PERFORMANCE OF A PHOTOVOLTAIC MODULE WITH AN INTEGRATED COMPOUND PARABOLIC CONCENTRATOR AND A COOLING SYSTEM.

BY

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University or any other award.

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DEDICATION

To my parents

Daniel Lelmet and Christina Kiplagat

for their unconditional love and great sacrifices they have made to me.

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ABSTRACT

In recent years, Photovoltaic (PV) power generation has been receiving considerable attention as one of the promising energy alternatives for rural areas in developing countries. However, their widespread adoption has been hampered by the high capital cost and low conversion efficiencies of the available systems. Incorporation of a solar concentrator has been found by a number of researchers to increase the electrical power output of a PV module. However it exceedingly raises the module temperature, consequently lowering further its conversion efficiency.

The study was carried out to improve the conversion efficiency of an amorphous silicon PV module and to reduce the cost per unit output of the energy generated. This was done by incorporating a Cooling Unit (CU) and a Compound Parabolic Concentrator (CPC) to the PV module, forming a Combined Heat and Power (CHP) system generating electricity and hot water. By circulating a fluid with a lower inlet temperature at the back surface of a PV module, heat is extracted from the PV module, thus maintaining the module cell temperatures at a lower level. This improves the electrical conversion efficiency of the cells. The extracted heat can be directed into useful purposes. This forms a Combined Heat and Power (CHP) PV system. Use of low cost concentrators on a CHP system increases the radiant energy available per unit surface of the module resulting in lower cost per unit of energy generated.

Four experimental systems were investigated: (i) Plain PV module

(ii) PV module with cooling unit (PV/CU) (iii) PV module with a CPC (PV/CPC) and (iv) PV module with a CPC and a Cooling Unit (PV/CPC+CU). Water was used as the cooling agent at a controlled flow rate. Three flow rates of 20 l/hr, 30 l/hr and 40 l/hr were tested in the study. Data collected were: current, voltage, solar radiation, ambient temperature, module temperature, and the inlet and outlet cooling water temperatures. A data logger (model Fluke 2286 series, U.K) was used to record data continuously at regular intervals from 9.00AM to 5.00PM. The power output, electrical and thermal efficiencies for the various study modules were computed and compared. Financial evaluation was performed by comparing the Levelized Energy Cost (LEC) of the systems tested.

The results obtained indicated that the cooling of a 51Wp PV module increases its electrical conversion efficiency. The PV module was cooled by an average of 14 °C from 48.5 °C to 34.4 °C, which increased the electrical power output and efficiency by 45.6% and 37.5% respectively. Combined CPC and cooling showed better electrical performance on the PV system than either the CPC or cooling alone. In total, an integrated CPC/CU had the best performance at a cooling water flow rate of 40 l/hr, which increased the electrical power output and efficiency by 118.74% and 120.0% respectively in comparison to PV Plain.

The 25% truncated CPC also increased the thermal energy output of the combined heat and Power (CHP) PV system. The maximum thermal energy output was observed at a cooling water flow rate of 30 l/hr. At this point the thermal energy output was 3.018 KWh/day.

This study has shown that a CHP-PV system with added CPC increased the electrical power output of conventional PV modules with the benefit of generating useful heat energy in the process. These findings are important contributions in the research efforts aimed at increasing the acceptability and affordability of solar technology in the rural areas of developing countries.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	Description	Units
A_m	Module area	[m^2]
A_L	Aperture area	[m^2]
A_S	Absorber area	[m^2]
A_{con}	CPC area	[m^2]
A	Solar cell area	[m^2]
C_p	Specific heat capacity	[kJ/kg.K]
C	Concentration ratio	[-]
C_f	Specific heat capacity of fluid	[kJ/kg.K]
C_T	Concentration factor for the truncated CPC	[-]
d	Discount factor	[%]
E	Energy	[kJ]
E_e	Electrical energy	[W]
E_{th}	Thermal energy	[kJ]
E_g	Semiconductor gap energy	[eV]
E_{ph}	Photon energy	[eV]
F_{pg}	Panel to ground view factor	[-]
F_{ps}	Panel to sky view factor	[-]
G	Solar Radiation	[W/m^2]
H	Height of the CPC	[m]
h	Coefficient of heat transfer	[$W\ m^{-2}\ {}^0C^{-1}$]

I_{sc}	Short circuit current	[A]
I_{ph}	Photocurrent	[A]
I_o	Saturation current	[A]
I_{mp}	Maximum power current	[A]
I_{tot}	Total Radiation	[W/m^2]
i	Inflation rate	[%]
k	Boltzman constant	[J/kg]
$(MC_p)_{mod}$	Effective thermal capacity of the PV module	[J/K]
m	Mass flow rate	[kg s^{-1}]
N	Period of analysis	[years]
P_{mod}	Power delivered by the module	[W]
q	Electronic charge	[Coulombs]
Q_{rad}	Radiative heat loss	[W]
Q_{in}	Solar radiation absorbed by the module	[W]
Q_{con}	Convective heat loss	[W]
Q_{elect}	Electrical power produced	[W]
T	Temperature	[^{0}C]
T_c	Cell temperature	[^{0}C]
T_a	Ambient temperature	[^{o}C]
T_o	Outlet water temperature	[^{0}C]
T_i	Inlet water temperature	[^{0}C]
T_g	Ground temperature	[^{0}C]

T_s	Sky temperature	[^{0}C]
V_{oc}	Open circuit voltage	[V]
V_{mp}	Maximum power voltage	[V]
V	Voltage	[V]
W	Aperture width	[m]
α_{abs}	Overall absorption coefficient	[-]
ε	Surface emissivity	[-]
σ_R	Wien's constant (=5.670 X 10^{-12} W $cm^{-1}K^4$)	[$Wcm^{-1}K^4$]
η_e	Electrical efficiency	[%]
η_t	Thermal efficiency	[%]
θ_a	Aperture angle	[degrees]
θ_T	Acceptance angle for the truncated CPC	[degrees]
β	The tilt angle	[degrees]
δ	Stephan-Boltzman constant (=5.67x10^{-8} W/m^2K^4)	[W/m^2K^4]
ε_p	Average emissivity of panel	[-]
ε_g	Average emissivity of ground	[-]
ε_s	Average emissivity of sky	[-]

Abbreviations

Ah	Ampere hour
ALCC	Annualized Life Cycle Cost
LEC	Levelized Energy Cost

AM	Air mass
CPC	Compound Parabolic Concentrator
FF	Fill (or curve) factor
Ksh.	Kenya Shillings
LCC	Life Cycle Cost
LEC	Levelized Energy Cost
PV	Photovoltaic
PV/T	Photovoltaic/Thermal system
Wh	Watt-hour
CHP	Combined Heat and Power
CU	Heat exchanger / Cooling Unit

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

The steady increase in demand for energy in developing countries has been triggered by technological developments, rapid population growth and increased economic activities. In the recent past, it has become obvious that the fossil fuel resource is fast depleting and its era is gradually coming to an end. This has called for enhancement and adoption of greater efficiency in production and consumption of this energy resource, and more strongly the reliance on environmental friendly, alternative energy sources such as solar and wind.

The majority of populations in developing countries live in rural areas. The combined effect of population growth, poor supply and high prices of conventional fuels is putting an ever-increasing pressure on traditional fuel supplies such as wood fuel, crop residues and animal residues. In Kenya, there are no known fossil fuel reserves. Over 70 % of the population is dependent on traditional fuel supplies mainly in form of fuel wood. This is needed to provide cooking and heating energy requirements (Republic of Kenya, 2000). The rate of fuel wood consumption exceeds replenishment; this has led to over exploitation of forests contributing to environmental degradation. Electrical energy is also needed to provide essential services such as refrigeration of vaccines in health institutions, lighting in schools, commercial sector, and households, just to mention a few. The provision of electricity to rural or remote locations is difficult and expensive; the extension of the main grid over arduous terrain and long distances is seldom economic for small power demands. This is why the Kenya rural electrification programme, through the extension of the main grid, has so far been unable to achieve its objective. The problem of economic viability also affects diesel generators, which rely heavily on the availability of imported, expensive petroleum fuels and maintenance (Hilsop, 1992).

Among alternative and renewable energy sources, solar energy and especially solar photovoltaics seems, to be one of the most promising. Solar cells are reliable, modular, durable and generally low maintenance and therefore suitable in isolated rural and remote areas. In addition, solar cells are quiet, benign, compatible with almost all environments, respond instantaneously to solar radiation, and have long expected lifetime of twenty or more years (Garg and Adhikari, 1997).

The UN estimates that two million villages within 20^{o} of the equator have neither grid electricity nor easy access to fossil fuels. It is also estimated that almost half of all people worldwide do not have electricity, with large number of these living in climates suited to PV applications (Markvart, 1994). PV modules are currently in use all over the world. However, the cost of fabrication and manufacture of solar cells is still relatively high and this is an impediment to the widespread utilization of PV technology in developing world where it is most needed. Ironically, the large percentage of countries that comprise the developing world lie in the Sunbelt of the world (Overstreaten and Mertens, 1986), and hence have the greatest percentage of solar radiation available to them throughout the year. Therefore it is these regions that stand to benefit most from solar technology.

