COMPUTER SIMULATION FOR OPERATIONAL AND ECONOMICAL EVALUATION OF GRID CONNECTED BUILDING SCALE PHOTOVOLTAIC GENERATION SYSTEM UNDER CLIMATIC CONDITIONS OF JORDAN

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COMMITTEE DECISION

This Thesis (Computer Simulation for Operational and Economical Evaluation of Grid Connected Building Scale Photovoltaic Generation System under Climatic Conditions of Jordan) was Successfully Defended and Approved on May 7th, 2009.

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DEDICATION

To My Parents

ACKNOWLEDGMENT

I am grateful to my supervisor Prof. Mohammad A. Alsaad for the valuable discussions during the course of this study.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A	Annual monetary amount (currency)
A_i	Anisotropy index (dimensionless)
C_{pv}	Photovoltaic array rated capacity (kW)
E	Energy (kWh)
E_c	Storage charging energy (kWh)
E_d	Storage discharging energy (kWh)
$E_{inv,AC}$	Inverter output AC energy (kWh)
$E_{inv,DC}$	Inverter input DC energy (kWh)
E_{pv}	Photovoltaic array output energy (kWh)
$E_{rec,AC}$	Rectifier input AC energy (kWh)
$E_{rec,DC}$	Rectifier output DC energy (kWh)
E_s	Storage energy content (kWh)
E_t	Equation of time (minutes)
F	Future value (currency)
f_D	Derating factor (dimensionless)
G_o	Extraterrestrial radiation on a horizontal surface (kW/m^2)
G_{on}	Extraterrestrial normal radiation (kW/m^2)
G_{sc}	The solar constant (1.367 kW/m^2)
G_T	Irradiance (kW/m^2)
G_{TS}	Irradiance at standard conditions (1 kW/m^2)
i	Real interest rate
I	Hourly total irradiation on a horizontal surface (kWh/m^2)
I_b	Beam radiation (kWh/m^2)
I_d	Diffuse radiation (kWh/m^2)

I_o	Hourly extraterrestrial irradiation on horizontal surface (kWh/m^2)
I_T	Hourly total irradiation incident on a tilted surface (kWh/m^2)
k_T	Hourly clearness index (dimensionless)
L_{loc}	Longitude of the location (degrees)
L_{st}	Standard meridian of the current time zone (degrees)
n	Day number in year
N	Number of years
P	Present value (currency)
P_{av}	Average power (kW)
P_{pv}	Photovoltaic array output power (kW)
R_b	Ratio of beam radiation on titled surface to that on horizontal surface (dimensionaless)
t_{solar}	Solar time (hours)
$t_{standard}$	Standard time (hours)

ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
GIS	Geographical Information System
GMT	Greenwich Mean Time
GR	Ground Reflectance
JD	Jordanian Dinar
MPPT	Maximum Power Point Tracker
NREL	U.S. National Renewable Energy Laboratory
PVGIS	Photovoltaic Geographic Information System
toe	Tons of Oil Equivalent
USD	U. S. Dollar

GREEK LETTERS

β	Slope of the surface (degrees)
ϕ	Latitude angle (degrees)
γ	Azimuth of the surface (degrees)
δ	Sun declination angle (degrees)
Δt	Time step (hour)
η_c	Storage charging efficiency (dimensionless)
η_d	Storage discharging efficiency (dimensionless)
η_{inv}	Inverter efficiency (dimensionless)
η_{rec}	Rectifier efficiency (dimensionless)
θ	Angle of incidence (degrees)
θ_z	Zenith angle of the sun (degrees)
ρ_g	Ground reflectance (dimensionless)
ω	Hour angle (degrees)
ω_s	Sunset hour angle (degrees)

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ABSTRACT

A computer software application was constructed in this study to simulate the hourly energy flow of a grid connected photovoltaic system over a full year. The system model consists of a photovoltaic array, a converter and an optional energy storage component. The storage component supports scheduled charging/discharging for operation as a demand peak shaving unit. Besides hourly simulation results, daily, monthly and full year sums are recorded. This information is useful in assessing the operational value of the system in terms of its effect on the electrical demand profile of a building that uses it.

The simulation simultaneously finds the amount of energy exchanged with the electrical grid in two cases; a reference case that does not include the system and another case with it included. The financial benefit is calculated as the difference in grid energy cost between the two cases. The software weighs the financial benefit resulting from the system against its cost through a cost-benefit analysis.

With solar radiation amounts specific to Amman/Jordan, the produced software was used to investigate the effect of varying system parameters on its energy output and economical value. For example, the effect of array slope angle on yearly energy output was studied. The hourly resolution of results was used to demonstrate the effect of the system on local demand profile. Simulation runs under current electrical energy pricing in Jordan show that further reduction in system investment cost and/or suitably high energy sellback price are needed before it is considered economically feasible.

CHAPTER 1

INTRODUCTION

This study is motivated by the prospective benefits of distributed grid connected photovoltaic energy generation. Computer simulation is harnessed by constructing a software applicatoin that is useful in performing operational and economical evaluation of a proposed system. This chapter presents the study problem, scope and objectives. It ends by outlining the study approach and thesis organization.

1.1 Motivation

Conventional electric power systems are generally built around the scheme of central power generation. A power plant produces energy either by burning fossil fuels, utlilizing nuclear energy or using a renewable resource such as hydropower of a large dam. In either case, such a plant produces large amounts of energy and hence takes advantage of economies of scale. For logistical reasons and to minimize environmental impact on demand centers, power plants are usually constructed far away from cities. Power thus produced is transmitted over long transmission lines, and hence some of it is wasted as transmission losses. Normally, as demand for electrical power increases, existing power plants are expanded and new ones are commissioned.

This study is inspired by an alternative approach which effectively transforms power consumers connected to the electric grid into power producers. This approach is called distributed generation. At the consumer side, excess energy, as it occurs, is transfered to the electrical grid and any deficit at other times is supplied by that grid. In this way the grid effectively acts as a storage medium to the consumer. Although each such contributer produces a relatively small amount of energy compared to a power plant, the collective contribution of so many sources is significant and is envisioned to delay or even alleviate the need to build new central power plants. The contribution of energy consumers to the generation needs of the entire power system translates to lighter demand on central power stations. It also means lower transmitted power and hence less transmission losses.

Solar energy has many merits for usage in such a scheme. Being a clean source allows it to be utilized within demand centers without any local environmental impact. Solar energy is also a renewable resource; once a conversion system is installed it enjoyes a virtually free source of energy throughout its operating lifetime. Daily availability of solar energy generally matches well with peak demand for electrical energy. A photovoltaic solar energy conversion system operates noise-free and requires very little maintance, and hence it is particularly suitable for small scale distriubeted installations such as those which fit on the rooftops of typical buildings. The cumulative area of building rooftops within cities is large, and so receives a large amount of solar energy. Such area is usually unused for any competing purpose, and there is no cost of land acquisition that is otherwise associated with land installations of solar systems.

In 2007 Jordan consumed 3.03 million tons of oil equivalent (toe) for generation of electrical energy. This amount represented 41.8% of the Kingdom's total consumption of primary energy. That amount also reflected an increase by 12.5% over the 2.7 million toe consumed for the same purpose in 2006 (Electricity Regulatory Commission, 2007). Jordan, imports most of the needed primary energy. As energy prices from conventional fossil fuels rise, alternative renewable energy applications become more economically competitive.

1.2 Definition of the Problem and Importance

For a building that uses a grid connected photovoltaic system, the amount of energy withdrawn from or supplied to the electrical grid during a certain time interval, depends on both the amount of locally generated electrical energy and the amount of electrical load of the building during that time. The photovoltaic system supplies a net energy, and in the process modifies the demand profile of the building from the electrical grid perspective. Additionally, when the system includes a local energy storage medium, the demand profile can be modified further by controlling charging and discharging strategy of the storage medium.

While the solar energy resource is free, the conversion system is not. That warrants an economical evaluation of the viability of system adoption. A life cycle cost analysis is needed to determine if a proposed system is worthwhile. For a grid connected photovoltaic system, this analysis takes in consideration the cost of the system and the financial savings or revenue resulting from its use. The system design parameters (such as rated capacity of the photovoltaic array and its installation angles) and economical parameters (such as components cost and energy prices) affect its suitability and economical value for the building it serves.

This study employs a method of computer simulation to construct a computer software application that simulates the energy exchange of a grid connected photovoltaic system with the electrical grid on an hourly basis. Computer simulation readily lends itself to incorporating variations present in the solar energy resource and the electrical load. By running the simulation to cover an extended period of time, accumulated energy values are obtained. These values are used to determine system financial benefits.

Using software simulation for conducting a pre-installation analysis of a proposed system is a relatively low cost method for performing otherwise time-consuming real life experimentation with costly real systems. The effect of a design or an economical parameter on an observed system output can be studied simply by repeating simulation with different values of that paramter. In this way conclusions can be drawn on the best choices of these parameters. Uncertainity in operational conditions such as solar resrouce and load profile is alleviated similarly by conducting a sensitivity analysis over a range of these conditions.

While the simulated system is generic in nature, this study serves the local energy sector by using the simulation to evaluate a proposed system under Jordan's solar energy resource and electrical energy pricing schemes. Since distributed grid connected photovoltaic generation is not yet applied in Jordan, a parametrical study of a hypothesized system facilitates decisions regarding its adoption and deployment. The developed software, moreover, has an educational value for demonstrating operation of a system that has many interacting components. It can also be used as an engine for future research.

1.3 Scope

The subject of this simulation is a single grid connected photovoltaic system. The probed quantity is the flow of energy between a building using the system and the electrical grid, given hourly solar radiation, load data and system design parameters. That flow depends on energy flow between system components. The system is modeled as consisting of the following components: a photovoltaic array, a converter for DC/AC power conversion, a load connection, a grid connection including energy metering and an optional energy storage component. The photovoltaic array is of a fixed orientation, which is most commonly found in building scale installations. The generation capacity scale in this study is in the range of one to few killowatts, which is consistent with installation area available in most common buildings such as residential ones.

A schematic block diagram of the simulated system is displayed in Figure 1.1. It depicts system components and possible energy flows between them. Storage is considered as an optional component, and is modeled as a generic technology-independent energy storage device. The storage component features a scheduled charging/dischagring capability to demonstrate controlled modification of the building demand profile. Energy may flow from the AC to the DC bus only when the storage component is present. With no storage, energy flows only from the DC to the AC bus.

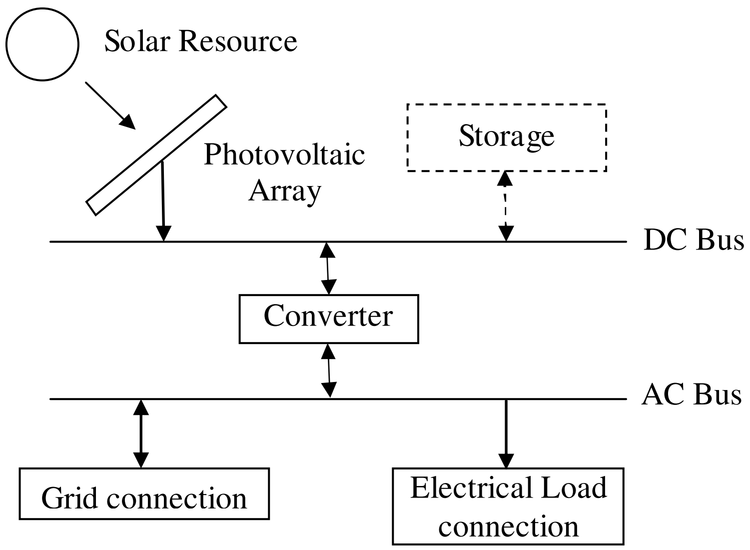

Figure 1.1: Schematic diagram of the simulated phovoltaic generation system

In this study, each system component is modeled as a black box that accepts input energy, employs an approximate linear energy conversion scheme that accounts for energy losses and produces output energy. The inner workings of the components are hidden, and in this way the simulation of electrical quantities is avoided for being outside the scope of study. Hourly effect of temperature on the photovoltaic array efficiency is ignored. Other devices typically found in a photovoltaic system are conceptually merged with major components they uniquely serve. For example, a maximum power point tracker (MPPT) is considered part of the photovoltaic array, while a charger and a discharger are part of the storage component.

The simulation is performed on an hourly basis for a full simulated year. Solar radiation data input is a series of hourly global radiation values on a horizontal surface for the whole year. The simulation converts each of these values to global radiation at the tilted surface of the photovoltaic array. Accordingly, the simulatoin finds, for each hour, the output energy produced by the array, and that depends on its rated capacity. An energy balance at system buses ultimately determines the hourly amount of energy exchanged with the electrical grid.

