurate and robust models, were identified.

To do this, first, the number of physical and economic factors that directly influence the final outcome of both a typical photovoltaic system and an advanced energy management system were determined. Next, a tool consisting of TRNSYS simulation models of each of these systems and an Excel spreadsheet interface was developed. Finally, with the insight gained from these processes, a guide to creating accurate and robust models for advanced energy management systems was written.

The identified approaches discussed in this section are:

Approach 1: the development of an actual advanced energy storage technology component, and an actual, complimenting time-programmable inverters and charge controller component

Approach 2: the development of an actual advanced energy storage technology component, and the development of a simplified Power Manager component representing the time-programmable inverter and charge controller
**Approach 3:** the use of an existing battery component, and the development of a complimenting, simplified Power Manager component (which was the approach taken in this simulation work.)

This section discusses these suggested approaches, identifies the current barriers for each, and explains specific work needed to successfully model the system within TRNSYS for each approach. Suggestions are provided based on the experience of creating the simulation models within TRNSYS, examining existing components, and conferring with current TRNSYS programmers.

### 6.1 Approach #1: Battery and MPPT components

Approach #1 is the development of an actual advanced energy storage technology component, and an actual, complimenting, economic-dependent control system, consisting of two time-programmable, MPPT inverters and charge controller.

**Reason to take this approach:**

This approach would be taken, in order to create the most accurate and robust models of this system. Further, the creation of the advanced energy storage technology component would allow for the use of this component in future simulations as a stand-alone component, thus allowing for greater modeling opportunities.
Current Major Barriers to this work:

The largest barriers to completing this approach are the:

1. Lack of comprehensive technical data on the mathematical behaviors of the advanced energy storage technology
2. Lack of control logic in relation to the advanced energy storage technology and this specific system
3. Lack of simulation modeling language expertise within TRNSYS and Fortran to successfully program these components without significant aid from TRNSYS programmers, or someone with extensive knowledge and expertise in simulation modeling and Fortran

How to complete this work for TRNSYS:

To complete this work for TRNSYS, a combination of creating the advanced energy storage technology component and a complimenting, MPPT component will be needed. Chapter 4 discussed the process of creating components within TRNSYS and the two distinct, yet overlapping, needs of creating a new component: the Fortran code of its mathematical behavior model and the proforma for creating the system simulation.

This section discusses the experimental work needed to gather required data for the coding, as well as the proforma considerations when linking it in the proposed system within TRNSYS. The consideration of both of these sections when developing the components will lead to successful component and system modeling.
Energy Storage Technology

To successfully create the energy storage component, a number of things need to happen. First, experimentation on the behaviors of the energy storage technology under system-specific dynamics and interaction is necessary. From such experimentation, technical data on the characteristics of the batteries can be collected, so as to translate the behaviors into mathematical models. For a battery, needed information for dynamic modeling includes:

- Appropriate internal algorithms
- I/V curves
- Discharge / charge characteristics
- Temperature effects on each of these aspects

Experiments to gather this type of information generally take into account the environment and system in which the batteries will be subjected, so as to properly translate behaviors into mathematical models. Therefore, it is suggested that battery testing be done within system-specific constraints.

Based off the end modeling needs of TRNSYS, two approaches can be taken to test and experiment for appropriate models. As this technology is a mixed collection of lithium ion batteries, a combined model of the electrochemical responses to charging and discharging of the lithium ion batteries in conjunction with the controls on the battery can be one approach.

However, the experiment could be setup to treat the battery pack as a “black box”; thus, characteristics can be defined as an input/output response, as opposed to
dissecting the battery to determine exact control logic and internal battery workings. This would more greatly simplify the experiments, while still obtaining enough information to effectively model the battery within the given system.

Additionally, due to the unique architecture of the battery, extra considerations for developing the components and simulation models will need to be taken into account. The largest consideration is the two input and output terminals on the battery pack. This will then be reflected in the proforma of the battery component within TRNSYS.

These unique characteristics may also affect its interoperability with existing components, including the MPPT inverters and charge controller. Thus, these components will need to be specifically programmed with this battery configuration in mind.

**Battery Proforma considerations**

Unlike typical battery components, this specific advanced energy management technology would need additional characteristics added to its proforma. Code variables would then be based off of these parameters, inputs, and outputs.

Through the experience of creating the simulations, and based off examinations of the TYPE 185 battery component, which is a lead-acid battery with gassing effects, and the TYPE 47b battery component, which is a lead-acid battery based off of Shepherd’s equations, suggested parameters for the advanced energy storage technology component are:

- Nominal battery capacity of one battery pack
- Number of battery packs
The typical input for a battery component is either “Power to/from the Battery” or “Current to/from the Battery”, depending on the modeling needs of the user. Due to this specific battery architecture and its ability to charge and discharge at the same time, suggested inputs are:

- Power (or current) to the battery (charging)
- Power (or current) from the battery (discharging)

Suggested outputs for this battery component are:

- Power (or current) to the battery (charging)
- Power (or current) from the battery (discharging)
- State of charge
- Fractional state of charge
- Power lost during charge
- Total current
- Total voltage
- Max. Power for charge
- Max. Power for discharge
- Discharge cutoff voltage (DCV)
- Power corresponding to DCV
- Charge cutoff voltage (CCV)
- Power corresponding to CCV

**MPPT Inverters and Charge Controller**
Due to the power flow decisions based on grid economics and the unique ability to charge and discharge at the same time, a custom controller component that compliments this battery technology would be needed. The closest component to this currently within TRNSYS is the TYPE 48c, a combination component of two maximum power point tracking inverters (DC to AC and AC to DC) and a charge controller (DC to DC) for a system with battery storage, and which tracks both the state of charge and the state of voltage of the battery.