1.2 Statement of the Problem

Solar photovoltaic modules are potentially important energy devices, which can provide valuable energy for use in rural areas to provide essential services. However, they have not been widely used in Kenya and other developing countries. High capital cost and low conversion efficiencies of available systems are two main barriers to the widespread dissemination of these technologies (McNelis et al., 1988). Solar radiation has a low power density and hence the area of PV modules needed to produce significant power output can become quite large.

The process of producing solar cells is costly due to the use of expensive pure silicon and the amount of energy consumed (Lasnier and Ang, 1990). This high cost of solar cell production requires that these cells be used in the most optimum way. Therefore, there is need to look for some avenues for enhancing the electrical output while keeping the cell surface area small as possible to justify the high cost of producing PV modules. It has been envisaged that a promising cost reduction technique, which can ensure the use of small cell areas, could be effective coupling with a solar concentrating device (Lique, 1989). As a result the output of solar cells would be increased, as more solar insolation would fall on the cell. In addition, for a given electrical output, the system cost would be less for concentrated cells as optical concentrating devices are cheaper than solar cells. This is an important and promising way of solar energy utilization.

During photovoltaic energy conversion, thermal energy is also generated resulting in the increase in cell temperature. Moreover, the introduction of concentrators generates even more elevated temperatures in the cells. The increase in temperature has been known to cause a great reduction in efficiency in converting solar energy into electrical energy (Odote, 1994; Neville, 1995; Diarra, 1998). Therefore, there is a need for a cooling system to transfer the thermal energy from the cells and ensure low cell temperatures. The extracted heat from the solar cells may be channelled for productive purposes e.g. water heating. Combining the PV module and a heat extraction device which channels the heat energy for productive purposes forms a Combined Heat and Power (CHP) system that can provide electricity and heat simultaneously.

This study examines the performance of a PV module with an integrated Compound Parabolic Concentrator (CPC) and a cooling unit as a measure of increasing the solar conversion efficiency and reducing the cost of unit energy output.

1.3 Significance of the Study

The cooling of PV module lowers the operating temperature of solar cells in the module resulting in an increase in electrical power output and efficiency. In addition, the cooling agent (water) taps the heat energy from the PV module, which could otherwise be wasted. The heat tapped can be used for bathing at homes, in hotels and boarding schools, space-heating application among other uses.

Although the integrated PV system with a CPC and a cooling unit will be more expensive than a PV module alone, the total energy output generated by the integrated system is higher than that of plain PV module. Furthermore, the use of a relatively inexpensive CPC to concentrate sunlight upon the PV module results in a further increase in both electrical and thermal energy. The increased energy output generated results in a lower cost per unit of the energy (Sh/kW). With the user understanding of the concept, this would enhance greater adoption and use of the CHP PV system.

This will help in providing essential services such as water pumping, lighting, vaccine refrigeration and telecommunications services especially in rural and remote locations resulting in improvement in the quality of life. In addition, reliance on imported fossil fuels such as kerosene commonly used for lighting and diesel used to power generator sets especially in remote urban centers, is reduced. This reduces environmental pollution and saves on foreign exchange.

1.4 Objectives of the Study

The general objective of this study is to improve the conversion efficiency of the existing commercial PV module and reduce the unit cost of energy output, by incorporating integrated Compound Parabolic Concentrator (CPC) and a Cooling Unit (CU), forming a CHP system generating electricity and hot water.

The specific objectives of the study were to:

1. Design and construct a Combined Heat and Power (CHP) PV system.
2. Investigate the effect of a CPC on the PV module power output.
3. Investigate the effect of cooling on combined PV/CPC system power output.
4. Investigate the effect of CPC on the thermal output of the CHP PV system.
5. Perform a financial evaluation of the CHP PV system.

CHAPTER TWO

LITERATURE REVIEW

2.1 Photovoltaic Technology

Photovoltaic effect is the generation of electricity directly from solar radiation. French Physicist Edmund Bacquerel first observed it in 1839 when he discovered that shining a light onto certain chemical solutions could produce an electric current. Later in 1877, Albert Einstein found out that photons could interact with electrons surrounding an atom's nucleus to cause a free stream of electrons, i.e. an electric current (Wolfgang, 1987). Work on PV properties of selenium in the 1870's resulted in the first selenium photovoltaic cell in 1883, which was used for many years for photographic light meters. This served its specialist purpose admirably but its cost and low efficiency of about 1% made it impractical as a means of producing electricity on a more substantial scale (Lasnier and Ang, 1990).

The development of modern PV systems dates from the mid-1950 when PV cells made from silicon began to come to the market. Chapin, *et al.* (1954) was able to develop a silicon solar cell with solar conversion efficiency of 6 percent that was used in specialized applications such as orbiting space satellites. They found applications in space programmes to power satellites (Wolfgang, 1994). Following the 1973 oil crisis, interest in PV as a terrestrial source of power increased greatly and many countries including several developing countries instituted PV research. This has led to steady fall in costs, development of additional uses and increase in conversion efficiency (Foley, 1990).

2.2 Efficiency of Solar Cells

The efficiency of solar cells is the proportion of solar energy falling upon it that is converted into electricity. The efficiency of solar cells varies with the cell type. It ranges between 13% - 33% for laboratory cells and 5% - 15% for commercial flat plate modules (Green, 1999). The efficiency of some common solar cells is given in Appendix B.

Considerable number of contributions has been made aiming at improving the performance of solar cells and solar power systems. One method has been to ensure that only a limited range, the optimum wavelengths, reach the solar cells. Dichronic mirrors have been employed to split the solar spectrum to separate sunlight photons of different wavelengths. These photons impact a number of solar cells constructed of various semiconductors with selected optimum photons wavelength ranges. Thus each solar cell operates with maximum conversion efficiency. The use of this method alone has proved to be expensive and non economical (Neville, 1995).

Green (1999), reported the use of tandem cells, which involves constructing a series of solar cells, one layered upon another. The top cell has the widest energy gap and only the highest energy photons are absorbed in this cell, the remainder being passed on to the subsequent solar cells. While an intriguing arrangement, a number of technological problems have been reported in this approach. In the first place, the construction of one solar cell upon a second semiconductor is not simple, as the fabrication process has to adjust for varying atomic sizes and interatomic spacing.

Another improvement technique involves the use of concentrators (mirrors or lenses). This method has been considered a promising method of reducing cost and increasing the efficiency of photovoltaic cells. The first experiment related to photovoltaic concentration was done by Adams and Day in London in 1876 where they used a convex glass lens to illuminate platinum - selenium junction and obtained an electromotive force of 0.5volts (Lique, 1989). In modern times, the first complete panel made with the aim of demonstrating a potential low cost technology for photovoltaic energy conversion was developed at Sandia Laboratories in Albuquerque (New Mexico), U.S.A. in 1977 (Burgess and Pritchard, 1978). Since then several prototypes have been developed, both in the U.S.A. and in Europe.

2.3 Solar Concentrator Systems

Various studies have been carried out on different concentration schemes since 1960's when they were first described (Duffie and Beckman, 1991). Several concentration schemes have been explored with positive results. In the past, several designs of optical concentrating devices for solar energy collection have been developed in order to generate high temperatures at high efficiency. These concentrators can be reflecting, refracting, imaging (e.g. parabolic mirrors and Fresnel lenses) or non-imaging (e.g. heliostat, and compound parabolic concentrators (CPC) (Lique, 1989). Figure 2.1 presents schematic diagrams of some different concentrating optics.

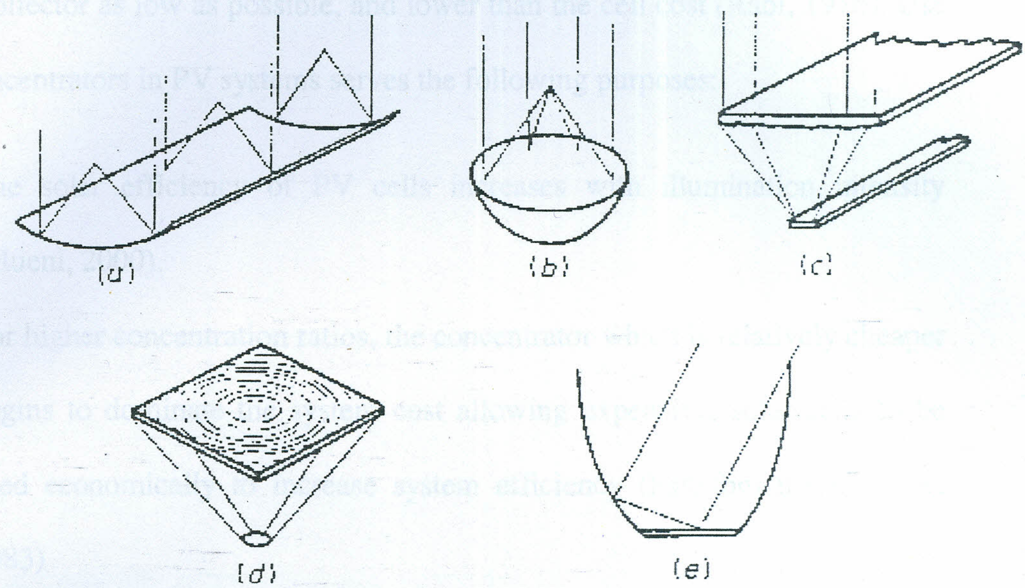

Fig 2.1 Sketch of some solar concentrating devices (a) Cylindrical - parabolic reflectors (b) Points focus paraboloid (c) linear Fresnel lens (d) Point focus Fresnel lens (e) Compound parabolic concentration (CPC). Source: Lique (1989)

Point focus concentrators such as shown in Fig 2.1 (a), (b), (c), and (d) are suitable for high concentration with one or some few solar cells with a specific arrangement. However high concentration presents some drawbacks when compared to flat non-concentrated panels. They require high accuracy tracking systems in order to keep the cells in focus, which introduces a certain amount of complexity in the design, increased maintenance requirements and increased costs. These factors make them unsuitable for rural or remote areas. In terrestrial applications concentration should be cost competitive; first with other photovoltaic approaches and then with other electricity sources. The saving is based primarily in keeping the cost of the optical surface acting on the sun collector as low as possible, and lower than the cell cost (Rabi, 1976). Use of concentrators in PV systems serves the following purposes:

(i) The solar efficiency of PV cells increases with illumination intensity (Mueni, 2000).