The simulation software implementation provides the ability to advance the timeline in increments down to a single hour step, and up to the full simulated year at once. Hourly energy flow results are graphically displayed on a schematic diagram of the system and collected in tabular format. The results are also aggregated in daily, monthy and full year sums. The software collects data simultaneously for two scenarios. The reference scenario is of the grid directly supplying the load with no photovoltaic system installed. The second is with the presence of the photovoltaic system. The difference in electrical energy cost is the financial benefit of the system. At the completion of a simulation run of one year, the benefit and cost values are projected on the project lifetime. The software performs a lifecycle cost analysis to calculate economic indicators. These are net present value, internal rate of return of the system investment, and simple payback time.

The produced simulation is used to conduct a parametric evaluation of a proposed system in Jordan, specifically the capital city of Amman. The study is concerened with the effect of local climate in terms of incident monthly average daily global irradiation. Data synthesis is used to incorporate a range of resource availability conditions on hourly basis. This enables evaluating the system under a sample set of distinct daily operational conidtions in terms of resource amount. An external software is used to synthesize hourly global solar radiation data on a horizontal surface from monthly average daily global radiation. Another aspect of localization of the study relates to applying the special sliced pricing scheme used in Jordan as part of calculating the system financial benefit. The methods explained in this study are generally applicable to other locations within or outside Jordan.

1.4 Objectives

1. Develop a computer software application that simulates energy flow of a grid connected photovoltaic system as defined in the study scope above.
2. Use this software to perform a parametric evaluation of a proposed system in Amman/Jordan. Evaluation covers system energy contribution under selected operating conditions in terms of daily load profile and solar radiation resource.
3. Use the software to perform an evaluation of the system economical viability under current and hypothesized economical conditions.

1.5 Approach and Thesis Orgnaization

The study approach procedure consists of the following steps:

1. Introduce the study problem and define study scope and objectives. (Chapter 1)
2. Perform a literature review to cover topics relevant to this study. (Chapter 2)
3. Describe the mathematical model used to simulate the studied system. (Chapter 3)

4. Develop a softwae application that implements the above model, accepts simulation input, records output and calculates economic indicators. Explain software operation and features. (Chapter 4)
5. Determine configuration scenarios and operational coniditons for system simulation runs. Determine economical settings. Run the simulation under the determined conditions, gather and discuss results. (Chapter 5)
6. Draw summary conclusions on the study and provide recommendations. (Chapter 6)

CHAPTER 2

LITERATURE REVIEW

This thesis builds on basic understanding of solar energy, photovoltaic generation systems and computer simulation as a system evaluation method. This chapter reviews concepts most relevant to this study and highlights related research. A section is dedicated for comparing the present software with two software packages that perform close evaluations.

2.1 Solar Radiation

Geographic variability due to different climates (primarily cloudiness) and latitudes cause spatial variability in solar radiation resource (Riordan, 1995). The number of solar radiation measuring stations is usually limited. Therefore correlations are used to estimate radiation at other locations. Alsaad (1990) utilized correlations between measured sunshine hours and global radiation at 10 locations in Jordan to estimate monthly average daily horizontal global radiation for another 14 stations where only records of bright sunshine hours were available. In that study the data was used to draw a solar radiation map of Jordan that consisted of isolines of the annual mean daily global radiation. Satellite remote sensing is also used in providing solar resource data. Sorensen (2001) employed geographical information system (GIS) to map satellite based solar resource data and matched it to habitat based demand model to estimate potentials for photovoltaic systems. Suri et al. (2007) studied the potential of solar electricity generation in the European Union countries using data available in the Photovoltaic Geographic Information System (PVGIS).

2.2 Photovoltaics

A photovoltaic cell is basically a semiconductor junction, with metal contact partially covering it to allow light entrance (Figure 2.1). Light absorption generates nonequilibrium electron-hole pairs. Potential energy changes caused by these pairs produce DC voltage that drives DC current for power delivery to an external load (Partain, 1995). The physics of the photovoltaic phenomena is widely covered in photovoltaic solar energy literature. For example, Overstraeten and Mertens (1986) reviewed physics of photovoltaic cells both in general and as applied to cells of different materials. From a physics perspective, Areeda (1990) simulated photovoltaic cells based on their semiconductor characteristic parameters such as donor concentration, acceptors concentration, and depth of the junction.

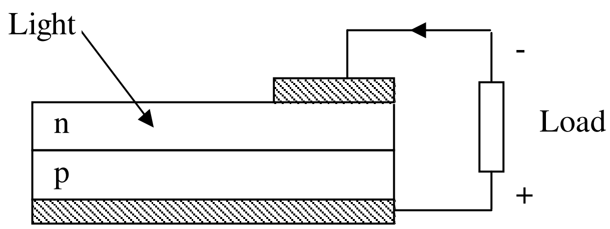

Figure 2.1: Simple structure of a typical photovoltaic cell

To produce enough power, photovoltaic cells are connected in series-parallel configurations to form modules. Modules are connected to form arrays. Messenger and Ventre (2000) described electrical characteristics of solar cells and various configurations used in connecting solar cells and modules. Different materials and manufacturing technologies are used to produce photovoltaic cells. The most familiar material used is silicon. Silicon is fabricated into cells using monocrystaline, multicrystaline, thin film, and amorphous silicon technologies. Other materials are also used in crystalline and thin film technologies. Goetzberger and Hoffmann (2005) described these manufacturing technologies.

The conversion efficiency of a photovoltaic cell is defined as follows (Patel, 1999)

$$\eta = \frac{electrical\ power\ oputput}{solar\ \ power\ impending\ the\ cell}$$

Green et al. (2009) listed the highest independently confirmed efficiencies of different types of solar cells and modules. In this listing crystalline silicon cells achieved 25.0% efficiency, while GaAs scored 26.1%. Silicon thin film transfer cells recorded 16.7% efficiency. Module efficiency of a certain technology is lower than cell efficiency, for example crystalline silicon efficiency is shown as 22.9%.

In a practical sense a solar module (also called panel) is defined by its rated power; that is the maximum power it produces under irradiance of 1 kW/m^2 and standard conditions. This power rating is derived from the conversion efficiency and surface area. The power production capacity of a photovoltaic array is the sum of rated power of its constituting modules.

This study is concerned only with the power capacity of the solar array. In other words, the solar array is viewed merely as an energy converter of solar energy. This view goes afar from underlying physics, electrical behavior or wiring.

2.3 Grid Connected Photovoltaic Generation

There are two types of terrestrial photovoltaic power systems (Goetzberger and Hoffmann, 2005); Stand-alone photovoltaic systems and grid connected photovoltaic systems. A stand alone photovoltaic system may either supply power only at times of sufficient solar radiation, or use an energy storage medium to provide power at other times. Contrary to a stand-alone photovoltaic system, a grid connected photovoltaic system always has a connection to the public electricity grid. Central grid connected photovoltaic systems power is up to the megawatt range. These are mostly setup on a dedicated land. With these central systems it is possible to feed power directly into the medium or high voltage grid. On the other hand, decentralized grid connected photovoltaic systems have mostly a small power range and are installed on buildings. Installation possibilities of photovoltaic modules on a building rooftop depend on the type of the roof. A roof could be sloped or flat. Photo 2.2 displays an example of photovoltaic modules installed on a flat roof. An advantage provided by flat roofs is the ability to optimally mount the modules in terms of installation angles.

Photo 2.2: Example of installation on a flat roof (Goetzberger and Hoffmann, 2005)

A photovoltaic system employs an inverter to adapt the generated photovoltaic direct current into the alternating current characteristics of the grid. Kaltschmitt et al. (2007) and Schultz et al. (2008) discussed various types and aspects of electronic devices constituting a photovoltaic generation system. Electrochemical storage by lead battery with sulfuric acid as the electrolyte is the most common way of storing electricity for photovoltaic energy systems. Electrolysis is another form of chemical storage which employs electrolysis of water into oxygen and hydrogen as storage medium, and later transformation into electricity by fuel cells (Krauter, 2006). Jaber et al. (2003) studied the concept of using compressed air storage in an integrated photovoltaic and gas-turbine hybrid configuration power plant in satisfying peak demand. Rüther et al. (2007) demonstrated the potential of building integrated grid connected photovoltaic power in reducing demand peaks.

Fernández-Infantes et al. (2006) presented a design of a grid connected photovoltaic installation for usage in Spain, and presented optimization strategies used in the design. Mondol et al. (2006) used simulation to determine optimum ratios for photovoltaic array to inverter size in terms of certain objectives such as total system output and photovoltaic surface orientation relevant to grid-connected system in certain European locations. Pacca et al. (2006) assessed modeling parameters that affect the life cycle performance of certain photovoltaic electricity generation technologies and systems. Eid (2008) calculated sizes of photovoltaic systems to meet yearly energy needs of three categories of consumption of domestic consumers in Jordan, while studying relevant technical and economical aspects.

2.4 Simulation Software

The closest found software to the scope of this study is HOMER[1] Micropower Optimization Model, developed by the U.S. National Renewable Energy Laboratory (NREL). HOMER models both conventional and renewable micropower systems and evaluates different design options. Features added in the presented software, developed in this study, close a gap against the requirements. The present software is dedicated to simulation of only one type of system (grid connected photovoltaic system). It provides a user interface design that is specific to the system being simulated.

[1] Available at http://www.nrel.gov/homer

Similarities with HOMER are

1. Performing hourly simulation over a full year.
2. Using linear mathematical models to represent operation of photovoltaic array and inverter. HOMER modeling is explained by Lambert et al. (2006).
3. Calculating global hourly irradiation on tilted surface from values on horizontal surface using the method explained in Duffie and Beckman (1991). Detailed description of this method is provided in chapter 3.

The present simulation software is distinctly different from HOMER by providing the following functions and features.

1. The present software provides a user interactive progression of the simulation time line in hourly, daily and monthly increments. All relevant tabular results are updated at the end of these increments. So, the user can inspect the results before the end of the simulation and observe changing accumulations.
2. Display of energy flow simulation results in amounts and directions graphically on a schematic diagram of the system during simulation on an hourly basis.
3. Display of details of solar resource calculations with each simulated hour. These include declination angle, hour angles and incidence angle.
4. The present software implements a generic technology-independent storage device. This optional system component is controlled through scheduled charging/discharging in order to demonstrate usefulness in meeting peak loads in a grid connected configuration.
5. Support of the pricing scheme used in Jordan for the domestic sector which is based on slices of monthly consumption.
6. The present software simultaneously calculates monthly electrical cost in two separate scenarios. The first is a reference scenario where the whole

photovoltaic system is not present and the load is fed directly by the electrical grid. The second is with that system present. The resulting difference is savings (or revenue) resulting from the system. Using this method the present software calculates internal rate of return and simple payback time.

The following functions of HOMER are used in the present study to provide input to the present simulation software.

1. Synthesizing hourly solar radiation data from monthly average daily radiation.
2. Synthesizing hourly load data from typical daily profile.

RETScreen[1] is a software tool that facilitates pre-feasibility and feasibility analysis of clean energy technologies. It is implemented as a spread sheet. Notably, RETScreen does not perform hourly simulation for a full year but rather bases its calculations on typical days of months.

[1] Available at http://www.retscreen.net

CHAPTER 3

SYSTEM MODELING

Computer simulation, the method of choice of this study, is based on mathematical representation of the relevant functions of the system under study. This chapter presents a mathematic model of the studied system. This model is the basis of the developed computer simulation application, which will be described in the next chapter.

3.1 System Modeling Overview

A mathematical model of the system being studied is the core of the simulation process. The model is a logical representation of the real system from the perspective of the quantity being studied. The quantity sought after in this study is the amount of energy flow between the system and the electrical grid on an hourly basis. That amount is determined by the energy flow within the system and across its boundary. The system is modeled as a group of components corresponding to their physical counterparts in the system. These components are:

1. Photovoltaic Array.
2. Converter.
3. Storage (optional)
4. Electrical Load Connection
5. Grid Connection

These components are interconnected through two system buses; AC and DC. Figure 3.1 shows a schematic diagram of the system in the more common configuration; that is without storage. Figure 3.2 shows the schematic diagram with storage included. These diagrams illustrate component interconnections and possible electrical energy flow directions in both cases respectively.