This component currently acts without regard to economics – it operates solely based on incoming loads and battery state of charge. It also is programmed for a typical battery in mind, i.e. one that cannot charge and discharge at the same time.

In order to program this component, experimentation and optimization of this type of system will be needed. A greater understanding of the decisions made, and why those decisions are made, needs to be determined, in order to create the most robust model.

Considerations into how the decisions are made include:

- Cost of electricity throughout the day
- Time of day / amount of solar power coming in
- Price differential to justify buying/selling
- Cost of the battery pack
- State of charge / voltage of the battery

Further, the coding style can be adapted from the TYPE 48c component.

**MPPT Inverters and Charge Controller Proforma Considerations**
With controls based on economics, alterations to the proforma would be necessary. Based off the needs of the system and the TYPE 48c MPPT controller component, suggested parameters for the economic-dependent MPPT include:

- Regulator efficiency (DC to DC)
- Inverter efficiency (DC to AC)
- Power output limit (based on inverter capacities)
- Inverter efficiency (AC to DC)
- Current for grid charging of battery

Further, as the power flow decisions of the battery are based on economic information, the opportunity to specify electricity costs should be included. Such parameters of the system would include:

- Electricity buying rates for every hour (1 to 24)
- Electricity selling rates for every hour (1 to 24)
- Cost of each battery pack

Internal controls, based upon optimization experiments for the system, would base decisions off of economics and internally calculate variables currently inputted into the TYPE 48c, which include:

- High limit on fractional state of charge (FSOC) (0 to 1)
- Low limit on FSOC (0 to 1)
- Charge to discharge limit on FSOC
- Upper limit on FSOC for grid charging

*Benefits to this approach:*
This approach would provide the most accurate and robust models. It is also the approach that most closely fits with the strengths and modular style of TRNSYS. Additionally, by having both of these components within the TRNSYS library, greater simulation models can be made that utilize these components.

**Drawbacks to this approach:**

This is the most time consuming approach, as it will not only require the commissioning of TRNSYS programmers and/or someone with extensive knowledge on simulation modeling and Fortran, but also extensive experimentation and optimization studies of the components and proposed systems.

6.2 **Approach #2: Advanced Energy Storage Technology Model + Simplified Power Manager**

Approach #2 is the development of an actual advanced energy storage technology component, and the development of a simplified Power Manager component that represents two time-programmable inverters and a charge controller.

**Reason to take this approach:**

This approach would be taken if battery testing is anticipated but system optimization experiments have not been performed. This approach would provide more accurate dynamics for the charging and discharging characteristics of the battery technology for the system. By having a simplified controlling component, system
optimization experiments can be significantly reduced, while still representing the general dynamics of the system.

*Current major barriers to completing this work:*

   The current major barriers to completing this work are:

   1. Lack of comprehensive technical data on the mathematical behaviors of the advanced energy storage technology
   2. Lack of in-depth information on how control decisions are made in relation to the advanced energy storage technology, grid economics, and this specific system
   3. Lack of simulation modeling language expertise within TRNSYS and Fortran to successfully program these components without significant aid from TRNSYS programmers or someone with extensive knowledge and expertise in simulation modeling and Fortran

*How to complete this work for TRNSYS:*

   The first step towards completing this work is to create the advanced energy management technology component. Steps on how to complete this work are described in Approach 1.

   The second step towards completing this work is the creation of a simplified Power Manager component. Unlike the “actual” MPPT controller component that was described in Approach 1, exact mathematical equations of the behavior of the component,
based on various inputs, are not needed. Rather, a general understanding of where power should go at varying times is necessary.

For the “actual” MPPT controller component, when it is time for a specific subroutine (charging, discharging, providing power to a load, etc.), inputs are put into the characteristic equations, and an appropriate output to achieve this action is sent to the respective component.

However, for the simplified controller, it is looked at “backwards”, as in, an empirically found output is defined that achieves the desired action.

For example, if the action to be performed is to fully discharge the battery, the actual MPPT controlling component would go to the subroutine that describes discharging; state of charge, voltage and temperature readings from the battery would be inputted into characteristic equations that describe discharge characteristics; and a resulting power or current output that discharges the battery would be sent to the battery component.