(ii) For higher concentration ratios, the concentrator which is relatively cheaper begins to dominate the system cost allowing expensive, solar cells to be used economically to increase system efficiency (Farenbruch and Bube, 1983)

Further work on static concentrators for photovoltaic modules at high latitudes has been done by several authors [Ronnelid et al (1996), Peres (1995), and Ovestraeten and Mertens (1986)]. Ronnelid et al (1996) has shown that booster mirror reflectors are suitable for panels that can utilize uneven illumination, and therefore amorphous silicon or thin film PV panels are preferable to crystalline panels. Peres (1995) reports an increase of 30% in the annual output of a solar thermal collector equipped with booster reflectors, with only 10% increase in installation cost. Overstraeten and Mertens (1986) points out that the economic viability of concentrator PV systems depends on maintaining a high cell and optical efficiency, a low concentration cost per unit area and a high reliability of the systems.

High concentration systems (up to 500X) have been found to be cost effective measure of energy production in solar thermal systems with a substantial amount of research being carried out in this area (Duffie and Beckman, 1991). However, the high temperatures generated by such concentration make it undesirable for PV systems (Green, 1982).

2.4 Compound Parabolic Concentrator (CPC)

The Compound parabolic concentrator (CPC) illustrated in Fig 2 (e) has been shown to be the most promising high concentration device, which provides elevated operating temperatures and represents the optimum optical properties for use in PV modules (Winston, 1974; Rabi, 1976).

Design factors of CPC's for equatorial latitudes are given by Mwamburi and Karsson (1996). It is shown in this study that series resistance have a large detrimental effect on the performance of solar cells under concentration. It recommends that the effective series resistance must be reduced to values less than $0.5\,\Omega/cm^2$ in order to preserve the solar efficiency. Mueni (1999) studied the performance of a CPC/PV system for equatorial latitudes and reported high module temperatures of up to 101.5°C and a power increase of 2X as a result of concentration with a 2D CPC with an acceptance angle of 15°. Additionally, she observed that wind reduces the maximum temperature reached by the

CPC/PV system to 65°C.

Acharya *et al.* (1993) and Lique (1989) have pointed out the advantages of CPC for PV concentration;

a) It has a high acceptance angle hence requiring only occasional adjustments.
b) Its concentration ratio is equal to the maximum value possible for any given acceptance angle.
c) They are non imaging and hence suitable for flat modules.
d) Does not require a tracking mechanism.
e) Can be easily fabricated at low cost using locally available materials.
f) Can collect diffuse component of radiation.

Because of its large acceptance angle, a CPC has a large acceptance of diffuse light than concentrating collectors using imaging optics. If the reflector is perfect, any radiation entering the aperture at the maximum acceptance angle will be reflected tangentially to the receiver at the base of the concentrator. Winston and Hinterberger (1975) showed that a non-imaging ideal concentrator configuration exists for any arbitrary cross-sectional shape of absorber. For solar applications, absorber shapes of interest are flat, fin, inverted 'V' and tubular (Ralb, et al, 1979). The tangents to the reflectors at the topmost points are parallel to the optic axis. These points are the upper end of the reflector and contribute little to the radiation reaching the absorber. The CPC can therefore be truncated to reduce its height with a resulting saving in the reflector area and little sacrifice in performance (Duffie and Beckman, 1991).

By using truncated CPC it is possible to concentrate solar radiation up to a concentration of 8X without diurnal tracking, only seasonal adjustments are necessary (Acharya, et al, 1993). The number of seasonal tilt adjustments of CPCs decreases with increase in acceptance angle as shown in Table 2.1 below.

Table 2.1 Tilt requirements of CPC's with different acceptance angles

Acceptance Half-Angle	Collection Time Average over year (h/day)	No. of adjustments per year	Shortest periods without adjustments (days)	Average collection Time if Tilt Adjusted every day (h/day)
19.5^0	9.22	2	180	10.72
14^0	8.76	4	35	10.04
11^0	8.60	6	35	9.52
9^0	8.38	10	24	9.52
8^0	8.22	14	16	8.82
7^0	8.04	20	13	8.54
6.5^0	7.96	26	9	8.36
6^0	7.78	80	1	8.16
5.5^0	7.60	84	1	8.00

(Source: Rabl, 1976)

Garg and Prakash (1997) have outlined that due considerations must be given to the effect of accumulation of dust and contamination, stability of reflective coating, environmental effects, cleaning problems and cost in the design of CPCs. A variety of reflecting mirrors in use include: glass reflectors, metalized plastic films (in general aluminised), polished aluminium surfaces and other metallic surface such as stainless steel. Most fresh aluminium surfaces have reflectivities of 80-85% while new and front surface glass reflectors can achieve about 95% reflectivity. However, it is the reflectivity that is retained after several years of exposure that is of interest. The long-term effects of environmental factors such as dust, sand and miscellaneous contamination on mirror surfaces is not well known (Jiefeng et al, 1995).

2.5 Effects of Temperature on PV Module Output

The effects of temperature on photovoltaic modules have been reported by various researchers (Overstraeten and Mertens, 1986; Neville, 1995; Odote, 1994; Diarra, 1998). The results show that temperature plays a significant role in power output of PV modules. The increase in temperature reduces the efficiency of photovoltaic conversion. The dominant effect is the decrease in open circuit voltage with increasing module temperature. On the other hand, the short circuit current slightly increases with temperature due to decrease in gap energy, E_g, resulting in an increasing absorption. Lasnier and Ang (1990) reported a decrease of 2mV per ^{0}C in the open circuit voltage between 20^{o}C and 100^{0}C and a maximum power decrease of 0.35% per degree Celsius rise and a proportionate decrease in maximum efficiency. Diarra (1998) reported that as the temperature increases above the reference temperature of 25 ^{0}C, the power output of the solar cell module falls by 0.5% per degree Celsius rise, while the conversion efficiency falls by 4% per degree Celsius rise.

2.6 PV/Thermal Systems

Brazilian and Prasad (2002) created a numerical model to predict the heat transfer and system energy output of a residential-scale building integrated photovoltaic (Bipv) cogeneration system. The cogeneration system was based on existing Bipv roofing technology with addition of a modular heat recovery unit. The convection of air behind cooled PV panels provided heat source for the residence. The models ability to utilize climatic data to simulate annual performance of the system serves as an important decision support tool in identifying areas for implementation of PV cogeneration systems.

Garg and Adhikari (1999) compared the thermal efficiency measurements for a hybrid energy-generating unit constructed by pasting single crystal silicon cells on a black-flat plate solar heat absorber. Three collector configurations were: a) black plate absorber, b) PV cells pasted on absorber to form a PV/T absorber and c) thermal/PV absorber with an additional glass cover. Results showed that the thermal / PV absorber with an additional cover glass was the most efficient.

Garg and Akidari (1997) developed a theoretical steady state and transient simulation models to predict the performance of hybrid PV/T air heating collectors. They reported thermal efficiencies in the range of 45% to 65%, higher values were derived for systems that included thermal losses suppression by air gap with glazing. These improvements however increased the system cost. They also observed that in hybrid PV/T air heating systems, a larger area of solar cells is required. This calls for avenues for enhancing the electrical output while keeping the cell area at a lower level.

CHAPTER THREE

THEORY

3.1 Introduction

In order to assess the performance of the PV/T system, it is necessary to have an adequate understanding of the various aspects that make up the system. This chapter gives the basic theory of solar radiation, solar cells, CPC design and thermal and electrical energy computing. Electrical and thermal efficiency calculations are also given.