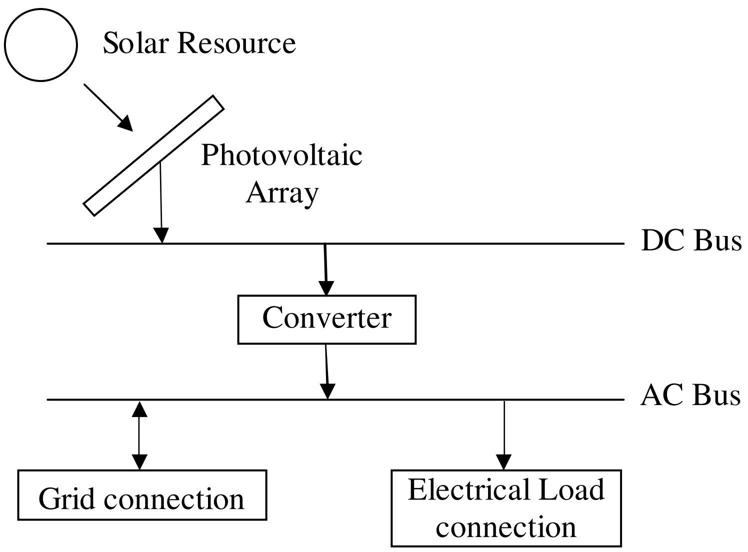

Figure 3.1: Schematic diagram of the system without storage

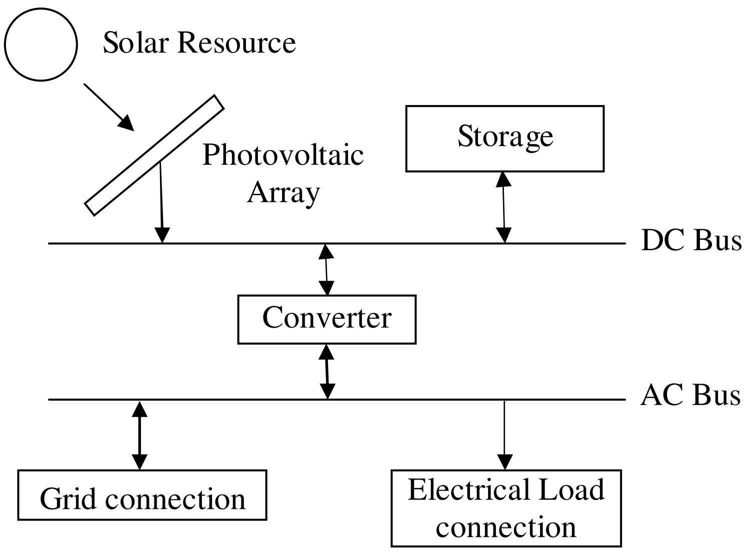

Figure 3.2: Schematic diagram of the system with storage

A component model represents its operation during a single simulation time step defined here as one hour. For each time step, each component accepts input, and produces output according to its parameterized conversion functions. The components are modeled as black boxes; the inner workings of these components (for example, electrical relations) are hidden. Energy conversion functions are approximated as linear relations between input and output energy of the components. These relations take in account energy losses by means of conversion efficiency ratings. Other minor devices not explicitly modeled are considered part of the component they uniquely serve as will be explained in component modeling.

Power is the flow rate of energy against time. For each time step the average power P_{av} flowing in or out of a component is the net energy amount E divided by the length of the time step Δt

$$P_{av} = \frac{E}{\Delta t} \qquad (3.1)$$

Similarly, starting with a certain average power rating during a certain time step the accumulated energy is given by

$$E = P_{av}\Delta t \qquad (3.2)$$

In this "hourly" simulation, the time step length is one hour. Being the finest level of temporal detail available, only average power during each hour, which is related to the net energy flow during that hour, may be known.

In this study energy is treated in units of kWh, average power in units of kW, and time in units of hour. From equations 3.1 and 3.2, since Δt = 1 hour, hourly energy and average power are numerically identical but different in units. For example a net energy flow from the system to the grid of 1 kWh during an hour is equivalent to an average power of 1 kW. In this thesis modeling is done in terms of energy units for each hour time step, bearing in mind the equivalence of hourly energy and average power.

3.2 Modeling of System Components

This section covers modeling of the system components. These components are photovoltaic array, converter and energy storage.

3.2.1 Photovoltaic Array

This study uses a linear photovoltaic array conversion model. This model is implemented in HOMER and described by Lambert et al. (2006). The model directly relates power output of the photovoltaic array (P_{pv} in kW) to incident solar irradiance according to the following equation

$$P_{pv} = f_D C_{pv} \frac{G_T}{G_{TS}} \tag{3.3}$$

Where C_{pv} is the photovoltaic array rated capacity in kW, which denotes the photovoltaic array output power at an irradiance of 1 kW/m^2 and standard conditions. f_D is a derating factor which roughly accounts for long-term power reducing factors. G_T is the irradiance in kW/m^2, and G_{TS} is the incident irradiance at standard conditions and is equal to 1 kW/m^2. Maximum power point tracker is assumed present and is considered as a part of the photovoltaic array.

Given an incident solar irradiation of I_T in kWh/m^2, during a certain one hour interval (Δt), on the surface of the photovoltaic array, the corresponding average irradiance G_T in kW/m^2 is given by

$$G_T = \frac{I_T}{\Delta t} \tag{3.4}$$

Substituting G_T in equation 3.3 gives

$$P_{pv} = f_D C_{pv} \frac{I_T}{\Delta t G_{TS}} \tag{3.5}$$

During an hour time step, from equation 3.2

$$E_{pv} = f_D C_{pv} \frac{I_T}{\Delta t G_{TS}} \Delta t \tag{3.6}$$

Where E_{pv} is the energy produced by photovoltaic array during that hour in kWh. Canceling out Δt then

$$E_{pv} = f_D C_{pv} \frac{I_T}{G_{TS}} \tag{3.7}$$

The rated capacity is directly proportional to array surface area and conversion efficiency. Usage of rated capacity is more useful in the practical sense. A photovoltaic array in this study is of fixed orientation installation defined by array slope angle and azimuth angle. Calculation of global radiation at the array surface from the value of radiation on a horizontal surface is the subject of section 3.3.1.

3.2.2 Converter

When no storage is included in the system configuration (Figure 3.1), the converter is just an inverter that transfers energy from the DC bus to the AC bus. When storage is included (Figure 3.2), there is a possibility that the storage is charged with more than the solar array can provide (for example at night when solar arrays do not produce energy). At such configuration the converter includes a rectifier that transfers energy from the AC bus to the DC bus when energy from the grid is needed to charge storage. An inverter and a rectifier produce output energy subject to less than perfect conversion efficiency. Energy produced by the inverter or rectifier is limited by their respective maximum output power capacity.

For each simulated hour time step, the inverter and rectifier energy outputs are modeled through approximate linear energy conversion. For the inverter, the output AC energy $E_{inv,AC}$ is given by

$$E_{inv,AC} = \eta_{inv} E_{inv,DC} \tag{3.8}$$

Where $E_{inv,DC}$ is the inverter input DC energy, and η_{inv} is the inverter efficiency. Similarly, for the rectifier, the output DC energy $E_{rec,DC}$ is given by

$$E_{rec,DC} = \eta_{rec} E_{rec,AC} \tag{3.9}$$

Where $E_{rec,AC}$ is the rectifier input AC energy, and η_{rec} is the rectifier efficiency.

3.2.3 Energy Storage

Storage in this study is an optional component. When included the purpose is to demonstrate possible enhancement of the demand profile through scheduled charging/ discharging. When present the storage component can also store energy produced by the photovoltaic array in excess of the inverter conversion capacity, which is a rare occurrence for a properly designed system. Since a controlled addition or retrieval from storage during a certain hour time step is the driving function of storage operation, a simple energy repository model is devised. This is a generic technology-independent model. It can be thought of as representing a battery with a charger and discharger, a hydrogen tank with an electrolyzer and fuel cell, or any device that can accept a defined amount of energy during a certain time interval and furnish another amount during another time.

In addition to usable storage capacity, the operation of the storage component is defined by maximum rates of addition or retrieval of energy, and time duration (in number of hours) for these operations. Proper selection of these values ensures component operation within the physical limits envelope of the device it represents. This modeling approach hides and makes irrelevant the internal mechanisms of a storage device whether electrical or chemical. Usable capacity is the difference between the upper and lower limits of energy content of the component.

If the storage component undergoes charging during a certain hour of the simulated time, its energy content E_s at the end of that hour is given by

$$E_s = E_{s,0} + \eta_c E_c \tag{3.10}$$

Where $E_{s,0}$ is the energy content of the storage component at the beginning of the hour. E_c is the charging energy at the component terminals, and η_c is the charging efficiency. E_c is limited by maximum allowable charging rate, remaining storage capacity, and energy available for storage.

On the other hand, if the storage component undergoes discharging during another hour of the simulated time, its energy content at the end of that hour is given by

$$E_s = E_{s,0} - E_d / \eta_d \tag{3.11}$$

Where $E_{s,0}$ is the energy content of the storage component at the beginning of the hour. E_d is the discharged energy at the component terminals, and η_d is the discharging efficiency. E_d is limited by the maximum allowable discharging rate, available stored energy and available inverter capacity.

3.3 System Boundaries

Solar resource is the input form of energy to the photovoltaic array. An electrical load withdraws energy from the system at the load connection. The balance is provided (or withdrawn) by the electrical grid at grid connection. These entities represent the interface or boundary of the system to its surroundings from an energy point of view.

3.3.1 Solar Resource

Input to the simulation is hourly values of global solar irradiation at a horizontal surface per square meter for each hour of the simulated year. Since the solar array is generally tilted from the horizontal plane, the solar irradiation needs to be calculated at the array tilted surface. This section explains the implemented conversion process. The conversion process explained here is based on Duffie and Beckman (1991). All equations in this subsection are syndicated from this reference. The conversion process is composed of two steps. First is splitting the total radiation on a horizontal surface into beam and diffuse components. The second step is finding total radiation at the tilted surface from both components, and accounting for ground reflectance.

Step 1: Splitting Total Radiation on a Horizontal Surface

The splitting procedure is based on the concept of hourly clearness index defined as

$$k_T = \frac{I}{I_o} \tag{3.12}$$

where I is total irradiation on a horizontal surface for an hour at earth level which is the input data for the simulation. And I_o is the extraterrestrial irradiation on a horizontal surface for that hour. The procedure for calculating I_o depends on the angular position of sun rays with respect to earth at the location being considered which depends on time of day and year. At any point of time the angle of incidence, denoted as θ, of beam radiation on a surface is given by

$$\begin{aligned}\cos\theta = \ & \sin\delta\sin\phi\cos\beta \\ & -\sin\delta\cos\phi\sin\beta\cos\gamma \\ & +\cos\delta\cos\phi\cos\beta\cos\omega \\ & +\cos\delta\sin\phi\sin\beta\cos\gamma\cos\omega \\ & +\cos\delta\sin\beta\sin\gamma\sin\omega\end{aligned} \tag{3.13}$$

where δ is the sun declination angle, ϕ is the latitude angle, β is the slope of the surface, γ is the azimuth of the surface, and ω is the hour angle.

The declination angle δ is found by

$$\delta = 23.45\sin\left(360^\circ\frac{284+n}{365}\right) \tag{3.14}$$

Since ω is the angular displacement of the sun east or west of the local solar noon due to rotation of earth on its axis at 15° per hour, it is given by

$$\omega = 15(t_{solar} - 12) \tag{3.15}$$

where the difference between solar time and standard time in minutes is given by

$$t_{solar} - t_{standard} = 4\,(L_{loc} - L_{st}) + E_t \quad (3.16)$$

L_{loc} is the longitude of the location and L_{st} is the standard meridian of the local time zone (both in degrees east). In terms of time zone T_z in hours ahead of Greenwich Meant Time (GMT) L_{st} is given by

$$L_{st} = 15 \cdot T_z \quad (3.17)$$

E is the equation of time in minutes and is given by

$$E_t = 229.2(0.000075 + 0.001868\,\cos B - 0.032077\,\sin B$$

$$- 0.014615\,\cos 2B - 0.04089\,\sin 2B) \quad (3.18)$$

where

$$B = (n-1)\frac{360}{365} \quad (3.19)$$

in degrees, and n is the day of year ranging from 1 to 365.

The zenith angle θ_z of the sun is its ray's incidence angle on a horizontal surface. For such a surface $\beta = 0$ and by substituting this value in equation 3.2

$$\cos\theta_z = \cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta \quad (3.20)$$

Extraterrestrial solar radiation varies with variation of earth-sun distance due to the earth elliptical orbit, as given by the following equation

$$G_{on} = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right) \quad (3.21)$$

where G_{on} is the extraterrestrial normal radiation (i.e. on a surface perpendicular to the sun rays), n is the day of year and G_{sc} is the solar constant equal to 1.367 kW/m^2. Multiplying G_{on} by $\cos\theta_z$ gives the extraterrestrial solar radiation incident on a horizontal surface G_o as given by

$$G_o = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right)(\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta) \quad (3.22)$$

I_o is calculated by integrating G_o over the considered hour period, and is given by

$$I_o = \frac{12}{\pi} G_{sc} \left(1 + 0.033 \cos \frac{360n}{365}\right)$$

$$\times \left[\cos\phi \cos\delta (\sin\omega_2 - \sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180°} \sin\phi \sin\delta\right] \qquad (3.23)$$

where I_o is in kWh/m^2. ω_1 and ω_2 are hour angles at the beginning and the end of the hour respectively. Lower limit on ω_1 is $-\omega_s$, and upper limit on ω_2 is ω_s where ω_s is sunset hour angle given by

$$\omega_s = \cos^{-1}(-\tan\phi \tan\delta) \qquad (3.24)$$

As I_o is calculated using equation 3.23, k_T is found using equation 3.12 above. Defining I_b and I_d as beam and diffuse radiation at earth surface respectively, the total solar radiation I is the sum of these two quantities.

$$I = I_b + I_d \qquad (3.25)$$

The ratio of diffuse radiation I_d is given by Erbs correlation as stated in Duffie and Beckman (1991)

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09k_T & \text{for } k_T \le 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & \text{for } 0.22 < k_T \le 0.80 \\ 0.165 & \text{for } k_T > 0.80 \end{cases} \qquad (3.26)$$

Subtracting diffuse radiation from total radiation gives beam radiation I_b.