With the simplified Power Manager, to fully discharge the battery, a power or current input that was empirically determined by the programmer to achieve the desired results is delivered to the battery over a certain time period. This value can be a function of inputs, however that is not required. An example piece of code is:

IF (Time.GE.10.AND.Time.LE.12) THEN !if it is between 10am and noon

        Power_Output_to_Battery = -5 !a -5W power draw is delivered to the battery over this time period, which achieves the result of completely discharging the battery over this two hour time period
In writing the code in this way, the issue of robustness comes into play. With the above code example, this may work best, for example, if the battery were full. Along the same lines, it may not work as well if the battery is nearly completely discharged, in which case the battery could either go below the allowed depth of discharge or the simulation could run into convergence errors.

**Proforma considerations**

Depending on how simplified power management decisions are made, which could be made based off of a number of varying factors, including economic inputs, time of day, state of charge of the battery, state of voltage of the battery, incoming solar power, magnitude of the loads, etc., the proforma for this component can vary significantly.

Based on the creation of the simplified Power Manager component for the simulation work, and based off the considerations of the battery technology, suggested baseline parameters for this component, which would be needed to effectively link within the simulation, are:

- Efficiency of Inverter, DC to AC
- Efficiency of Inverter, AC to DC
- Efficiency of Charge Controller, DC to DC

Baseline inputs are:

- Power from the PV
- AC load
• DC load

Potential inputs are:

• State of charge of the battery
• State of voltage of the battery
• Remaining battery capacity
• Time of day
• Costs of electricity
• Cost of battery packs

Minimum outputs are:

• Grid electricity counter
• Power (or current) to the battery
• Power (or current) from the battery

Benefits of this approach:

This approach is less time consuming than Approach 1, as it does not require the experimentation for system optimization. It also allows for simplified code for the decisions made, while still getting a more accurate representation of the charge and discharge characteristics of the battery.

Drawbacks to this approach:

A main issue with this approach is the potential lack of robustness with the code of the simplified Power Manager, particularly the simpler the coding. Experiments on the battery will also be time consuming.
6.3 Approach #3: Existing battery and simplified Power Manager component

Approach #3 is the use of an existing battery component and the development of a simplified, complimenting Power Manager component.

*Reason to take this approach:*

This approach is the least time consuming approach and requires the least amount of outside experimentation. This approach also allows for a general representation of the dynamics, for general analysis and comparison of dynamics.

*Current Major Barriers to this work:*

The major barriers to completing this work are the:

1. Lack of in-depth information on how control decisions are made in relation to the advanced energy storage technology, grid economics, and this specific system

2. Lack of simulation modeling language expertise within TRNSYS and Fortran to create robust code

3. Lack of data on the system to show if simulation is performing like an actual system

*How to complete this work for TRNSYS:*

This approach was taken for this thesis work. Steps on how to complete this work are found in Chapter 4, and an analysis of this work is found in Chapter 7.
Benefits to taking this approach:

The benefits to taking this approach are that, if well-programmed, one can create a simulation that uses novice-friendly coding language and structure. Further, it requires the least amount of technical data on the system, which allows for programming based off system behavior observations; thus, a simulation can still be made based off of as much available information as possible. Finally, it provides enough of a simulation to begin preliminary analyses to other systems.

Drawbacks to taking this approach:

There are a number of drawbacks to this approach. The major drawback is the lack of robustness in the code, as developed outputs to achieve a desired result may not achieve that result in every case.

Further, the Power Manager needs to be written to best interact with the given battery component, which may or may not be of comparable dynamic to the advanced energy management system. For example, lead acid batteries have longer charging and discharging times, which alters the dynamics of the system during these times. Also, existing batteries cannot charge and discharge at the same time, requiring a net difference in or out, instead of how the battery technology is actually behaving. Finally, the programmer is constrained by the allowable parameters of that battery type, such as the current and voltage allowable per cell, which adds a new dimension of system constraint when programming the Power Manager to move incoming power.
6.4 Conclusions

The purpose of this chapter was to identify and organize the barriers found that hindered the creation of accurate and robust advanced energy management system simulations in the program TRNSYS. Concurrently, three approaches to creating the models were identified, with barriers and required work noted for each.

The main barriers were the current lack of technical data on the system and the battery storage technology, as well as the need for greater expertise in programming robust code within TRNSYS.
Chapter 7

Conclusions

7.5 Summary of work

The main goal of this thesis is to determine appropriate ways to model advanced energy management systems within the simulation program TRNSYS (Transient Energy System Simulation Tool).

To do this, first, the number of physical and economic factors that directly influence the final outcome of both a typical photovoltaic system and an advanced energy management system were determined. Next, a tool consisting of TRNSYS simulation models of each of these systems and an Excel spreadsheet interface was developed. Finally, with the insight gained from these processes, a guide to creating accurate and robust models for advanced energy management systems was written.

The first step, leading up to the creation of the tool, an analysis of all relevant physical and economic factors that have a direct influence on the final outcome of the system was performed, and all factors were identified, categorized, and listed, as discussed in Chapter 4. This list was then used to account for all factors when creating the tool.