3.2 Solar Radiation

Solar irradiance refers to the rate at which radiant energy is incident on a surface. The intensity of solar radiation on a unit area perpendicular to the beam outside the earth's atmosphere, also known as the solar constant is 1353W/m^2 (Duffie and Beckman, 1991). The solar intensity on the earth's surface is usually lower than the solar constant due to losses in the atmosphere resulting from scattering or absorption by air molecules, clouds and particulate matter. Solar intensity also depends on the position of the sun in the sky, which varies according to the geographical location, season and time of the day, A concept that characterises the effect of a clear atmosphere on sunlight is the *air mass,* equal to the relative length of the direct beam path through the atmosphere. On a clear summer day at sea level, the radiation from the sun at zenith corresponds to air mass 1 (abbreviated AM1); at other times, the air mass is approximately equal to $1/\cos\theta_z$ where θ_Z is the zenith angle. The intensity of solar radiation on the surface of a solar panel module is also affected by the direction the panel is facing and its tilt.

In order to capture the optimum amount of solar radiation, PV modules should be inclined close to the latitude angle of the site (Markvart, 1994). In stand-alone systems, it is usual to choose a somewhat steeper angle to minimize storage requirements and also to facilitate cleaning of the module by rain and wind. The solar energy absorbed by the PV module is expressed as;

$$Q_{in} = \alpha_{abs} G A_p \qquad (3.1)$$

where α_{abs} = overall absorption coefficient, A_p = total area of PV module (m^2), G = Solar radiation on the PV module surface (W/m^2).

The maximum intensity of solar radiation at noon on a clear day in the tropics is about 1 kilowatt per horizontal square metre. The total amount of solar energy per square metre per day, called the daily insolation, varies between 3.5 and 7 $KWhm^{-2}$ depending on the geographical location and season. In Kenya, the maximum is around 4-6 kWh per day (Hankins, 1991).

The radiation emitted from the sun lies within the ultraviolet, visible and infrared spectral regions. The radiation, which is most important in photovoltaic conversion, is the visible light and semiconductor materials that are excited by light in this range of wavelength are desirable. Table 3.1 below shows the various intensities of solar radiation reaching on the earth.

Table 3.1 Radiation intensities reaching the earth according to wavelengths (Garg and Prakash, 1997).

Radiation	Wavelength (nm)	Percentage
Ultraviolet	200 – 400	9
Visible light	400 – 800	49
Near infrared	800 – 1500	22
Far infrared	> 1500	16

3.3 Solar Cell Output Parameters.

Solar cells are essentially p-n junction diodes formed by making a junction between n type and p-type semiconductor regions. Sunlight incident on a solar cell creates electron-hole pairs within the semi conducting material making up the cell. The electrons and holes making up these generated electron-hole pairs separate and create flow in a load connected between the cell terminals (Green, 1999).

A simplified steady state equivalent circuit of a solar cell is shown in Fig.3.1 in which R_L is the load resistance. The behaviour of a solar cell can be characterized using three parameters, the open circuit voltage V_{oc}, the short circuit current I_{sc}, and the fill factor, FF. The open circuit voltage V_{oc} is the voltage output when the load impedance is much larger than the device impedance, which means that no current is flowing and it is the maximum possible voltage.

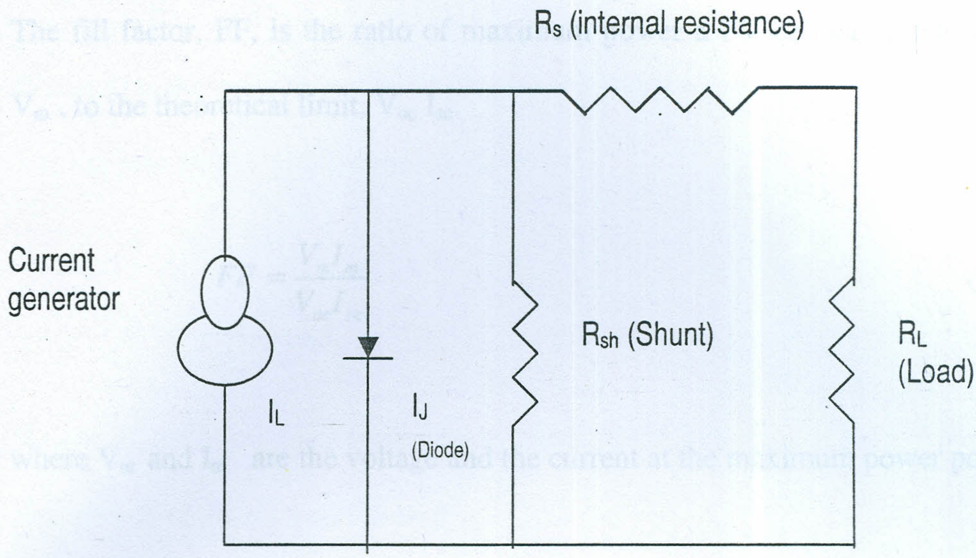

Fig. 3.1 Equivalent circuit of a solar cell (Garg, 1997)

The ideal value of V_{oc} is given by:

$$V_{oc} = \frac{KT}{q} \ln\left[\left(\frac{I_l}{I_o}\right) + 1\right] \qquad (3.2)$$

I_o is the saturation current, also called the dark generated current. I_o needs to be as small as possible for a maximum V_{oc}. For silicon, the maximum value is about 700mV. However, the value frequently used in calculation is 600mV (Overstraeten and Mertens, 1986; Rabl, 1976).

The short circuit current, I_{sc}, is the current output when the load impedance is much smaller than the device impedance and is the maximum possible current.

Ideally, it is equal to the light generated current I_L.

The fill factor, FF, is the ratio of maximum power a PV cell can produce, $I_m V_m$, to the theoretical limit, $V_{oc} I_{sc}$.

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{3.3}$$

where V_m and I_m are the voltage and the current at the maximum power point.

Equation 3.3 determines the shape of solar cell characteristics, and its value is higher than 0.7 for good cells (Lasnier and Ang, 1990). Ideally, the fill factor is a function of the open circuit voltage.

$$I_{sc} = I_o\left[\exp\left(\frac{qV_{oc}}{KT}\right) - 1\right] \tag{3.4}$$

No power is generated under the short or open circuit. The maximum power, P_{max}. is produced at a point on the characteristic where the product IV is the maximum.

$$P_{\max} = V_m I_m = FFV_{oc} I_{sc} \tag{3.5}$$

The energy conversion efficiency of a solar cell is the ratio of the optimum electric power delivered by the cell ($V_m I_m$) from the solar irradiance G received and is given by:

$$\eta = \frac{V_m I_m}{GA} = \frac{FFV_{oc}}{GA} \tag{3.6}$$

Where G is the solar radiation on the cell and A is the cell area.

The module electrical efficiency is given by:

$$\eta_e = \frac{P_{mod}}{GA_{mod}} \cos\beta \tag{3.7}$$

Where P_{mod} is the power generated by the module (IV), A_{mod} is the PV module area and β is the module tilt angle.

The thermal efficiency of the hybrid system can be calculated by the relation

$$\eta_{th} = \frac{\dot{m} c_f (T_o - T_i)}{GA_{mod}} \tag{3.8}$$

where $\dot{m}$ is the cooling fluid mass flow rate, c_f is the specific heat capacity of the fluid, T_o is fluid outlet temperature and T_i is the fluid inlet temperature.

In a CHP systems, the total efficiency can be calculated which corresponds to the sum of the electrical efficiency and the thermal efficiency for certain operating conditions. The total efficiency is given by:

$$\eta_{tot} = \eta_e + \eta_{th} \tag{3.9}$$

3.4 Geometry of 2D CPC

Winston (1974) noted the usefulness of geometry in the design of CPCs for solar energy collection. A two dimensional CPC as shown in Fig 3.2 consists of two distinct parabolic segments AB and DC, which are parts of two parabolas 1 and 2. AD is the aperture of width W and BC, the absorber surface of width b. The axes of the two parabolas are oriented to each other at an angle in such a manner that point C is the focus of parabola 1 and point B is the focus of parabola 2. The acceptance angle of the CPC is the angle AED ($2\theta_a$) made by the lines obtained by joining each focus to the opposite aperture edge.