Step 2: Calculating Total Radiation on Tilted Surface from Split Components

As the beam (I_b) and diffuse (I_d) components of solar radiation on a horizontal surface are found in step 1 above, the total solar radiation on a tilted surface I_T (in kWh/m^2) is found, according to the HDKR model as stated in Duffie and Beckman (1991), using the following equation

$$I_T = (I_b + I_d A_i)R_b + I_d(1 - A_i)\left(\frac{1+\cos\beta}{2}\right)\left[1 + f\sin^3\left(\frac{\beta}{2}\right)\right] + I\rho_g\left(\frac{1-\cos\beta}{2}\right) \quad (3.27)$$

where ρ_g is ground reflectance and β is the surface slope angle, R_b is the ratio of beam radiation on tilted surface to that on a horizontal surface, found at the middle of the time step, it is found using

$$R_b = \frac{\cos\theta}{\cos\theta_z} \quad (3.28)$$

A_i, an anisotropy index, is calculated as

$$A_i = \frac{I_b}{I_o} \quad (3.29)$$

whereas f is calculated using the follow equation

$$f = \sqrt{\frac{I_b}{I}} \quad (3.30)$$

3.3.2 Electrical Load Connection

The system is interfaced to the electrical load at the electrical load connection. Energy flows from the system towards the load so as to satisfy the demanded quantity. For each hour total electrical load is specified as energy consumed in kWh.

3.3.3 Grid Connection

Energy may flow across the grid connection in either direction; from or into the gird. The amount of energy exchanged with the grid during each hour depends on the amount produced by the system and the amount consumed by the electrical load. For example if the photovoltaic system produces more than the demand of electrical load, the excess is transferred to the electrical grid. Conversely if demand exceeds photovoltaic system energy production, the deficit is provided by the electrical grid.

CHAPTER 4

THE SIMULATION SOFTWARE

A graphical interface software application was created to implement the simulation process in this study. This chapter presents an overview of the simulation process performed by this software. It also describes the software in terms of input, operation and output.

4.1 Process Overview

As described in the preceding chapter, the system model specifies its constituting components input/output operation in a single hour. The purpose of the simulation process is to operate that model over a full year; that is for each of 8760 hours. For each simulated hour the simulation engine provides data input to system components, applies inter-component energy flow rules and records output data. The overall simulation procedure is summarized in the following steps.

1. Set a value for each parameter of the system model.
2. Set financial investment data.
3. Set grid energy pricing scheme.
4. Accept a series of hourly solar radiation data for a full year, values are global solar irradiation on a horizontal surface.
5. Accept a series of hourly electrical load demand for a full year.
6. Initiate the simulation timeline.
7. As simulation starts, for each simulated hour:
    a. Calculate global irradiation at the titled surface of the photovoltaic array.

b. Calculate energy output from the photovoltaic array.

c. Determine energy flow across the converter. That takes into account storage charging / discharging at the DC bus if storage is present.

d. Perform energy balance at the AC bus that takes into account the load demand. Hence, determine the amount of energy taken from or transferred to the electrical grid.

8. Keep records of hourly values of energy flow.
9. Keep aggregated records of daily, monthly, and full year energy flow amounts.
10. Keep records of monthly and full year grid energy cost (or revenue) using the applied energy pricing scheme. Calculate financial benefit as the difference in energy cost (or revenue) against a reference scenario where the load is only fed by grid energy.
11. At the end of the simulated year perform an economic analysis that takes into account investment costs and financial benefits projected over the lifetime of the project.

4.2 Software

As part of this thesis study, a computer software application was developed to implement the described simulation process. This software is a graphical user interface Windows application. It was coded in Visual Basic programming language implemented on the Microsoft .NET Framework 3.5, and using Microsoft Visual Basic 2008 Express Edition as the development tool. It took about 1000 lines of code to program this software. The application user interface was designed with intuitive ease of use in mind. Figure 4.1 displays the application main window. This main window is divided into several areas according to specific functions.

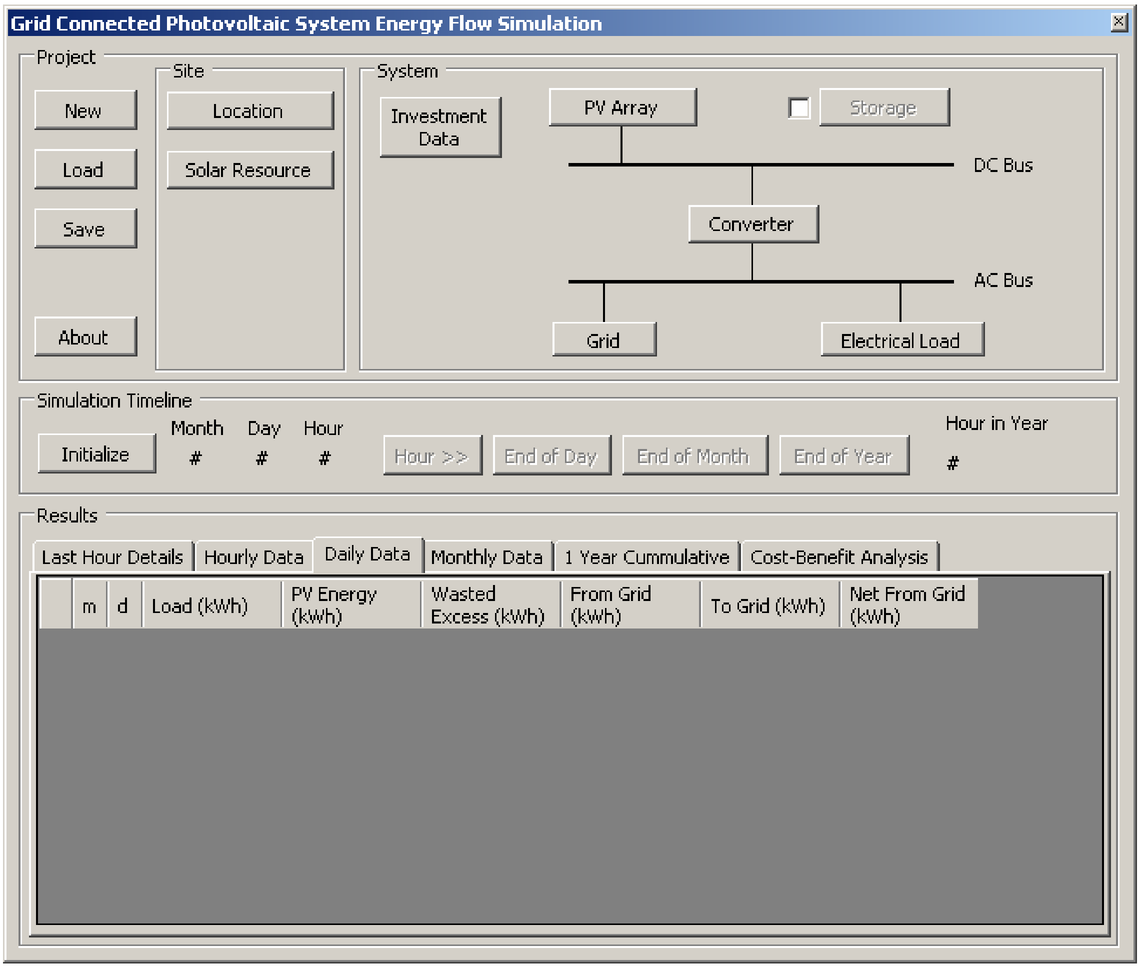

Figure 4.1: Simulation application main user interface

The topmost area in the user interface is the Project area. A project is a collection of input data to the simulation comprising various parameters that describe the simulated system design and operational conditions. A user starts by specifying these parameters using the graphical user interface as explained in the next section. The project can be saved to a file and later loaded directly from that file. The Simulation Timeline is where the user triggers the simulation and controls its progression either hourly, daily, monthly or for the full simulated year. In either case the software performs the simulation hour by hour, and updates tabular records in the Results area accordingly. The direction and amount of energy flow shown on the schematic diagram always correspond to the last simulated hour. Input entry software elements in the form of dialog boxes are accessed by clicking corresponding buttons. these elements are illustrated in upcoming sections.

4.3 Data Input

This section presents the user interface elements used to enter simulation data. The shown values are examples for illustration.

4.3.1 System Components: Photovoltaic Array, Converter and Storage

Figure 4.2 shows the dialog box used to specify photovoltaic array parameters. Sample values are shown. As described in the modeling chapter, the array output depends on its rated capacity in kW and a percentage derating factor. The installation angles (slope angle and azimuth angle) together with ground reflectance are used in calculating solar irradiation at the array surface.

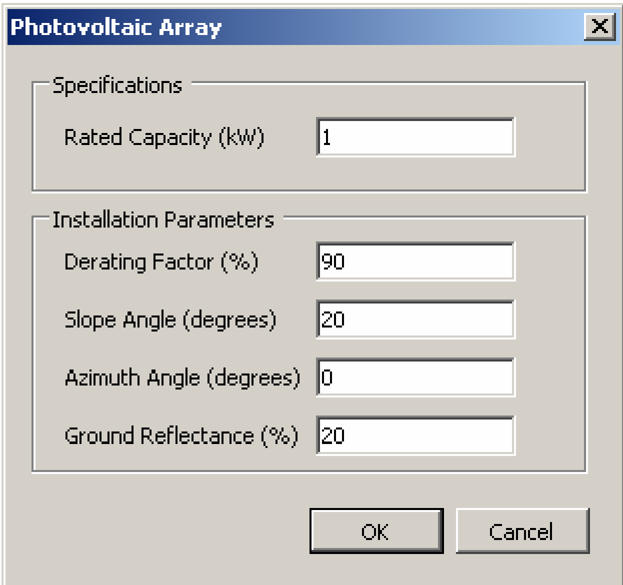

Figure 4.2: Photovoltaic array dialog box

The converter model requires defining inverter and rectifier in terms of capacity in kW and efficiency for each. These values are specified using the dialog box shown in Figure 4.3. Figure 4.4 displays the dialog box used to specify storage model parameters and controlling its charging/discharging. Storage is an optional component; simulation can be performed with or without it. As shown in the modeling chapter, storage is implemented as a generic technology-independent component. It is defined by usable capacity in kWh, maximum charging and discharging rates in kW and the efficiency for each. Scheduled charging and discharging are specified in terms of starting time and duration in hours for each. As shown, charging/discharging occurs at one cycle per day and aims at demonstrating the use of storage in enhancing the system demand leveling value. Moreover, whenever there is an excess in photovoltaic energy production beyond converter capacity, that excess is used to charge storage provided there is enough remaining storage space and up to the maximum charging rate.