The next step was the creation of the tool. The goals of the tool were to:

4) Properly account for all user-and system-specific inputs for the simulation models, as identified in Chapter 4
5) Provide the context of comparing the performance of the advanced energy management system with the typical system under the same user- and system-specific set of constraints

6) Allow for easy and flexible input and output of data to and from the simulation models

The tool consists of TRNSYS simulation models of both a typical photovoltaic system and an advanced energy management system, as well as an Excel spreadsheet interface containing load profile data on residential energy use throughout the day, electricity costs, and system costs.

Within the creation of the tool, first, the typical photovoltaic system simulation was completed, and the insight gained from this process was used to create the advanced energy management system simulation. This advanced energy management simulation required custom programming of components and additional software to complete.

Finally, through the process of creating and testing the TRNSYS simulation models for the typical photovoltaic system and the advanced energy management system, a number of barriers were identified that hindered the creation of accurate and robust models. Additionally, two alternate approaches to modeling this system, which could lead to more accurate and robust models, were identified.
7.6 Contributions

The biggest contribution by this thesis is the suggested procedures on how to make successful advanced energy system simulation models within TRNSYS.

By creating these two simulation models, the way in which TRNSYS typically works was identified, and the process for creating new components was explored and analyzed. Simultaneously, the data needed for creating the full advanced energy management systems was identified, and, depending on the level or amount of data collected, three approaches to creating these simulations were explained.

This contribution can be used by those seeking to create accurate and robust models, in order to properly lead both the experiments and data collection, as well as those with expertise in programming and TRNSYS.

7.7 Limitations

Through the process of creating the TRNSYS simulation model for the advanced energy management system, a number of challenges arose, which then directly contributed to the suggestions provided within the guide and suggestions for future work.

Due to a number of challenges, the original advanced energy simulation model did not properly run. However, despite this setback, insight gained through this challenging process proved more valuable to the development of the guide and future work suggestions than had it successfully run.

The largest factor that contributed to the challenge, and which directly influenced the guide and future work suggestions, was the lack of mathematical and technical data
about the system. Experiments and optimizations studies have not been performed for a solar, grid-integrated battery system with both AC and DC loads, and the setup of the system in Gettysburg, from which data can be collected, is yet to be complete.

Because of the lack of experimental data, decisions made by the Power Manager were developed based on observations of how the system could theoretically perform, as opposed to how they actually performed in a mathematical fashion.

Further, because of the lack of equations or mathematical behavior, empirical, simplified factors derived by the programmer to induce the desired result were necessary. For example, in charging and discharging, a constant current value was set during these time periods, instead of using an equation that would account for the varying voltages or temperature changes that would occur during such a charging or discharging time.

In combination with the mathematical complexity of the inner-workings and programming of battery components, this empirically-derived Power Manager lead to robustness challenges within the simulation. The approach for programming the Power Manager was based off an example Power Manager component written by a TRNSYS programmer which did not include batteries. The only other existing Power Manager coded by TRNSYS programmers that contained interaction with a battery was proprietary code, thus no insight or coding styles were able to be obtained.

Finally, as the lack of technical data and the complexity of the commercially-available iCeL battery packs proved it impossible to program this technology into TRNSYS at the time of this research, the dynamics of the system had to be translated within the constraints of the existing lead-acid battery component. This meant that a net value of the batteries either delivering or receiving power had to be accounted for within
the Power Manager, instead of simultaneously charging and discharging. Charging and
discharging times of the lead acid battery, which are significantly longer than the lithium
ion technology batteries, had to be accommodated for within this simulation.

However, the setup of experiments and optimization studies of the system; the
gathering of data from the system in Gettysburg; and, in close collaboration with actual
TRNSYS programmers, the programming of the actual lithium ion battery technology,
would all result in much more accurate and robust models in whichever approach is taken
to model it.

7.4 Future Work

In order to make future advanced energy management simulations through
TRNSYS better, there are a number of suggestions for future work.

The top future work suggestions are to perform experiments on the system, so as
to obtain the characteristic equations. Additionally, optimization studies, so as to
determine the best energy management decisions for myriad situations, are highly
suggested. Concurrently, the installation and data gathering from the installation of more
systems would contribute highly to testing the accuracy of the simulation models.

Once this data is obtained, a greater collaboration and input from TRNSYS
programmers would be beneficial in making the simulations robust and without running
and convergence errors.

Within the coding of either the time-programmable inverters, the Power Manager
component, or the battery itself, a set number of cycles per day should be set, based upon
results from the aforementioned experiments. This will be a critical factor in the lifecycle and economics of the system, and will ultimately affect energy management decisions made throughout the day.

Having an easier way to input time of use rate structures would also be useful. Currently timeframes are set within the Fortran coding of the Power Manager code. Having the possibility to input the timeframes into the proforma of the component would allow for greater applications and adaptation to changing electricity rate structures.

Additionally, the ability to input more situational load profiles, such as holidays, weekends, or week by week load profiles, may help better simulate and represent an actual system.

Once accurate and robust models are completed, a suggested step is converting the TRNSYS simulation into a .exe file. TRNSYS has the capability to make simulations into an .exe format that anyone can then run on their computer. This would allow for an interface in which one can type in the specifications of the solar panels, batteries, etc. Load profiles would still need to be created and inputted. However, this would allow a much more user-friendly way of inputting component parameters, as well as allowing more people to access the simulations.