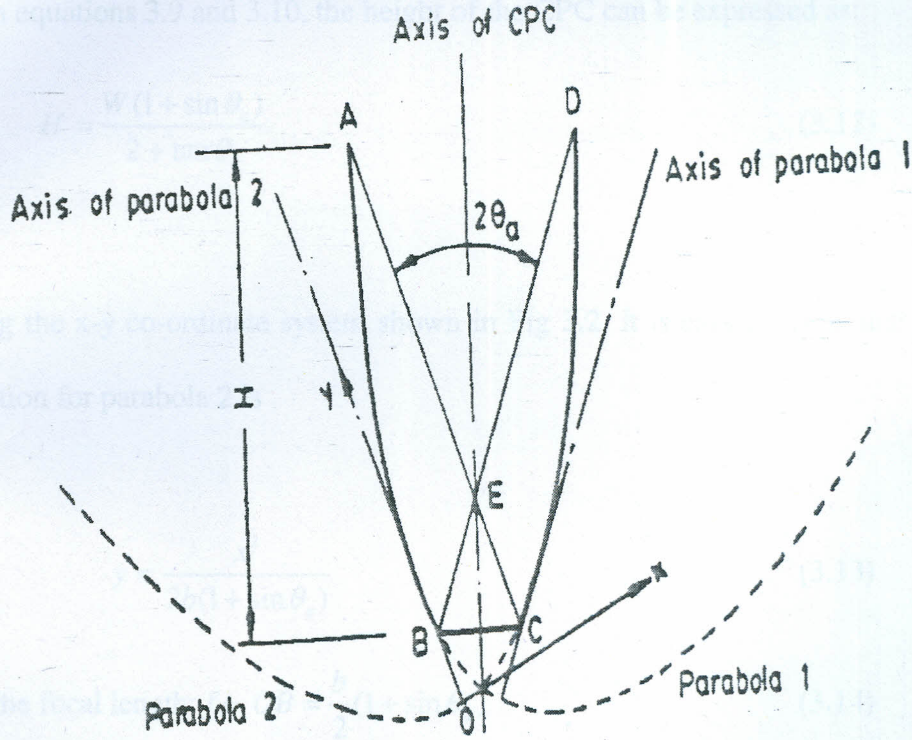

Fig 3.2 Geometry of a compound parabolic concentrating collector [Sukhatme, 1994)

For the simple geometry, it can be shown that

$$\tan\theta_a = \frac{W+b}{2H} \qquad (3.10)$$

where, W is the size of the entrance, b of exit aperture and H the height of the CPC.

The maximum possible concentration ratio achieved by the CPC with an acceptance angle of $2\theta_a$ is given by;

$$C = \frac{W}{b} = \frac{1}{\sin\theta_a} \tag{3.11}$$

From equations 3.9 and 3.10, the height of the CPC can be expressed as:

$$H = \frac{W(1+\sin\theta_a)}{2+\tan\theta_a} \tag{3.12}$$

Using the x-y co-ordinate system shown in Fig 3.2, it is easy to show that the equation for parabola 2 is

$$y = \frac{x^2}{2b(1+\sin\theta_a)} \tag{3.13}$$

and the focal length; $f = OB = \frac{b}{2}(1+\sin\theta_a)$. (3.14)

Sukhatme, (1994) has shown that the co-ordinates of the end points of the segment CD are given by:

Point C: $x = b\cos\theta_a$ (3.15)

$$y = \frac{b}{2}(1-\sin\theta_a). \tag{3.16}$$

Point D: $x = (b + w)\cos\theta_a$. (3.17)

$$y = \frac{b}{2}(1 - \sin\theta_a)\left(1 + \frac{1}{\sin\theta_a}\right)^2 \quad (3.18)$$

and the height to aperture ratio of the concentrator is given by

$$\frac{H}{W} = \frac{1}{2}\left(1 + \frac{1}{\sin\theta_a}\right)\cos\theta_a = \frac{1}{2}(1 + C)\left(1 - \frac{1}{C^2}\right)^{\frac{1}{2}} \quad (3.19)$$

Rabl (1978) has shown that the area of the concentrator or reflector, A_{con}, is related with the area of the aperture A_a, as:

$$A_{con} = A_a(1 + \sin\theta_a)\left[\frac{\cos\theta_a}{\sin^2\theta_a} + \ln\left\{\frac{(1 + \sin\theta_a)(1 + \cos\theta_a)}{\sin\theta_a\left\{\cos\theta_a + (2 + 2\sin\theta_a)^{\frac{1}{2}}\right\}}\right\} - \frac{\sqrt{2}\cos\theta_a}{(1 + \sin\theta_a)^{\frac{3}{2}}}\right]$$

(3.20)

3.5 Energy Balance on the PV Module.

An energy balance that indicates the conversion of incident solar energy into useful gain and thermal losses is used to describe the thermal performance of a solar PV module. The useful energy output of the module is given by the difference between the absorbed solar radiation, convective and the thermal loss. The absorbed solar energy is converted into electrical energy output, thermal radiative and conductive energy losses, a thermal energy stored in the PV module, causing change in temperature of the panel, T_p. The rate of change of T_p is suggested by Chugpaibulpatana *et al*, (2001) as:

$$(MC_p)_{\text{mod}} \frac{dT_p}{dt} = Q_{in} - Q_{rad} - Q_{con} - Q_{elect} \qquad (3.21)$$

Where $(MC_p)_{mod}$ = effective thermal capacity of the PV module at temperature T_p , Q_{in} = Solar radiation absorbed by the module (W) , Q_{rad} = radiative heat loss, Q_{con} = conductive heat loss (W) and Q_{elect} = electrical power produced (W).

The total radiation heat loss from the PV panel results from the radiative heat exchange between the panel and the sky, and between the panel and the ground. Chugpaibulpatana (2001) gives the expression for radiation heat loss as:

$$Q_{rad} = Q_{radn\text{-}ground} + Q_{radn\text{-}sky} \qquad (3.22)$$

Where, $Q_{radn\text{-}ground} = S_p F_{py} \delta(\varepsilon_p T_p^4 - \varepsilon_g T_g^4)$

$Q_{radn\text{-}sky} = S_p F_{ps} \delta(\varepsilon_p T_p^4 - \varepsilon_s T_s^4)$

Neville (1995) has given an energy balance on a PV module as shown in Fig. 3.3

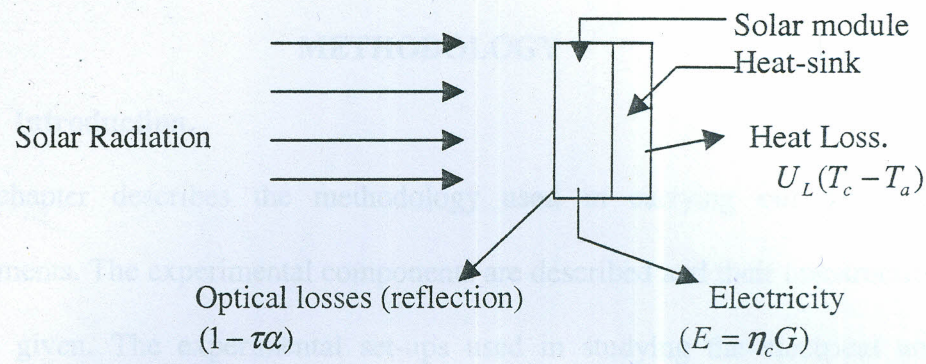

Fig.3.3 Energy balance on a PV module.

The electricity supplied each year can be estimated as;

Electricity per year = I x AE_m x E_s x 365 (KWh/year). (3.23)

or

Electricity per year = Average Power Output x Average mean daily sunshine hours x 365 (KWh/year)

Where: I= average annual irradiation in KWh/m^2-day, E_m= module efficiency, E_s= system efficiency, A= array area in m^2 and 365 = days in a year.

Hankins (1991) gives the mean daily sunshine hours for Kenya as 5.45 hrs.

CHAPTER FOUR

METHODOLOGY

4.1 Introduction.

This chapter describes the methodology used in carrying out series of experiments. The experimental components are described and their construction details given. The experimental set-ups used in studying the electrical and thermal performance of the systems under investigation are also given.

4.2 Experimental Components.

The experimental system as shown in figure 4.1 consisted of two units: the electrical power unit and the heat recovery unit, which produced electricity and hot water respectively. The electric power unit consists of a Compound Parabolic Collector (CPC), amorphous silicon (a-Si) Photovoltaic modules, blocking diodes, 100Ah storage battery, solar water pump (load), power conditioning controller and electrical wires.

The heat recovery unit consists of a cooling device (heat exchanger), a solar water pump, water flow meter, cold water and hot water storage tanks, CPC and connecting pipes. The CPC and the solar water pump are common components to both electrical and thermal unit. The PV modules (M1 and M2), solar battery, two charge controllers (10 Amp each), two blocking diodes (1W each), a diaphragm solar water pump and connecting wires were purchased from commercial dealers in Nairobi, Kenya. The CPC, and the cooling device were designed and fabricated at the Appropriate Technology Centre workshop.