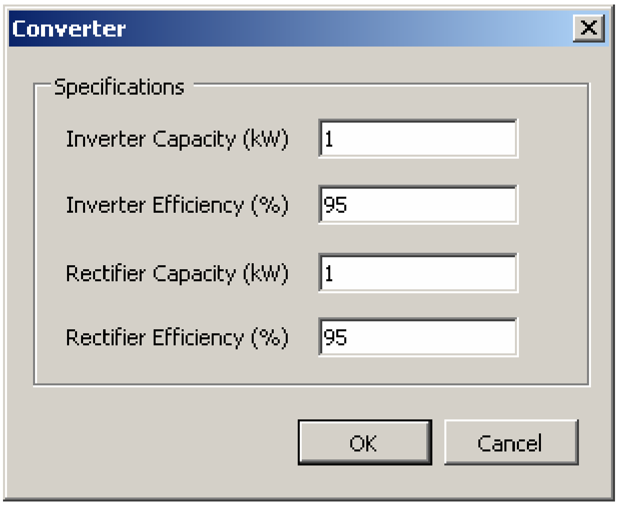

Figure 4.3: Converter dialog box

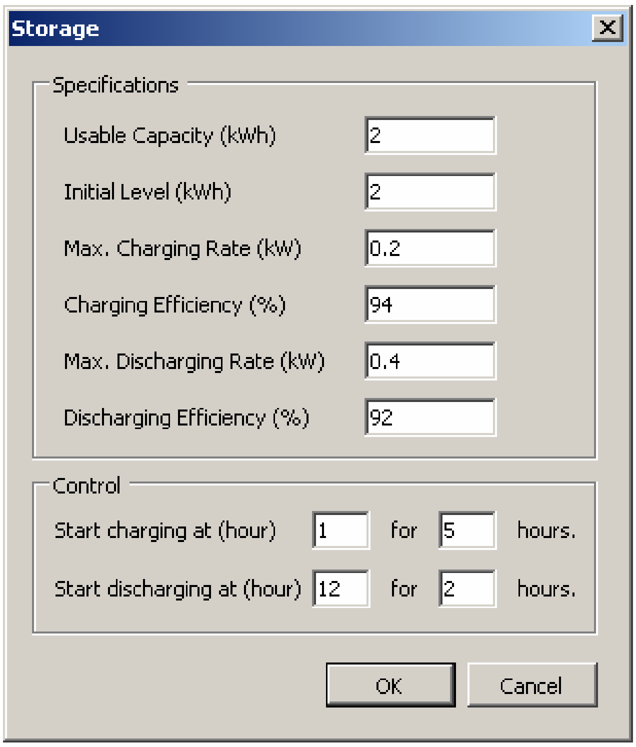

Figure 4.4: Storage dialog box

4.3.2 System Boundary: Solar Resource, Electrical Load and Grid Connection

This simulation software accepts solar radiation data as a time series of 8760 values representing hourly solar irradiation on a horizontal surface for a full year. This data is provided to the software as a text file. Figure 4.5 shows the dialog box used to specify this text file. As shown in the modeling chapter, calculating irradiation at the tilted surface of the photovoltaic array requires specification of the current location coordinates and time zone. Figure 4.6 shows the dialog box used to specify latitude and longitude in degrees in addition to time zone in hours ahead of GMT.

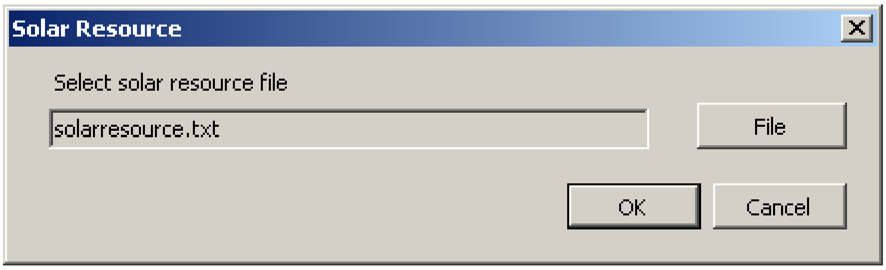

Figure 4.5: Solar resource dialog box

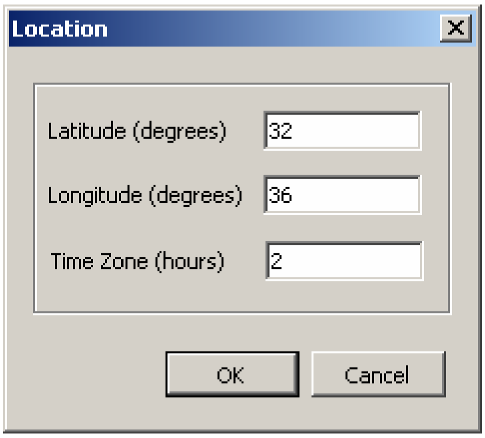

Figure 4.6: Location dialog box

In this simulation electrical load is defined by its total hourly energy consumption amounts in kWh for a full year. This data is input to the simulation application as a text file containing a list of 8760 values. The dialog box used to select this text file is shown in Figure 4.7.

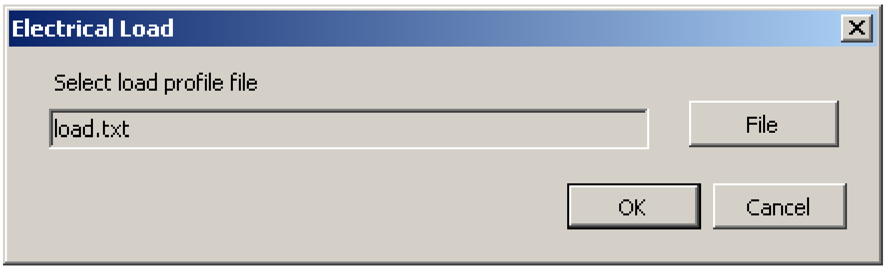

Figure 4.7: Electrical load dialog box

The simulation software meters accumulated energy exchanged with electrical grid and calculates monthly electrical energy cost (or revenue). Figure 4.8 shows the dialog box used to specify energy price and sellback tariffs. If net metering is selected the energy cost is calculated based on the net monthly energy drawn from the grid. If this net flow is negative meaning net energy is injected into the grid the revenue is calculated using the sellback price. On the other hand if net metering is not selected, then energy cost and revenue are calculated separately based on total monthly energy intake and injection respectively. In this case the actual monthly cost (or revenue) is the balance of the two amounts.

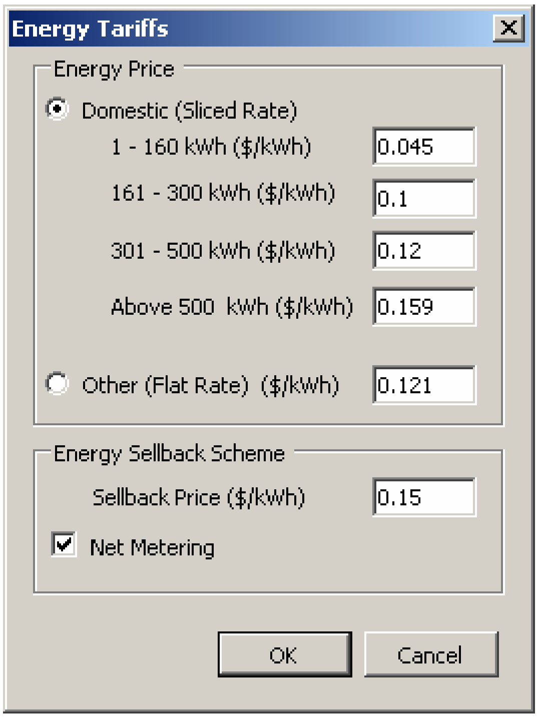

Figure 4.8: Grid connection - Energy tariffs dialog box

Either using net metering or not, energy purchase cost is calculated in one of two supported schemes. First is the sliced energy pricing scheme used for the domestic consumers in Jordan. The other is the flat rate scheme. Domestic tariff data shown in Figure 4.8 are actual current prices in Jordan converted to USD at 0.71 JD/USD conversion rate. The shown flat rate is the one used for commercial customers converted similarly. The displayed sellback price is hypothetical.

4.3.3 Investment Data

Figure 4.9 shows the user interface used to enter financial investment data with example values. This data includes components initial cost, replacement cost, yearly maintenance cost and lifetime in years. Other needed data parameters are project lifetime in years, project fixed initial cost, project fixed maintenance cost and the real interest rate. The latter is the interest rate adjusted to remove inflation effect. This data is used in the cost-benefit analysis for economical evaluation of the system viability.

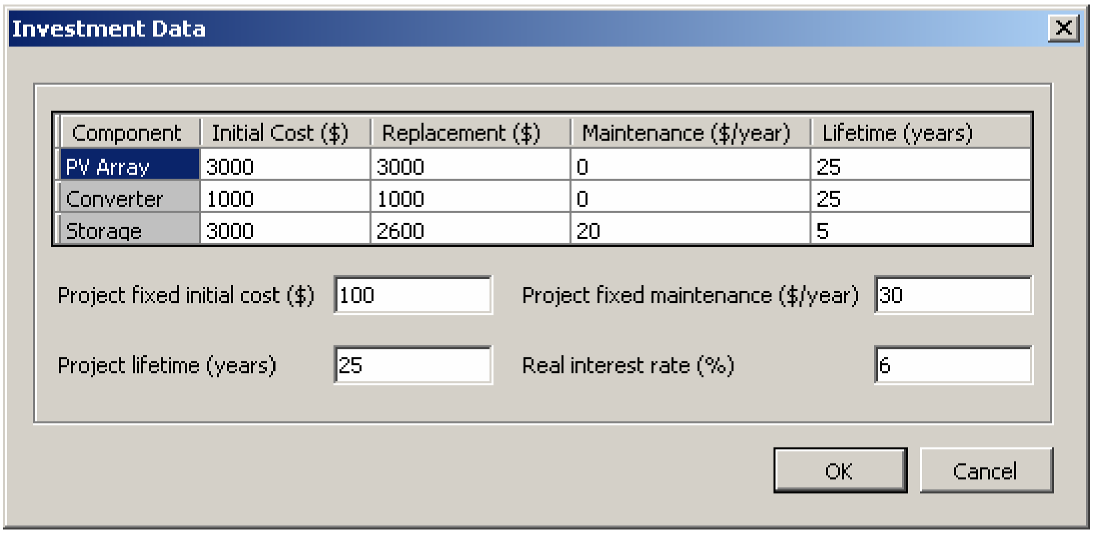

Figure 4.9: Investment data dialog box

4.4 Timeline Control and Simulation Output

When all required parameters are set, the user initializes the simulation. The timeline control, shown in Figure 4.10, is set up so as to enable the user to advance the simulation timeline at various increments. At any point on the time line, the user can advance the simulation for a single timeline hour at a time, or up to the end of the current timeline day, month, or year. At the end of any such increment the simulation is paused to allow the user to examine the various output records produced up to the reached point. In any case the simulation is performed in hourly steps. At the end of any of the selected simulation increments, the tabular data is updated to reflect the cumulative recorded values.

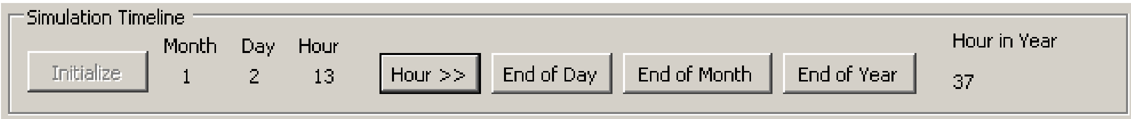

Figure 4.10: Simulation timeline control

In order to be able to relate simulation result to the specified system design (defined by various system parameters), which is fixed throughout the system lifetime, the user is not allowed to change parameters while advancing the simulation timeline throughout simulation. But dialog boxes can still be accessed to view the parameter values. As the end of the simulated year is reached, a cost-benefit analysis is performed by projecting the financial results over the system lifetime. Economic indicators are calculated and displayed. Afterwards, the user may continue to view or copy the simulation results, and may adjust parameters and restart simulation from the beginning.

During simulation, the results of the last simulated hour are also displayed graphically as arrows on the system schematic diagram. The arrows point in the direction of energy flow between components and the buses they are connected to. For example a snapshot of the system at the end of a simulated hour during a simulation run is shown on Figure 4.11. This example shows that energy produced by the photovoltaic array during that hour exceeds the energy demand by the load even after inverter losses are deducted. The remaining energy is fed into the utility grid. Figure 4.12 shows an example of a system configuration that has an energy storage component. The example shows storage contribution during a scheduled discharge. Detailed results of solar resource calculations are displayed in a dedicated output panel (Figure 4.13).