Further, to account for the economic factors over the lifetime of the system, a greater economic analysis and model can be performed and created.

With the gained expertise in creating the accurate and robust models within the scope of this system, other systems can be incorporated and modeled. This includes the integration of an electric car into the dynamics, a hybrid wind system, or other hybrid energy systems.
Bibliography


40. Figure 2.1a: Energy consumption by sector overview. (2006). Energy Information Administration. Retrieved May 22, 2008 from 


   <http://www1.eere.energy.gov/solar/program_planning.html>.
Appendix A

FORTRAN Power Manager Code

C***************************************************
C Object: Advanced Power Manager
C Simulation Studio Model: new power manager
C
C Author: Sarah Klinetob
C Editor:
C Date: October 01, 2008 last modified: December 12, 2008
C
C ***
C *** Model Parameters
C ***
C Efficiency of Inverter, DC to AC - [0;1]
C Efficiency of Charger, AC to DC - [0;1]
C Time Step - [-Inf;+Inf]
C
C ***
C *** Model Inputs
C ***
C Hour any [1;24]
C Battery Capacity (Ah) - [-Inf;+Inf]
C State of Charge (Ah) - [0;+Inf]
C Fractional SOC - [0;1]
C Power from PV (W) - [0;+Inf]
C DC Energy (kWh) - [0;+Inf]
C AC Energy (kWh) - [0;+Inf]
C Battery Voltage - [-Inf;+Inf]
C
C ***
C *** Model Outputs
C ***
C Current Output to the Battery - [-Inf;+Inf]
C Excess Energy from PV - [0;+Inf]
C Final Grid Counter - [-Inf;+Inf]
C Energy from Grid to Battery - [-Inf;+Inf]
C Energy to Grid from Battery - [0;+Inf]
C Energy to the Grid from PV - [0;+Inf]
C Energy from Grid to Load - [-Inf;+Inf]
C
C ***
C *** Model Derivatives
C ***
C
C (Comments and routine interface generated by TRNSYS Studio)
C***************************************************  **
C TRNSYS acess functions (allow to acess TIME etc.)
USE TrnsysConstants
USE TrnsysFunctions

C---------------------------------------------------------------------
---------------------------------------------------------------------
C REQUIRED BY THE MULTI-DLL VERSION OF TRNSYS
!DEC$ATTRIBUTES DLLEXPORT :: TYPE204 !SET
THE CORRECT TYPE NUMBER HERE
C---------------------------------------------------------------------
---------------------------------------------------------------------
C---------------------------------------------------------------------
---------------------------------------------------------------
C TRNSYS DECLARATIONS
IMPLICIT NONE !REQUIRES THE USER TO DEFINE ALL
VARIABLES BEFORE USING THEM

  DOUBLE PRECISION XIN !THE ARRAY FROM WHICH THE INPUTS TO THIS
   TYPE WILL BE RETRIEVED
  DOUBLE PRECISION OUT !THE ARRAY WHICH WILL BE USED TO STORE
   THE OUTPUTS FROM THIS TYPE
  DOUBLE PRECISION TIME !THE CURRENT SIMULATION TIME - YOU MAY
   USE THIS VARIABLE BUT DO NOT SET IT!
  DOUBLE PRECISION PAR !THE ARRAY FROM WHICH THE PARAMETERS FOR
   THIS TYPE WILL BE RETRIED
  DOUBLE PRECISION STORED !THE STORAGE ARRAY FOR HOLDING VARIABLES
   FROM TIMESTEP TO TIMESTEP
  DOUBLE PRECISION T !AN ARRAY CONTAINING THE RESULTS
   FROM THE DIFFERENTIAL EQUATION SOLVER
  DOUBLE PRECISION DTDT !AN ARRAY CONTAINING THE DERIVATIVES TO
   BE PASSED TO THE DIFF.EQ. SOLVER
  INTEGER*4 INFO(15) !THE INFO ARRAY STORES AND PASSES
   VALUABLE INFORMATION TO AND FROM THIS TYPE
  INTEGER*4 NP,NI,NOUT,ND !VARIABLES FOR THE MAXIMUM NUMBER OF
   PARAMETERS,INPUTS,OUTPUTS AND DERIVATIVES
  INTEGER*4 NPAR,NIN,NDER !VARIABLES FOR THE CORRECT
   NUMBER OF
  INTEGER*4 IUNIT,ITYPE !THE UNIT NUMBER AND TYPE NUMBER FOR THIS
   COMPONENT
  INTEGER*4 ICNTRL !AN ARRAY FOR HOLDING VALUES OF CONTROL
   FUNCTIONS WITH THE NEW SOLVER
  INTEGER*4 NSTORED !THE NUMBER OF VARIABLES THAT WILL BE
   PASSED INTO AND OUT OF STORAGE
  CHARACTER*3 OCHECK !AN ARRAY TO BE FILLED WITH THE
   CORRECT VARIABLE TYPES FOR THE OUTPUTS
  CHARACTER*3 YCHECK !AN ARRAY TO BE FILLED WITH THE
   CORRECT VARIABLE TYPES FOR THE INPUTS
C---------------------------------------------------------------------
---------------------------------------------------------------------
C USER DECLARATIONS - SET THE MAXIMUM NUMBER OF PARAMETERS (NP),
  INPUTS (NI),
PARAMETER (NP=3, NI=8, NOUT=7, ND=0, NSTORED=0)