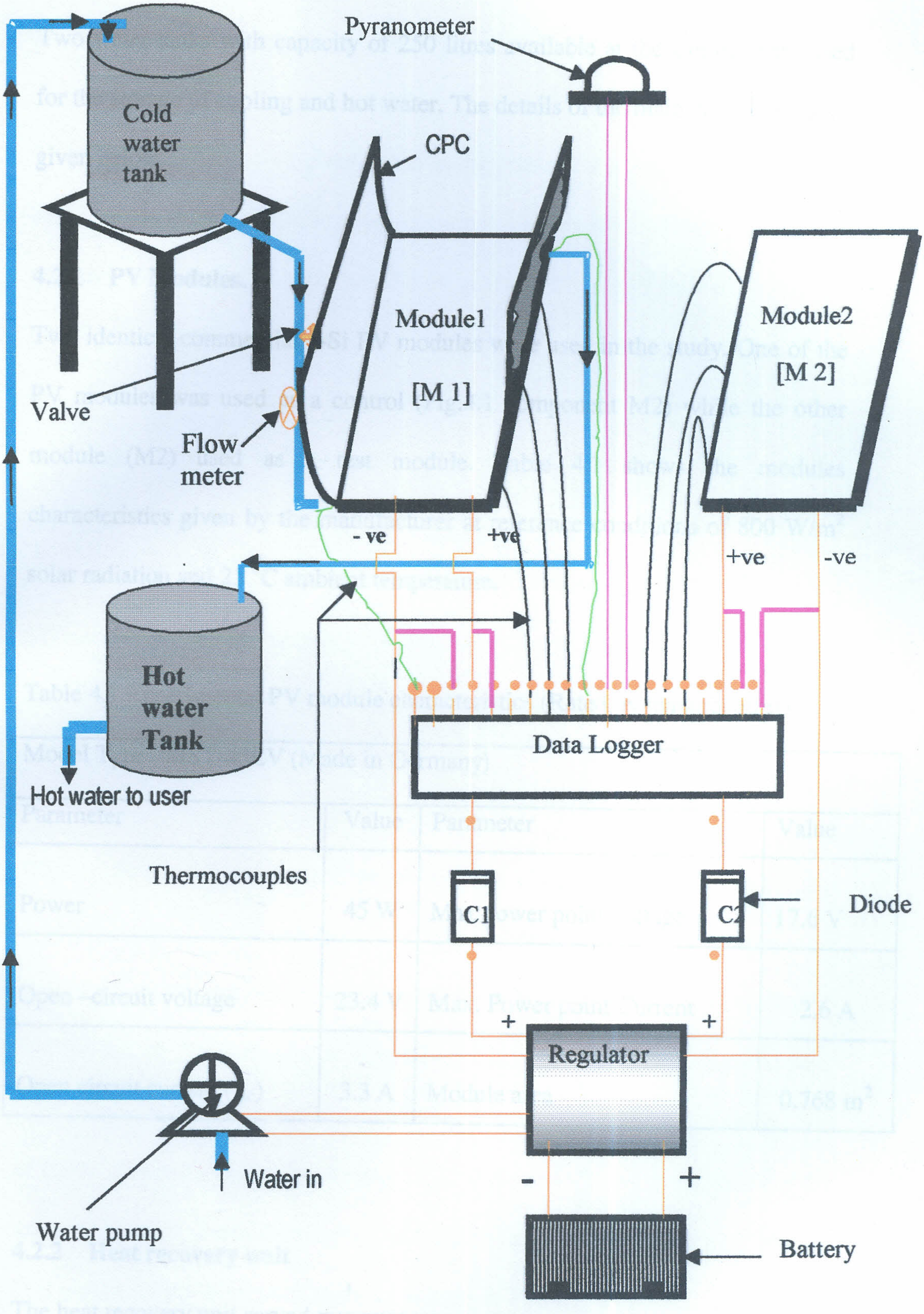

Fig.4.1 Schematic diagram showing the experimental set up.

Two water tanks with capacity of 250 litres available at the Centre were used for the storage of cooling and hot water. The details of the main components are given below.

4.2.1 PV Modules.

Two identical commercial a-Si PV modules were used in the study. One of the PV modules was used as a control (Fig.4.1 component M2) while the other module (M2) used as a test module. Table 4.1 shows the modules characteristics given by the manufacturer at reference conditions of 800 W/m^2 solar radiation and 25 ^{o}C ambient temperature.

Table 4.1 Experimental PV module characteristics (Rated by manufacturer).

Model Type –MST-43LV (Made in Germany)			
Parameter	Value	Parameter	Value
Power	45 W	Max power point voltage	17.6 V
Open –circuit voltage	23.4 V	Max. Power point Current	2.6 A
Open circuit current (I_{sc})	3.3 A	Module area	0.768 m^2

4.2.2 Heat recovery unit

The heat recovery unit served two purposes:

i) cooled the PV Module using the circulating water and

ii) acted as a trap for the heat lost from the PV module and transmits it for water heating application.

This heat exchanger was constructed at the workshop using a copper pipe of 0.018 m and 0.0194 m inside and outside diameters respectively. The copper pipe was cut into smaller pieces of 0.66 m and 0.03 m and joined together by brazing with copper-to-copper rods to form the heat exchanger as shown in Fig. 4.2. The heat exchanger was then fixed at the rear surface of the PV module. A heat sink compound (silicon oxide) with a conductivity of 0.9 W/mK was applied between the PV surface and the heat exchanger in order to ensure a good thermal contact. The unit was connected to the cooling and hot water storage tanks. A Diaphragm solar water pump (7 amps RVDC 1.8 Gpm) made in USA was used to pump cold water to the cold-water tank (this tank was raised arbitrarily at 3.5 m high).

Water from the cold-water tank passed through a water flow meter, which was used to measure the water flow rate. Three different water flow rates were chosen arbitrarily and used to cool the PV module. The flow rates were 20 l/hr, 30 l/hr, and 40 l/hr and were designated low (l), medium (m) and high (h) flow rates respectively. A water valve regulated the water flow. Thermocouples (Tci) of Cu-Ni type with temperature range of –185 to +300 ^{o}C were installed for the measurements of water temperature at the inlet denoted (T_i) and outlet denoted (T_o) points of the heat exchanger as shown in Fig.4.2. Thermocouples of the same type were also glued at regular intervals on the back surface of the PV modules, as shown in Fig. 4.3 in order to measure the temperature distribution, T1, T2 and T3 at the back surface of the two modules. These thermocouples were then connected to a data logger which was programmed to record and compute the average module temperature for each of the PV module i.e. TM1 and TM2 at intervals of 15 minutes.

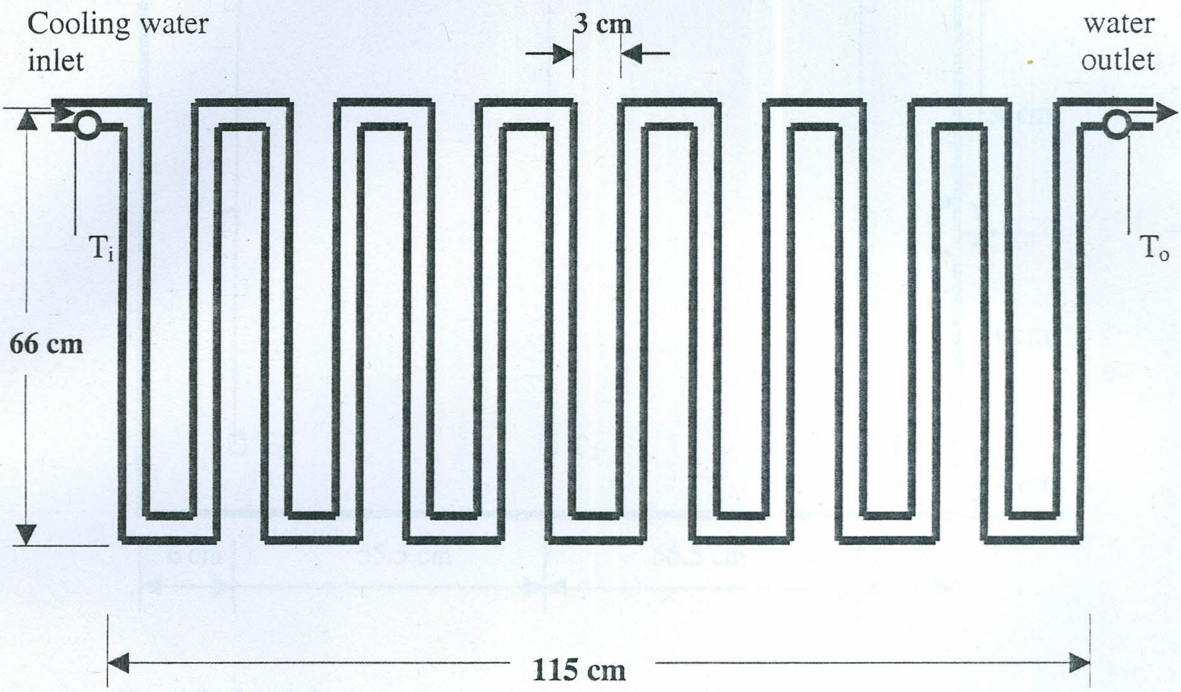

Fig. 4.2 Sketch showing the heat exchanger.

4.2.3 Design and Fabrication of the CPC.

In order to design a CPC, it is necessary to know the magnitude of the exit aperture, b, and the desired half angle θ_a. Using these parameters, the size of the entrance aperture, W, the focal length of the parabola and the concentration factor C, can be calculated. In this experiment, the desired acceptance half angle was $\theta_a = 14^o$ as recommended by Ralb (1980). This gives an average collection time of 8.76 hours per day, and a theoretical concentration ratio of 4.13 calculated from equation 3.11. The value of b is the width of the PV module used, which gave $b = 68$ cm.