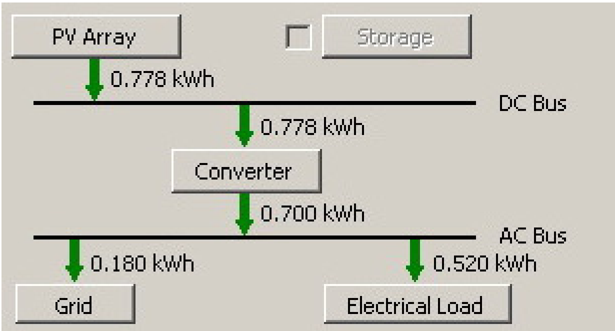

Figure 4.11: Energy flow shown on the system schematic diagram (no storage)

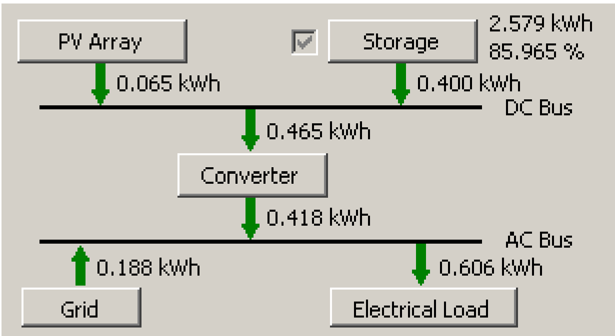

Figure 4.12: Energy flow shown on the system schematic diagram (with storage)

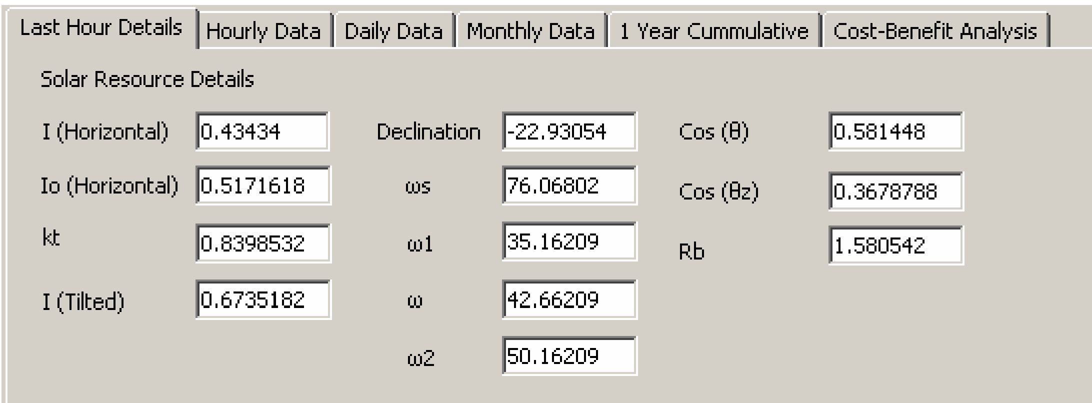

Figure 4.13: Display of detailed results of solar resource calculations

The software displays results for the 8760 hours of the simulated year. A sample of these hourly results is shown in Figure 4.14. As the timeline progresses, hourly values are aggregated into daily, monthly and yearly totals. Figures 4.15, 4.16 and 4.17 show samples of such results as displayed in the software main window. The simulation software records energy drawn from or transferred to the electrical grid, accumulated in each flow direction separately, on a daily, monthly, and yearly basis. The net energy flow from the grid is accumulated similarly. Net energy flow is the difference between energy drawn from the grid and energy added to the grid. Other energy flow quantities are also metered and accumulated and can provide useful information in studying the operation of the system. For example hourly photovoltaic array output is recorded and accumulated in daily, monthly and yearly sums. Data in tables can be copied to a spread sheet application, possibly for further analysis and graphical representation.

Last Hour Details | Hourly Data | Daily Data | Monthly Data | 1 Year Cummulative | Cost-I

No.	m	d	h	Load (kWh)	PV Energy (kWh)	Wasted Excess (kWh)	From Grid (kWh)
33	1	2	9	0.56106	0.098	0.000	0.468
34	1	2	10	0.55336	0.228	0.000	0.337
35	1	2	11	0.48021	0.548	0.000	-0.040
36	1	2	12	0.52041	0.781	0.000	-0.222
37	1	2	13	0.60045	0.792	0.000	-0.152
38	1	2	14	0.67002	0.605	0.000	0.095
39	1	2	15	0.68233	0.609	0.000	0.104
40	1	2	16	0.62638	0.280	0.000	0.361
41	1	2	17	0.77991	0.000	0.000	0.780
42	1	2	18	0.9098	0.000	0.000	0.910

Figure 4.14: Tabular display of hourly energy flow results

Last Hour Details | Hourly Data | Daily Data | Monthly Data | 1 Year Cummulative | Cost-Benefit Analysis

m	d	Load (kWh)	PV Energy (kWh)	Wasted Excess (kWh)	From Grid (kWh)	To Grid (kWh)	Net From Grid (kWh)
3	1	14.514	3.953	0.000	10.903	0.144	10.759
3	2	15.670	1.740	0.000	14.016	0.000	14.016
3	3	19.555	6.268	0.000	13.684	0.085	13.600
3	4	18.254	5.616	0.000	13.264	0.346	12.919
3	5	16.860	5.890	0.000	11.487	0.223	11.265
3	6	15.919	6.339	0.000	10.715	0.818	9.897
3	7	15.707	7.274	0.000	10.065	1.268	8.797
3	8	15.691	5.006	0.000	11.365	0.430	10.935

Figure 4.15: Tabular display of daily energy flow results

Last Hour Details | Hourly Data | Daily Data | Monthly Data | 1 Year Cummulative | Cost-Benefit Analysis

m	Load (kWh)	PV Energy (kWh)	Wasted Excess (kWh)	From Grid (kWh)	To Grid (kWh)	Net From Grid (kWh)	Ref. Pay ($)	Pay ($)	Benefit ($)
1	508.131	105.401	0.000	417.044	9.043	408.001	46.493	34.160	12.333
2	450.530	113.031	0.013	352.446	9.282	343.164	39.264	26.380	12.884
3	520.846	159.485	0.077	383.524	14.116	369.408	48.514	29.529	18.985
4	497.305	176.527	0.000	347.512	17.908	329.604	44.877	24.752	20.124
5	501.205	202.387	0.005	333.255	24.314	308.941	45.392	22.273	23.119
6	499.301	217.406	0.033	322.580	29.783	292.797	45.116	20.480	24.636

Figure 4.16: Tabular display of monthly energy flow results

Last Hour Details | Hourly Data | Daily Data | Monthly Data | 1 Year Cummulative | Cost-Benefit Analysis

Load (kWh)	PV Energy (kWh)	Wasted Excess (kWh)	From Grid (kWh)	To Grid (kWh)	Net From Grid (kWh)	Ref. Pay ($)	Pay ($)	Benefit ($)
6,022.481	1,988.103	0.764	4,351.466	217.940	4,134.526	548.581	318.699	229.882

Figure 4.17: Tabular display of one year cumulative energy flow results

For each month the software calculates (and displays in the monthly results table) two energy bill values. These are calculated according to the specified grid energy pricing scheme. One is calculated assuming the load is fed only by the grid (i.e. as if the photovoltaic system is not installed), and the other with the results of the simulation of the photovoltaic system. The monthly benefit is the difference between the two bills. The yearly benefit of the system is accumulated from the calculated monthly benefit values. At the end of simulation the software uses this financial benefit result along investment data to perform a cost-benefit analysis of the system. Figure 4.18 displays a sample of such analysis as displayed by the software.

Last Hour Details | Hourly Data | Daily Data | Monthly Data | 1 Year Cummulative | Cost-Benefit Analysis

Present value of cost

Item	Initial Cost ($)	Replacement ($)	Maintenance ($)	Salvage ($)	Total ($)
PV Array	3000	0	0	0	3000
Converter	1000	0	0	0	1000
Storage	0	0	0	0	0
Fixed	100	0	383.5007	0	483.5007
Total	4100	0	383.5007	0	4483.5

Present value of benefit ($) 2938.666   Internal Rate of Return (%) 1.583743

Net Present Value ($) -1544.834   Simple Payback (years) 20.51208

Figure 4.18: Display of cost-benefit analysis results

These financial results are used in assessing the economic viability of the system. The results of this analysis include present value of all cost items, the total present value of cost, the total present value of benefit, and net present value. Results also include internal rate of return and simple payback time. Present value P of an annual monetary amount A, such as annual benefit or annual maintenance, is calculated using the following equation (Newnan, 1991)

$$P = A\left[\frac{(1+i)^{N}-1}{i(1+i)^{N}}\right] \tag{4.1}$$

Where i is the real interest rate and N is the number of years. Present value P of a future value F, such as replacement cost, is calculated using the following equation

$$P = \frac{F}{(1+i)^{N}} \tag{4.2}$$

Internal rate of return is the value of i that makes total net present value equal to zero. It is found by iteration. Simple payback time is found by dividing total initial cost by annual benefit.

CHAPTER 5

SIMULATION RUNS: RESULTS AND DISCUSSION

The simulation is run under a variety of settings to inspect the effect of certain system parameters on a studied case. Section 5.1 explains the preparation of input data used in the simulation runs. Section 5.2 presents a set of operation scenarios for system parametrical evaluation. In Section 5.3 a comparison is made of a sample of results obtained using the present software with those of an established software package.

5.1 Input Data

The input data consist of an hourly time series of solar radiation and another hourly time series of electrical load. The following subsections describe how the input data is prepared for the simulation.

5.1.1 Solar Resource Data

The solar resource data used in the simulation runs is a list of 8760 hourly global irradiation values on a horizontal surface representing a full year. The data is synthesized from monthly average daily global irradiation on a horizontal surface. The source of the monthly average data is PVGIS[1]. The selected location is the University of Jordan in Amman/Jordan (Longitude: 35.872º East, Latitude: 32.010º North). The monthly average daily global irradiation data returned by PGVIS for this location is shown in Table 5.1. The data is also plotted in Figure 5.1. HOMER software is used to

[1] Available at http://re.jrc.ec.europa.eu/pvgis. According to the FAQ page the data source is "HelioClim-1 database (© Ecole des Mines de Paris/Armines), consisting of daily sums of global horizontal irradiation calculated from Meteosat Prime images over the whole disc. The values represent the period 1985-2004." (Accessed February 2009)

synthesize hourly data from the given monthly averages. A sample of the generated data is given in Table 5.2. Figure 5.2 is a plot of that sample data against the timeline. This sample shows three different daily cloudiness conditions.

Table 5.1: Monthly average daily global solar irradiation data on a horizontal surface for the studied location.

Month	Average Daily Irradiation (kWh/m^2)
January	2.69
February	3.47
March	4.78
April	6.00
May	7.16
June	8.27
July	7.96
August	7.26
September	6.11
October	4.54
November	3.24
December	2.58

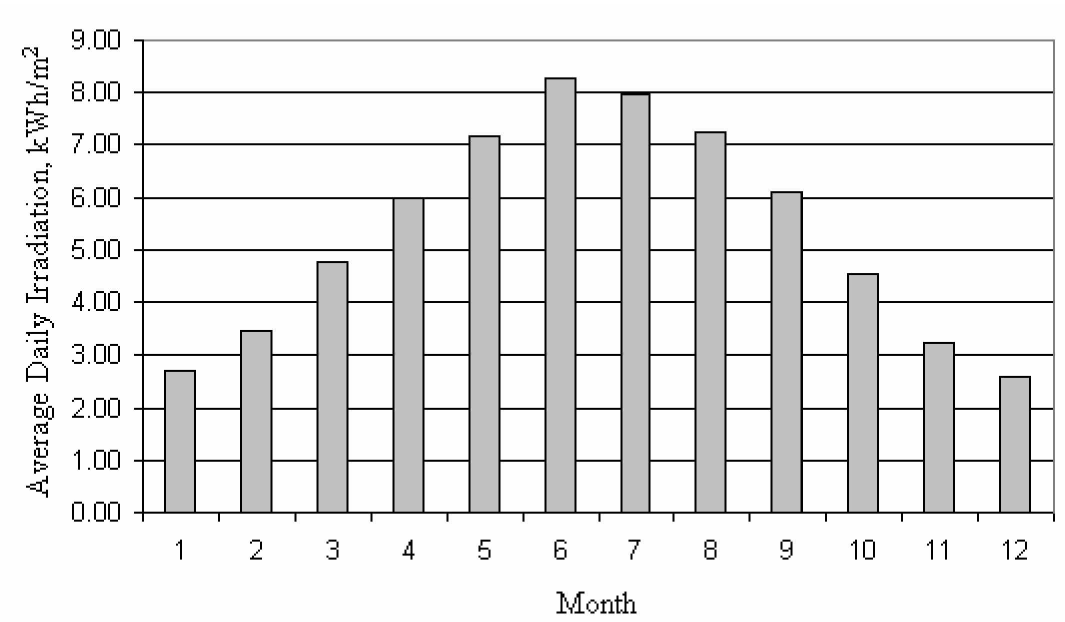

Figure 5.1: Column diagram representing the monthly average daily global irradiation data on a horizontal surface for the studied location

Table 5.2: A sample of the synthesized hourly solar radiation data used in the simulation runs.