DIMENSION XIN(NI), OUT(NOUT), PAR(NP), YCHECK(NI), OCHECK(NOUT),
1 STORED(NSTORED), T(ND), DTDT(ND)
INTEGER NITEMS

PARAMETERS
DOUBLE PRECISION Efficiency_DC_to_AC
DOUBLE PRECISION Efficiency_AC_to_DC
DOUBLE PRECISION Time_Step

INPUTS
DOUBLE PRECISION Hour
DOUBLE PRECISION Battery_Capacity
DOUBLE PRECISION State_of_Charge
DOUBLE PRECISION Fractional_SOC
DOUBLE PRECISION Power_PV
DOUBLE PRECISION DC_Energy
DOUBLE PRECISION AC_Energy
DOUBLE PRECISION Battery_Voltage

INTERNAL VARIABLES
DOUBLE PRECISION Ah_at_25_SOC
DOUBLE PRECISION Ah_Available_in_Battery
DOUBLE PRECISION Energy_Needed_for_Loads

OUTPUTS
DOUBLE PRECISION Current_Output_to_Battery
DOUBLE PRECISION Energy_Excess
DOUBLE PRECISION Final_Grid.Counter
DOUBLE PRECISION Energy_from_Grid_to_Battery
DOUBLE PRECISION Energy_to_Grid_from_Battery
DOUBLE PRECISION Energy_to_Grid_from_PV
DOUBLE PRECISION Energy_from_Grid_to_Load

READ IN THE VALUES OF THE PARAMETERS IN SEQUENTIAL ORDER

Efficiency_DC_to_AC = PAR(1)
Efficiency_AC_to_DC = PAR(2)
Time_Step = PAR(3)
C--------------------------------------------------------------------------
--- RETRIEVE THE CURRENT VALUES OF THE INPUTS TO THIS MODEL FROM THE XIN ARRAY IN SEQUENTIAL ORDER

Hour = XIN(1)
Battery_Capacity = XIN(2)
State_of_Charge = XIN(3)
Fractional_SOC = XIN(4)
Power_PV = XIN(5)
DC_Energy = XIN(6)
AC_Energy = XIN(7)
Battery_Voltage = XIN(8)

IUNIT = INFO(1)
IUNIT = INFO(2)

C--------------------------------------------------------------------------
--- SET THE VERSION INFORMATION FOR TRNSYS

IF (INFO(7).EQ.-2) THEN
  INFO(12) = 16
  RETURN 1
ENDIF

C--------------------------------------------------------------------------
--- DO ALL THE VERY LAST CALL OF THE SIMULATION MANIPULATIONS HERE

IF (INFO(8).EQ.-1) THEN
  RETURN 1
ENDIF

C--------------------------------------------------------------------------
--- PERFORM ANY 'AFTER-ITERATION' MANIPULATIONS THAT ARE REQUIRED HERE

C e.g. save variables to storage array for the next timestep

IF (INFO(13).GT.0) THEN
  NITEMS = 0
  STORED(1) = ... (if NITEMS > 0)
  CALL setStorageVars(STORED, NITEMS, INFO)
  RETURN 1
ENDIF

C--------------------------------------------------------------------------
--- DO ALL THE VERY FIRST CALL OF THE SIMULATION MANIPULATIONS HERE

IF (INFO(7).EQ.-1) THEN
C       SET SOME INFO ARRAY VARIABLES TO TELL THE TRNSYS ENGINE HOW
THIS TYPE IS TO WORK
   INFO(6)=NOUT
   INFO(9)=1
   INFO(10)=0       !STORAGE FOR VERSION 16 HAS BEEN CHANGED

C       SET THE REQUIRED NUMBER OF INPUTS, PARAMETERS AND DERIVATIVES
THAT THE USER SHOULD SUPPLY IN THE INPUT FILE
C       IN SOME CASES, THE NUMBER OF VARIABLES MAY DEPEND ON THE VALUE
OF PARAMETERS TO THIS MODEL....
   NIN=NI
   NPAR=NP
   NDER=ND

C       CALL THE TYPE CHECK SUBROUTINE TO COMPARE WHAT THIS COMPONENT
REQUIRES TO WHAT IS SUPPLIED IN
C       THE TRNSYS INPUT FILE
   CALL TYPECK(1,INFO,NIN,NPAR,NDER)

C       SET THE NUMBER OF STORAGE SPOTS NEEDED FOR THIS COMPONENT
   NITEMS=0
   CALL setStorageSize(NITEMS,INFO)

C       RETURN TO THE CALLING PROGRAM
   RETURN 1

ENDIF
C---------------------------------------------------------------------------------
OUT(4)=0
C    Energy to Grid from Battery
OUT(5)=0
C    Energy to the Grid from PV
OUT(6)=0
C    Energy from Grid to Load
OUT(7)=0
C    Energy to Battery from Grid
OUT(8)=0
C    Energy from Battery to Grid
OUT(9)=0