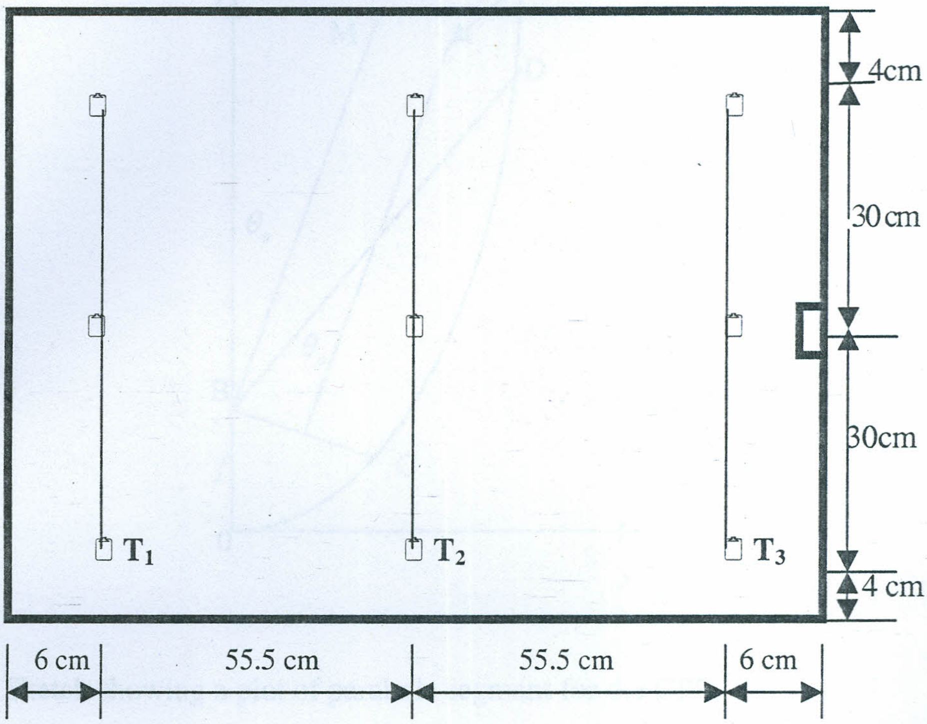

Fig. 4.3 Module temperature measurement points

The focal length, f was calculated using equation 3.14 which gave $f = 42.22$ cm. The next step was to plot the parabola to scale in Cartesian coordinates using equation 3.13 as shown in Fig.4.4. Values of y were plotted for x = 1 to x =100. After plotting, the focus of the parabola B was marked on the y – axis and equations 3.15 – 3.18 were used to locate the end points; C and D of the parabola segment. This segment forms one section of the CPC. The line BC was then drawn and bisected perpendicularly. The height of the CPC was found to be 154 cm. Equation 3.12 was used to verify this height and was found to be correct. The height was truncated to approximately three quarters so that the final height used was 115 cm.

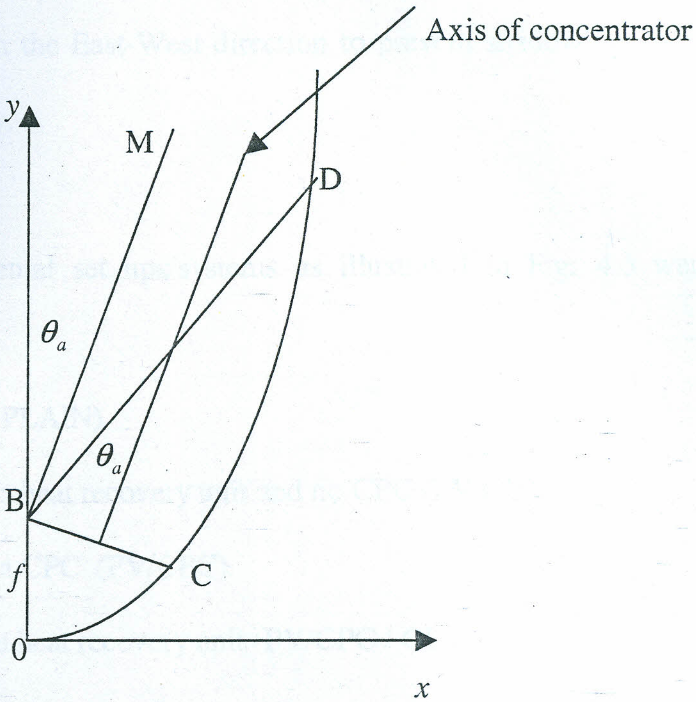

Fig. 4.4 Sketch showing a plot of parabola segment for the CPC

The length of the PV module was 123 cm. To reduce edge effects, it was necessary to make the CPC slightly longer than the PV module. The length of the CPC was calculated from the length of the module and was 135 cm. The reflective material used for the CPC was polished aluminum sheet of gauge 26 with a reflectivity of ≈ 0.85. The CPC support structure was made from angle bars, flat bars and round metal bars and mounted on to the PV module (M 1) as shown in Fig. 4.1.

4.3 Experimental set up.

A movable test rig was constructed using angle iron bars and the experimental components mounted on it. Figure 4.5 shows a photograph of the various components assembled together on the test rig. The experiment was set up at the Appropriate Technology Centre Solar Park, Kenyatta University. The modules were aligned in the East-West direction to prevent shadowing as the sun moves across the sky.

Four different experimental set ups/systems as illustrated in Fig. 4.6 were investigated, viz:

a) PV module (PV PLAIN).
b) PV module with a heat recovery unit and no CPC (PV/CU).
c) PV module with a CPC (PV/CPC).
d) PV with CPC and heat recovery unit (PV/CPC / CU).

PV PLAIN was used as the control for the different experiments. First, the two identical modules were tested and their electrical outputs compared under the same solar radiation conditions in order to determine whether the output of the two panels were the same and if not, a correction factor to be calculated. The aim of PV/CU was to study the effect of cooling on the performance of the PV module. The PV/CPC was designed to determine the performance of the PV module under solar concentration using a CPC, while the PV/CPC/ CU was designed to investigate the performance of the module under both solar radiation concentration and cooling effect. During the cooling of the module, active cooling technique was used. This was done by allowing water to flow from the cold water storage tank under the influence of gravity through a valve to the cooling unit and finally to the hot water storage tank.

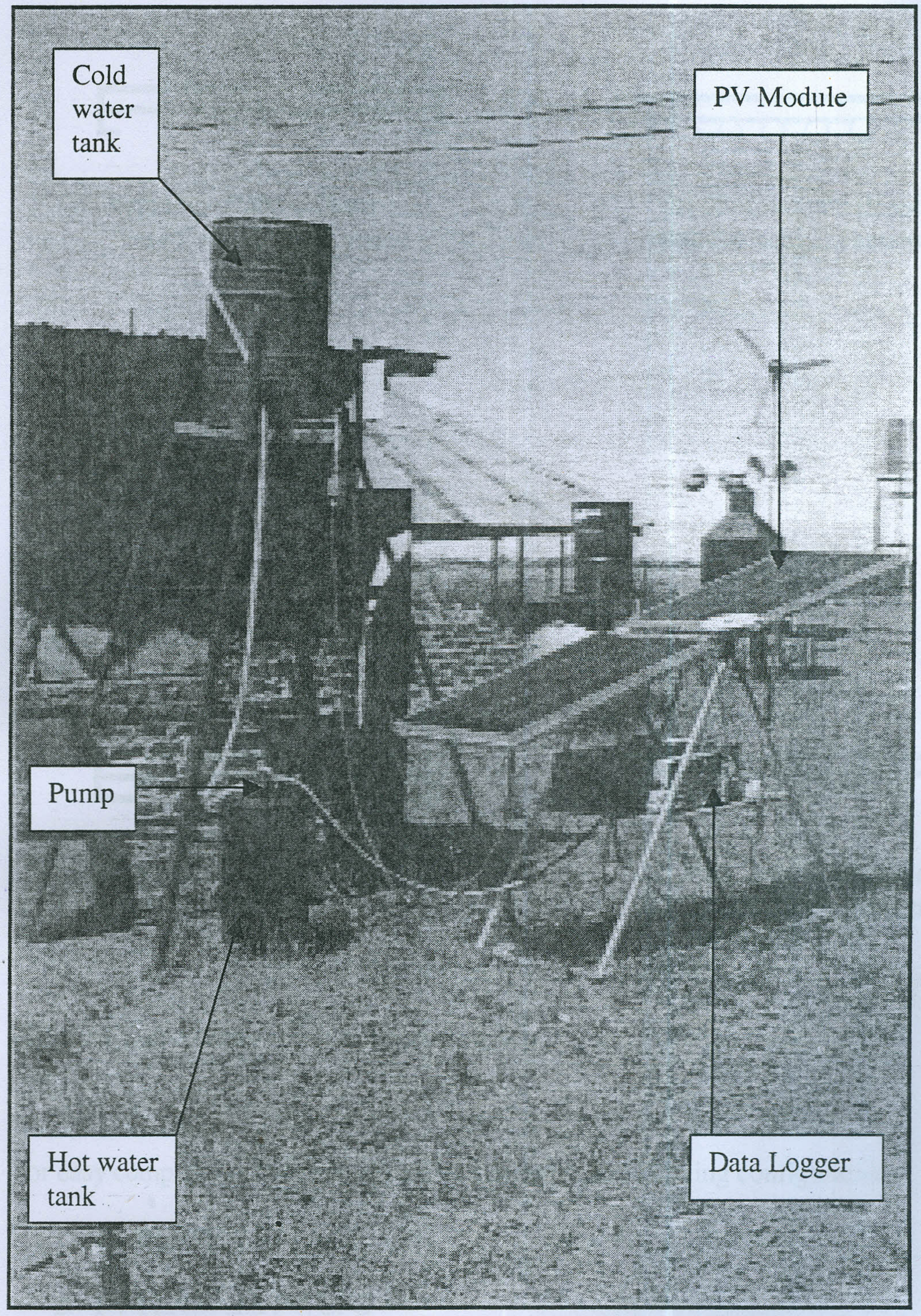

Fig 4.5 Photograph showing the experimental set up mounted on a test rig.