	Irradiation (kWh/m^2), I		
Hour (ending at)	**January 5**	**January 6**	**January 7**
1:00	0.00000	0.00000	0.00000
2:00	0.00000	0.00000	0.00000
3:00	0.00000	0.00000	0.00000
4:00	0.00000	0.00000	0.00000
5:00	0.00000	0.00000	0.00000
6:00	0.00000	0.00000	0.00000
7:00	0.00785	0.00660	0.00735
8:00	0.03690	0.11155	0.07473
9:00	0.07013	0.34368	0.16387
10:00	0.07083	0.56690	0.35599
11:00	0.10366	0.61763	0.57080
12:00	0.08344	0.61333	0.44707
13:00	0.12805	0.60217	0.53868
14:00	0.01527	0.59307	0.47055
15:00	0.06217	0.42278	0.38418
16:00	0.04780	0.25150	0.22758
17:00	0.01019	0.05237	0.04916
18:00	0.00000	0.00000	0.00000
19:00	0.00000	0.00000	0.00000
20:00	0.00000	0.00000	0.00000
21:00	0.00000	0.00000	0.00000
22:00	0.00000	0.00000	0.00000
23:00	0.00000	0.00000	0.00000
00:00	0.00000	0.00000	0.00000

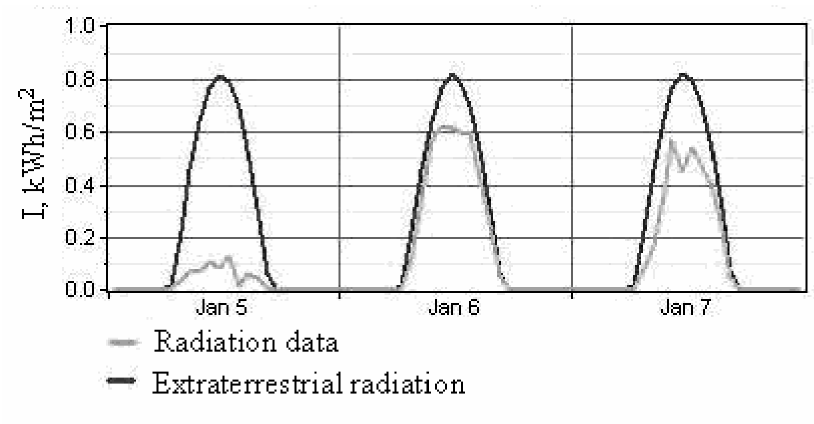

Figure 5.2: Plot of sample hourly data. The diagram also shows extraterrestrial solar radiation

5.1.2 Load Data

HOMER is also used to generate a list of 8760 values representing the electrical load hourly power demand for a full year. HOMER synthesizes the hourly data from daily load profiles. It can incorporate randomness from day to day and from one hour to another. A daily load profile is hourly demand for a full day represented by 24 values. Once a load profile is constructed a scaling factor can be used to obtain a required monthly total demand while preserving the shape of the load profile.

A sample load profile available with HOMER is shown in Figure 5.3. It can be noted that two peaks in load occur, a slight one in the morning and a larger one in the evening. This is an example of an unfavorable load profile in conjunction with a photovoltaic system, since its peak does not coincide with hours of maximum photovoltaic power generation at midday. In the next section it will be noted what load profile is used for each simulation case.

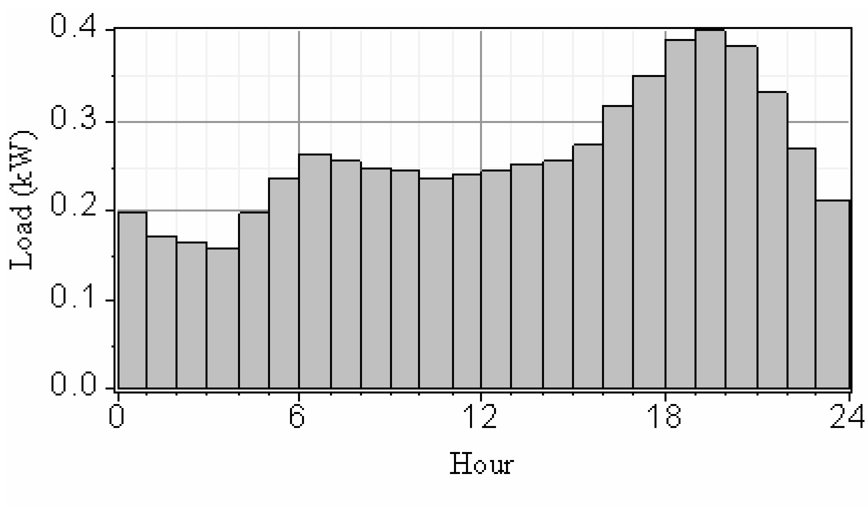

Figure 5.3: A sample load profile

5.2 Simulation Scenarios

The simulation scenarios are desinged to cover the system from three points of view; the amount of energy produced by the system, the effect of the system on the local demand profile and the economic value of the system.

5.2.1 Photovoltaic Energy Production

Photovoltaic array slope is optimized for maximum total yearly energy production. In this section the effect of the photovoltaic array slope angle on its energy production is studied. For this purpose it is possible to observe the direct output energy of the photovoltaic array component. However, to give the results additional sense in reflecting useful produced energy upon passing through the inverter, it is the system total energy outflow at the grid connection that is observed in this scenario while setting the load to zero.

In this scenario the simulation is repeated while fixing all variables except the photovoltaic array slope angle. Photovoltaic array capacity is set at 1 kWh, with 90% derating factor facing south at 0º azimuth angle. The inverter capacity is set at 2 kW to make sure no energy is blocked. Inverter efficiency is set at 92%. The observed output is the energy flowing into the grid in a full year. The sequence is repeated for two values of ground reflectance (0% and 20%).

Table 5.3 lists the results while ground reflectance is set to 0% and 20% respectively. The energy maximum output, denoting an optimum slope angle, is highlighted with a bold typeface. It can be noted from the tables that small changes of tilt angle around the optimal angle do not yield significant changes in total produced yearly energy. Moreover, it can be noted that increase in photovoltaic power production due to a higher ground reflectance at the shown tilt angles is not significant.

Table 5.3: Photovoltaic system electrical energy production for one year against photovoltaic array slope angle at two values of ground reflectance GR (0% and 20%).

	Electrical Energy (kWh)	
Slope (degrees)	GR = 0%	GR = 20 %
0	1615.969	1615.969
5	1660.575	1661.188
10	1694.055	1696.503
15	1716.300	1721.790
20	1726.375	1736.087
21	1727.042	1737.728
22	**1727.342**	1739.056
23	1727.012	1739.789
24	1726.370	1740.257
25	1725.223	**1740.271**
26	1723.322	1739.563
27	1721.327	1738.813
28	1718.515	1737.280
29	1715.300	1735.377
30	1711.373	1732.793

5.2.2 Photovoltaic System Effect on Demand Profile

Due to its intermittent nature, a photovoltaic system modifies a building demand profile from the perspective of the electrical grid. For the purpose of demonstrating this effect, two hypothesized load profiles are used. The first (Load A) has its peak demand hours matched in time with the photovoltaic system maximum production at midday. For example, this load may represent air conditioning electrical load. On the other hand, the second (load B) has its peak unmatched in time to photovoltaic generation. These two load profiles are shown in Figures 5.4 and 5.5, respectively. The output energy of the photovoltaic array in a sample day is shown in Figure 5.6. As the photovoltaic system operates with load A and load B profiles, the energy withdrawal from the grid is shown in Figure 5.7 and Figure 5.8, respectively.

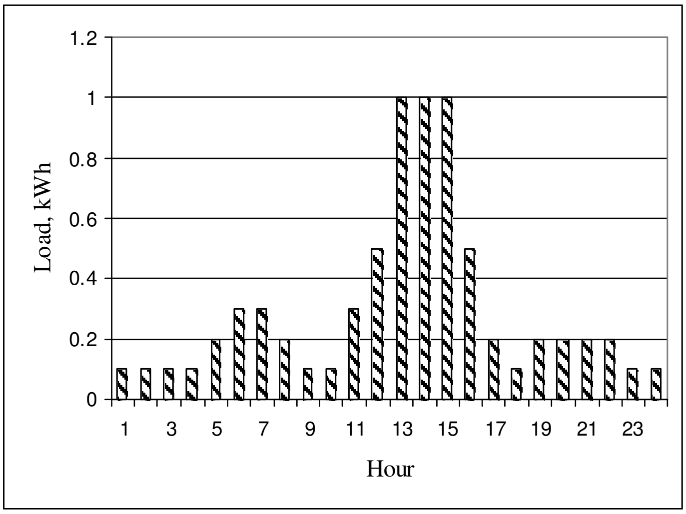

Figure 5.4: Load A profile, matched in time to photovoltaic generation

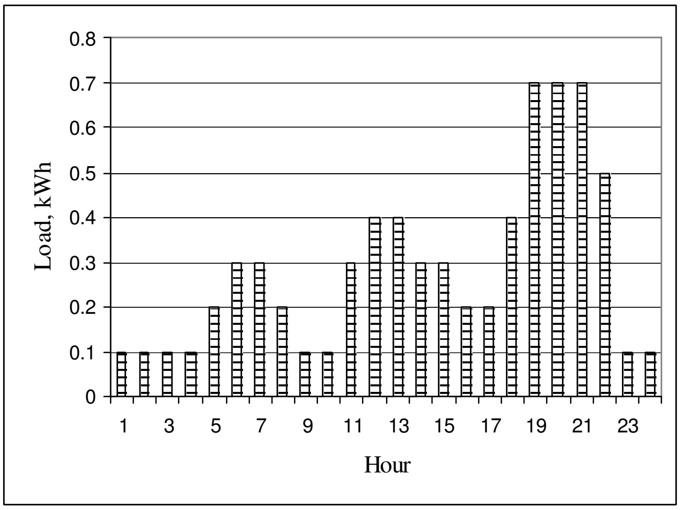

Figure 5.5: Load B profile, unmatched in time to photovoltaic generation

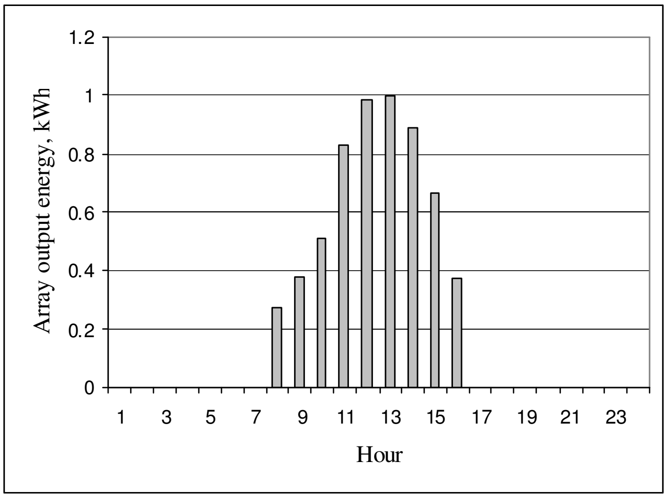

Figure 5.6: Photovoltaic array output energy in a sample day

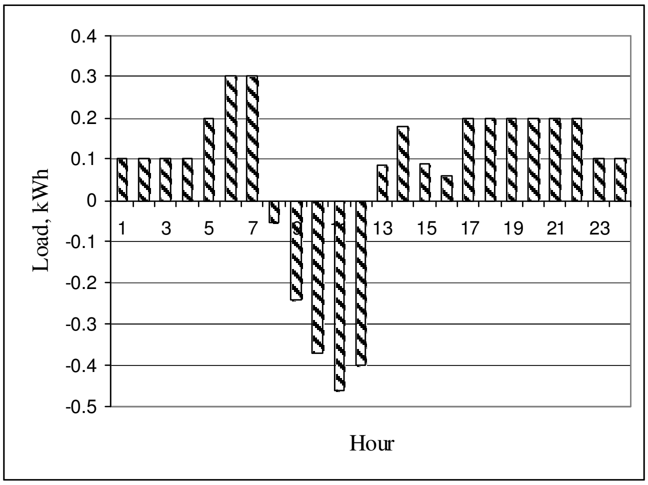

Figure 5.7: Load A with photovoltaic system

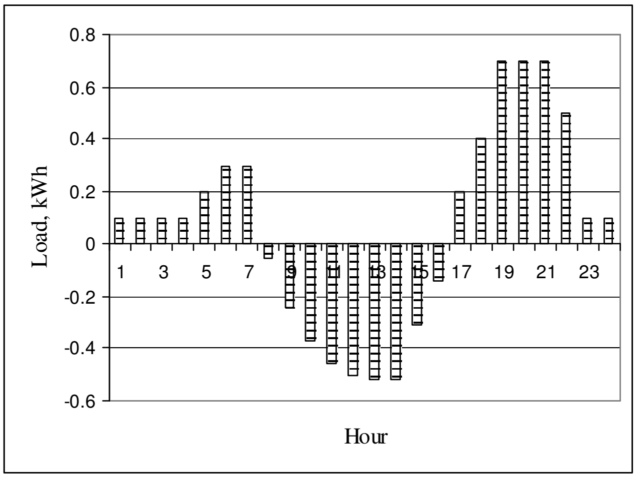

Figure 5.8: Load B with photovoltaic system

In the next simulation run, the role of storage in managing load B profile is demonstrated. Figure 5.6 shows that significant photovoltaic generation occurs from hour 9 to 15. Maximum load occurs from hour 18 and 22. The storage component capacity is chosen as 2 kWh. Maximum charging and discharging rates are set to 0.3 and 0.4 kW, respectively. Efficiency of both operations is set to 95%. Charging is scheduled to start at 8:00 (beginning of 9th hour), while discharging is set to start at 17:00 (beginning of 18th hour). The rectifier capacity is set to 0.3 kW with 92% efficiency. The effect of this arrangement on demand for grid energy is shown in Figure 5.9 as a more level profile.