C    PERFORM ANY REQUIRED CALCULATIONS TO SET THE INITIAL STORAGE
VARIABLES HERE
   NITEMS=0
C    STORED(1)=...
C    PUT THE STORED ARRAY IN THE GLOBAL STORED ARRAY
C   CALL setStorageVars(STORED,NITEMS,INFO)
C    RETURN TO THE CALLING PROGRAM
RETURN 1

ENDIF
C-----------------------------------------------------------------------------------
C-----------------------------------------------------------------------------------
C    *** ITS AN ITERATIVE CALL TO THIS COMPONENT ***
C-----------------------------------------------------------------------------------
C-----------------------------------------------------------------------------------
C    RETRIEVE THE VALUES IN THE STORAGE ARRAY FOR THIS ITERATION
C    NITEMS=
C    CALL getStorageVars(STORED,NITEMS,INFO)
C-----------------------------------------------------------------------------------
C-----------------------------------------------------------------------------------
C    CHECK THE INPUTS FOR PROBLEMS
C    IF(...) CALL TYPECK(-3,INFO,'BAD INPUT #',0,0)
C    IF(IERROR.GT.0) RETURN 1
C-----------------------------------------------------------------------------------
C-----------------------------------------------------------------------------------
C    *** PERFORM ALL THE CALCULATION HERE FOR THIS MODEL. ***
C-----------------------------------------------------------------------------------
ADD YOUR COMPONENT EQUATIONS HERE; BASICALLY THE EQUATIONS
THAT WILL
CALCULATE THE OUTPUTS BASED ON THE PARAMETERS AND THE
INPUTS.
REFER TO
CHAPTER 3 OF THE TRNSYS VOLUME 1 MANUAL FOR DETAILED
INFORMATION ON
WRITING TRNSYS COMPONENTS.

C

Ah_at_25_SOC = .25 * Battery_Capacity !(Ah)

IF (Hour.GE.4.AND.Hour.LE.19) THEN

C

IF (Fractional_SOC.GE.50) THEN

C

IF there is more solar power than needed to meet the loads,
meet all loads with PV power and give rest to the grid

IF (Power_PV / 1000 * Time_Step.GE.(AC_Energy / & Efficiency_DC_to_AC + DC_Energy)) THEN

! Energy_Excess = (Power_PV / 1000 * Time_Step) - & ! (AC_Energy / Efficiency_DC_to_AC + DC_Energy)

! Energy_to_Grid_from_PV = Energy_Excess *
& ! Efficiency_DC_to_AC

Energy_from_Grid_to_Battery = 0
Current_Output_to_Battery = -5

! Final_Grid_Counter = Energy_to_Grid_from_PV

ELSE ! not enough solar power

Energy_Excess = 0
Energy_to_Grid_from_PV = 0

! Energy_Needed_for_Loads = (AC_Energy / & ! Efficiency_DC_to_AC + DC_Energy) - & ! (Power_PV / 1000 * Time_Step)

Ah_Available_in_Battery = State_of_Charge - & Ah_at_25_SOC

IF (Energy_Needed_for_Loads.LE.Battery_Voltage * & Ah_Available_in_Battery) THEN

Current_Output_to_Battery = -10
& !- (Energy_Needed_for_Loads / 1000 / Battery_Voltage * Time_Step)

Final_Grid_Counter = 0
! here, all demand was just met by the battery,
and the ac load inefficiency was accounted for
ELSE

! here, I should probably have another
! efficiency factor, but i've combined my demands, sooo yeah

Current_Output_to_Battery = -15
& ! (Ah_Available_in_Battery * Battery_Voltage
* & !Time_Step)

! Energy_from_Grid_to_Load =
& ! (Energy_Needed_for_Loads -
& ! (Ah Available_in_Battery / 1000 *
& ! Battery_Voltage))

Final_Grid_Counter = Energy_from_Grid_to_Load

END IF

END IF

C Now if the battery is between 25% and 50% charged, then excess PV
power will go to the batteries
C Demand is still met primarily by the solar panels

ELSE IF (Fractional_SOC.GE.25.LT.50) THEN

IF (Power_PV / 1000 * Time_Step.GE.(AC_Energy /
& Efficiency_DC_to_AC + DC_Energy)) THEN

! Energy_Excess = (Power_PV / 1000 * Time_Step) -
& ! (AC_Energy / Efficiency_DC_to_AC + DC_Energy)

IF (Energy_Excess.LE.(Battery_Capacity -
& Ah_Available_in_Battery) * Battery_Voltage) THEN

Current_Output_to_Battery = 5 !Energy_Excess /
& !Battery_Voltage * Time_Step

Energy_from_Grid_to_Battery = 0
Energy_to_Grid_from_PV = 0

Final_Grid_Counter = 0

ELSE

!(Battery_Capacity -
C & !Ah Available_in_Battery) / Battery_Voltage /
C & !Time_Step