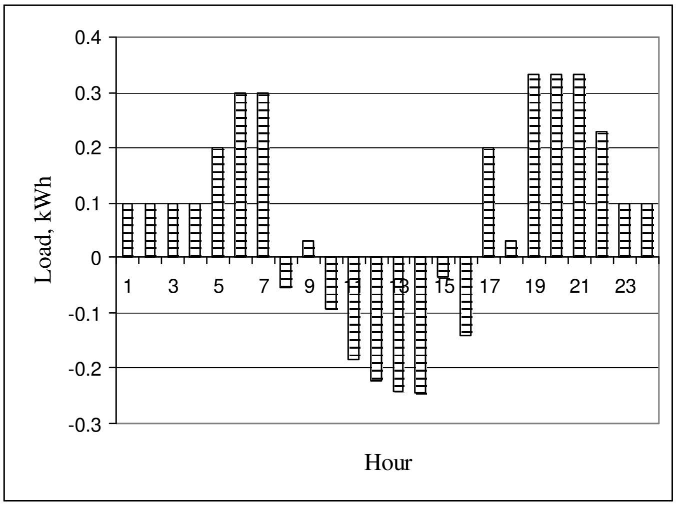

Figure 5.9: Use of storage with load B profile to level demand

5.2.3 Economic Value

Installing a grid connected photovoltaic system on a building reduces the monthly electrical energy bill and may even produce a net income to the investor. The economical question is whether the system financial benefit justifies the investment in its installation. The answer depends on a financial cost-benefit analysis, which depends on the cost of the system components and the applied energy pricing scheme. If the investment is not justified under current economical conditions then it is useful to know what conditions make the system profitable.

Grid connected photovoltaic generation is not yet applied in Jordan, and hence, hereby cost refers to expected cost which is assumed consistent with global figures. There is a range of prices of system components depending on manufacturer which is also subject to fluctuations with time. This evaluation scenario is based on example cost information of a photovoltaic system of a nominal capacity of 3 kW as discussed by Kaltschmitt et al. (2007). This system uses multicrystaline silicon cells of 16% efficiency. Table 5.4 summarizes the cost of the system components. Prices in Euro (€) are converted to USD ($) using a conversion factor of 1.3 USD/€.

Table 5.4: Investment data of the studied proposed system.

	Investment	
Item	€	$
Photovoltaic Modules	7800	10140
Inverter	1100	1430
Further Components	1200	1560
Miscellaneous	2900	3770
Total	13000	16900
Annual Maintenance	30	39

The price of electrical energy for the domestic sector in Jordan depends on slices of consumption. The presently applied prices, both in JD and USD at a conversion factor of 0.71 JD/USD, are shown in Table 5.5. For the commercial sector, a flat rate price of 0.086 JD/kWh is applied. This is equivalent to 0.121 USD/kWh.

Table 5.5: Electrical energy tariff for domestic consumers in Jordan.

	Price per kWh	
Consumption Slice (kWh)	JD	$
1-160	0.032	0.045
161-300	0.071	0.100
301-500	0.085	0.120
>500	0.113	0.159

Sum of "Further Components" and "Miscellaneous" constitutes "Project fixed initial cost" in the simulation software. All these financial parameters are entered in the simulation software along with system parameters as outlined in Table 5.6.

Table 5.6: Values of system parameters for the economic evaluation scenario.

Component	Parameter	Value
Photovoltaic array	Rated Capacity (kW)	3
	Derating Factor (%)	90
	Slope angle (degrees)	25
	Azimuth angle (degrees)	0
	Ground reflectance	0.20
Converter	Inverter Capacity (kW)	3
	Inverter Efficiency (%)	92

First test is to find the total energy production of the system per year. To do this, load in the simulation is set to zero so that all system energy production is transferred to the grid and metered at the grid connection. It turns out that this amount is equal to 5221 kWh/year. At a lifetime of 20 years and 4.5% real interest rate, the net present value of cost is $17407 (or 12360 JD). Under this zero loading, it is found (by iteration) that a value of $0.256/kWh as a sellback price results in present value of revenue equal to the total present value of cost (i.e. a net present value equal to zero). This means that functioning as a dedicated generator for the electrical grid this photovoltaic system produces energy at a cost of $0.256/kWh (0.182 JD/kWh) throughout its lifetime, which is not economical. By repeating the procedure with 25 and 30 years as lifetime (same interest rate) the produced energy cost decreases to $0.226 (0.160 JD/kWh) and $0.206/kWh (0.146 JD/kWh) respectively. These values are still above maximum energy rate for the domestic consumers. Figure 5.10 displays these energy cost values against lifetime in years.

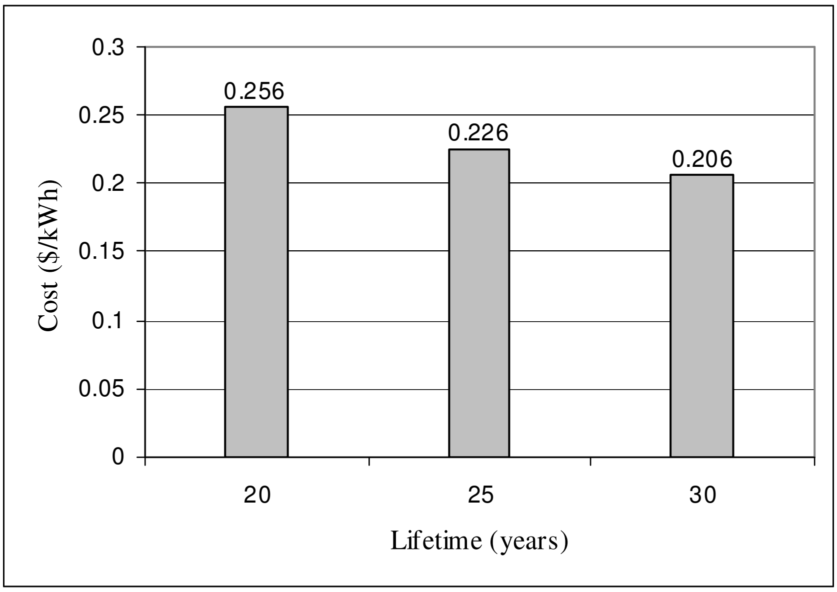

Figure 5.10: Cost of produced energy against lifetime, load set to zero

Next, this system is run with load A and load B profiles from the previous section scaled so that their total yearly consumption values are equal to the total useful photovoltaic energy production (i.e. after passing through the inverter, and equal to 5221 kWh/year as explained above). While energy is exchanged back and forth with the grid during the year, at the end of the year the load would have consumed the same amount generated by the photovoltaic system.

The aim of this simulation run is to determine the minimum sellback price for system profitability, under both load profiles. The applied sellback scheme uses two pricing arrangements for inflow and outflow energy separately (that is, the contrary of net metering). The sliced pricing scheme is used for energy purchase (i.e. the energy inflow). Starting with load A profile the minimum profitable sellback prices is found to be $0.46 (0.327)/kWh. With the load B profile this minimum sellback price is $0.337/kWh (0.239 JD/kWh).

This scenario shows that while load B is not time matched to the photovoltaic array production, it is more profitable in the described pricing scheme. The reason for this is that more photovoltaic energy is sold to the grid at midday because the local load is low during this time. And in the evening energy is bought from the grid at a price that is lower than the sellback price. This can be used as an incentive for consumers to shift their electrical load to off-peak hours in a way that is favorable to the electric utility company from a demand point of view. The avoided operation of expensive peaking generation units might justify that the utility pay the high sellback price.

5.3 Comparison of Sample Results

A sample of the results obtained in the previous section is compared with matching results obtained using HOMER. The first comparison is made between results recorded in Table 5.3 and Table 5.7. Table 5.7 illustrates results obtained using HOMER for the same conditions used to find the optimum slope angle of a photovoltaic array in Amman/Jordan in section 5.2.1. Matching results between the two tables are very close with error that does not exceed 0.5 %.

Table 5.7: Photovoltaic system electrical energy production for one year against photovoltaic array slope angle at two values of ground reflectance GR (0% and 20%), results obtained using HOMER.

	Electrical Energy (kWh)	
Slope (degrees)	GR = 0%	GR = 20 %
20	1731	1741
21	1732	1743
22	**1733**	1745
23	1733	1746
24	1733	1747
25	1732	**1747**
26	1731	1747
27	1729	1747

The second comparison is between net present value of cost described in section 5.2.3. The present software and HOMER give an identical result of $17407. The third and final comparison is of the produced energy at the grid interface for a full year as described also in section 5.2.3. HOMER records 5242 kWh vs. 5221 kWh by the present software. The difference is only 0.4 %.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the conclusions of the present study and introduces some recommendations for relevant future work.

6.1 Conclusions

The following conclusions are made from the present study:

1. In this study, a computer software application was constructed to simulate the flow of energy between the components of a grid connected photovoltaic generation system and with the electrical grid.
2. The simulation is done on an hourly basis. The software presents hourly results as well as daily, monthly and full year aggregates. This detailed data is useful in studying the operation of the system under different daily operational conditions in terms of solar resource availability and electrical load.
3. The simulation implements an optional generic storage device with scheduled charging and discharging to demonstrate the operational value of using local storage to improve the electrical energy demand profile.
4. The developed software determines the financial benefit of the system by comparing the energy cost for a building that uses that system against a reference case of depending solely on the electrical grid.
5. In this study, the developed software is used to determine the optimal slope angle of fixed photovoltaic array in Amman and found to be 25° at 0.20 ground reflectance.

6. High investment cost in the photovoltaic system is the primary hindrance against its economic value. This also applies under solar radiation amounts and present electrical energy pricing in Amman/Jordan. Methods to increase system financial competitiveness include measures to decrease investment cost by subsidies for example, or high electrical sellback prices. High sellback prices might be justified by system value in decreasing demand for electrical energy at peak times.

6.2 Recommendations

1. In this study, approximate linear energy conversion models were used for the system components. For a future research interested in identifying the electrical characterization (current and voltage) of these components, relevant models could be used.
2. This study approximates the effect of temperature using a long-term derating factor. This derating factor is generally tuned to more accurately represent energy production during months of maximum energy production, (i.e. summer months). Different modeling of temperature effect might be used in a future research.

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محاكاة حاسوبية لغرض التقييم التشغيلي و الاقتصادي لنظام التوليد الكهروضوئي المتصل بالشبكة بمستوى المبنى تحت الظروف المناخية للأردن

إعداد
أيمن أحمد إبراهيم حمد

المشرف
الأستاذ الدكتور محمد أحمد السعد

ملخص

تم إنشاء برنامج حاسوبي في هذه الدراسة لمحاكاة معدل التدفق للطاقة لكل ساعة لنظام توليد كهروضوئي متصل بالشبكة لسنة كاملة. نموذج النظام يتكون من عنصر التوليد الكهروضوئي، مغيّر طور التيار، و عنصر لتخزين الطاقة كمكون اختياري. عنصر التخزين يدعم الشحن و التفريغ المجدولان زمنيا لخفض ذروة الطلب. تسجل نتائج المحاكاة لكل ساعة و في مجاميع يومية، شهرية و للسنة كاملة. و تعتبر هذه المعلومات مفيدة لتقييم القيمة التشغيلية للنظام من حيث تأثيره على شكل الطلب على الطاقة الكهربائية لمبنى يستعمل هذا النظام.

يقوم برنامج المحاكاة و بشكل متزامن على إيجاد كمية الطاقة التي يتم تبادلها مع الشبكة الكهربائية بحالتين؛ حالة مرجعية لا تحتوي النظام و أخرى تحتويه. و يقوم البرنامج بحساب العائد المالي على أساس الفرق في تكلفة الطاقة الكهربائية من الشبكة ما بين الحالتين. يقارن البرنامج العائد المترتب على استخدام النظام و كلفته من خلال تحليل التكلفة–المنفعة.

تم استخدام البرنامج المنتج لتقصي تأثير تغيير محددات مواصفات النظام على كمية الطاقة التي ينتجها و قيمته الاقتصادية باستخدام كميات الاشعاع الشمسي في عمان–الاردن. فقد تم دراسة أثر تغيير زاوية ميل مجموعة التوليد الشمسية على الانتاج السنوي للطاقة. و قد استخدمت المعلومات المتوفرة لكل ساعة لتوضيح تأثير النظام على شكل الطلب اليومي على الطاقة. يظهر تشغيل المحاكاة بالأسعار الحالية للكهرباء في الاردن أن مزيدا من الانخفاض على تكلفة الاستثمار في النظام و/أو استخدام سعر مرتفع بشكل مناسب للطاقة التي يضيفها النظام للشبكة الكهربائية ضروريان لاعتبار النظام مجدٍ اقتصاديا.