! Energy_to_Grid_from_PV = (Energy_Excess -
& ! (Current_Output_to_Battery / 1000 *
& ! Battery_Voltage * Time_Step)) *
& ! Efficiency_DC_to_AC
Final_Grid_Counter = Energy_to_Grid_from_PV

END IF

ELSE  !if not enough solar power to meet both demands

Energy_Excess = 0
Energy_to_Grid_from_PV = 0

! Energy_Needed_for_Loads = (AC_Energy / &
! Efficiency_DC_to_AC + DC_Energy) -
&
! (Power_PV / 1000 * Time_Step)

Ah_Available_in_Battery = State_of_Charge - &
Ah_at_25_SOC

IF (Energy_Needed_for_Loads.LE.Battery_Voltage * &
& Ah_Available_in_Battery) THEN

Current_Output_to_Battery = 15
& ! (Energy_Needed_for_Loads / 1000 / &
C & !Battery_Voltage * Time_Step)

Final_Grid_Counter = 0
! here, all demand was just met by the battery, &
and the ac load inefficiency was accounted for

ELSE  ! here, I should probably have another

! efficiency factor, but i've combined my demands, sooo yeah

Current_Output_to_Battery = 12
& ! (Ah_Available_in_Battery * Battery_Voltage &
C & / &
C & !Time_Step)

! Energy_from_Grid_to_Load = &
& ! (Energy_Needed_for_Loads - &
& ! (Ah_Available_in_Battery / 1000 * &
& ! Battery_Voltage))

Final_Grid_Counter = Energy_from_Grid_to_Load

END IF

END IF

C Now, if the batteries are below 25% SOC then we shut them off and get 
everything from the PVs or the grid

ELSE IF (Fractional_SOC.LT.25) THEN

!IF (Power_PV / 1000 * Time_Step.GE.(AC_Energy / &
& !Efficiency_DC_to_AC + DC_Energy)) THEN

! Energy_Excess = (Power_PV / 1000 * Time_Step) -
IF (Energy_Excess.LE.(Battery_Capacity - Ah_Available_in_Battery) * Battery_Voltage) THEN

! Current_Output_to_Battery = 25 !Energy_Excess

! Battery_Voltage * Time_Step

! Energy_from_Grid_to_Battery = 0
! Energy_to_Grid_from_PV = 0

Final_Grid_Counter = 0

ELSE

Current_Output_to_Battery = 30

!(Battery_Capacity - Ah_Available_in_Battery) / Battery_Voltage * Time_Step

! Energy_to_Grid_from_PV = (Energy_Excess - ! (Current_Output_to_Battery / 1000 * ! Battery_Voltage * Time_Step)) * ! Efficiency_DC_to_AC

!Final_Grid_Counter = Energy_to_Grid_from_PV

END IF

ELSE !if not enough solar power to meet both demands

Energy_Excess = 0
Energy_to_Grid_from_PV = 0

! Energy_Needed_for_Loads = (AC_Energy / ! Efficiency_DC_to_AC + DC_Energy) - ! (Power_PV / 1000 * Time_Step)

! could use another efficiency thing here
Final_Grid_Counter = - (Energy_Needed_for_Loads)

END IF

END IF

ELSE

Current_Output_to_Battery = 0

END IF

C-----------------------------------------------------------------------------
-----------------------------------------------------------------------------
C-------------------------------------------------------------------
---------------------------------------------------------------------
C SET THE STORAGE ARRAY AT THE END OF THIS ITERATION IF NECESSARY
C
NITEMS=
STORED(1)=
CALL setStorageVars(STORED,NITEMS,INFO)
---------------------------------------------------------------------
---------------------------------------------------------------------
C REPORT ANY PROBLEMS THAT HAVE BEEN FOUND USING CALLS LIKE THIS:
C
CALL MESSAGES(-1,'put your message here','MESSAGE',IUNIT,ITYPE)
CALL MESSAGES(-1,'put your message here','WARNING',IUNIT,ITYPE)
CALL MESSAGES(-1,'put your message here','SEVERE',IUNIT,ITYPE)
CALL MESSAGES(-1,'put your message here','FATAL',IUNIT,ITYPE)
---------------------------------------------------------------------
---------------------------------------------------------------------
C SET THE OUTPUTS FROM THIS MODEL IN SEQUENTIAL ORDER AND GET OUT
C
Current Output to the Battery
   OUT(1)=Current_Output_to_Battery
Excess PV Energy
   OUT(2)=Energy_Excess
Final Grid Counter
   OUT(3)=Final_Grid_Counter
Energy from Grid to Battery
   OUT(4)=Energy_from_Grid_to_Battery
Energy to Grid from Battery
   OUT(5)=Energy_to_Grid_from_Battery
Energy to the Grid from PV
   OUT(6)=Energy_to_Grid_from_PV
Energy from Grid to Load
   OUT(7)=Energy_from_Grid_to_Load
---------------------------------------------------------------------
---------------------------------------------------------------------
C EVERYTHING IS DONE - RETURN FROM THIS SUBROUTINE AND MOVE ON
RETURN 1
END
C---------------------------------------------------------------------