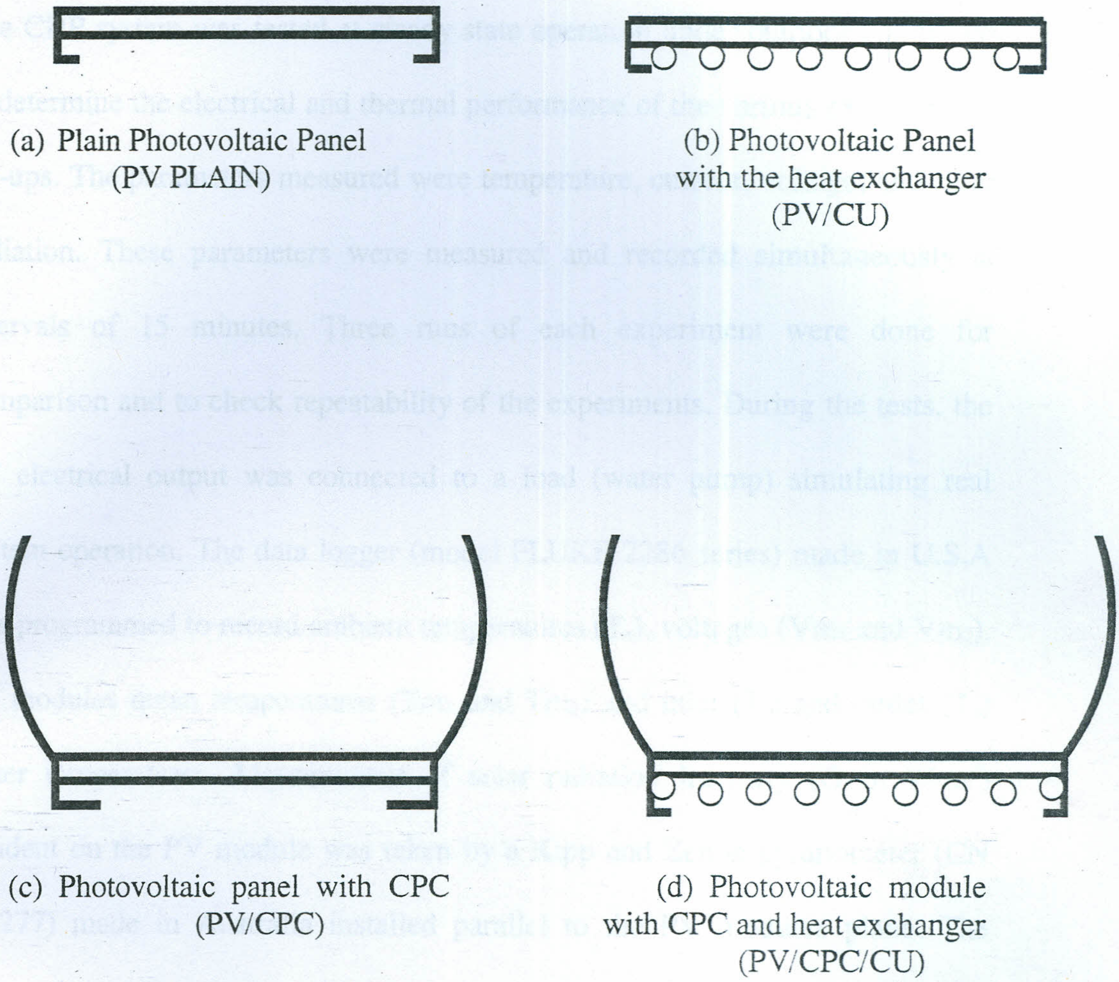

Fig. 4.6 Cross-Section of experimental models

For easy comparison, the experiment was done in the following configuration:

1. PV PLAIN and PV/CU
2. PV PLAIN and PV/CPC
3. PV PLAIN and PV/CPC + CU

The cooling water flow rate for experiment 1 and 3 was varied as a technique of varying temperature, and at the same time the module back surface temperature was monitored.

4.4 Experimental Measurements

The CHP system was tested at steady state operation under outdoor conditions to determine the electrical and thermal performance of the various experimental set-ups. The parameters measured were temperature, current, voltage, and solar radiation. These parameters were measured and recorded simultaneously at intervals of 15 minutes. Three runs of each experiment were done for comparison and to check repeatability of the experiments. During the tests, the PV electrical output was connected to a load (water pump) simulating real system operation. The data logger (model FLUKE 2286 series) made in U.S.A was programmed to record ambient temperatures (T_a), voltages (Vm_1 and Vm_2), PV modules mean temperatures (Tm_1 and Tm_2) and inlet (T_i) and outlet (T_o) water temperatures. Measurement of solar radiation intensity (G in W/m^2) incident on the PV module was taken by a Kipp and Zenon pyranometer (CN 27-277) made in Australia installed parallel to the PV modules plane. The sensitivity of the CN27-277 pyranometer was $91.68Wm^2$ per mV with a correlation coefficient of 0.99 (Odote, 1994).

The modules current output, Im_1 and Im_2 were recoded manually concurrently with the data logger (i.e. at 15 minutes interval) using two electronic multimeters (Model Sealey Gpi, MM30) with accuracies of 0.01A each. For the water flow rate, a water flow meter (Model S 050) was used for measuring the flow rates of the cooling water. The characteristics of the flow meter given by the manufacturers manual is as follows:

$$n < 1.98 \text{ then } V=31.17 \times n + 1.93$$

$$n \geq 1.98 \text{ then } V = 32.05 \times n + 0.19$$

$$n > 1.98 \text{ then } V = 33.44 \times n - 14.09$$

Where n = number of propeller revolutions per second

V = Velocity (m/s).

A volumetric flasque, made by Schott Duran West Germany was also used to check the mass flow rate as compared to the current flow meter.

Data collection was done for eight hours a day from 9.00 to 17.00 hours for a period of five months from September 2002 to January 2003. The rainy days, which were in the month of November and December, and other cloudy days during the data collection period were excluded.

CHAPTER FIVE

RESULTS AND DISCUSSION

5.1 Introduction

The data collected during the experiments were: PV current and voltage output, solar radiation, ambient temperature, module temperature and water temperatures at the inlet and outlet of the cooling unit. About 90 tests were conducted under various weather conditions. Only data from those experiments conducted during clear sky days are analysed and presented. This is because clear sky days have reasonably constant solar radiation and experiments done on different days can be easily compared. The data was retrieved from a diskette in the data logger and entered in excel spreadsheet computer software and analysed. Averages of three runs of each experiment was calculated and used to compare the performance of the different systems.

The power output and electrical efficiency of the PV module were computed. Thermal efficiency of the cooling unit was also computed. The computed values together with the temperature profiles were plotted separately against time of day and comparisons were made for the different experimental systems. Finally, financial evaluation of the investigated systems was done using the Life Cycle Costing (LCC) method. A summary of the results measured and calculated for the different experimental systems is given in Table 5.1. These results are analysed and discussed in details in the subsequent sections. Samples of raw experimental data are presented in Appendix A.

Table 5.1 Summarized Results of Test and Control PV Modules for the Different Experimental Systems.

Date	Experimental system	Day Av. Radiation, G (W/m^2)	Av. T_a (°C)	Flow rate l/hr.	Day Av. Current M1 (A)	Day Av. Current M 2 (A)	Day Av. Voltage M1 (V)	Day Av. Voltage M2 (V)	Day Av. Temp. T M1 (°C)	Day Av. Temp. T M2 (°C)	Day Av. Power M 1 (W)	Day Av. Power M 2 (W)	Av. Water Temp. rise(T_o-T_i) (°C)	Day Av. Elect. Eff. M1	Day Av. Elect. Eff M2	Day Av. Thermal Eff.
9/26/02	PV PLAIN	603.99	22.3	n/a	1.57	1.57	16.76	16.78	39.53	39.5	26.68	26.78	n/a	0.056	0.056	n/a
9/30/02	PV PLAIN	645.32	23.7	n/a	1.68	1.67	16.93	16.92	40.30	40.2	28.76	28.52	n/a	0.057	0.057	n/a
10/1/02	PV PLAIN	669.31	25.3	n/a	1.74	1.75	17.74	17.04	43.50	42.8	29.21	29.38	n/a	0.058	0.058	n/a
10/3/02	PV/CU	791.81	26.4	20	2.44	2.07	17.71	17.54	43.40	47.6	43.55	36.59	8.9	0.067	0.056	0.12
10/1/02	PV/CU	814.21	26.9	20	2.50	2.12	17.63	17.39	41.30	47.8	44.29	35.83	10.3	0.066	0.055	0.13
10/9/02	PV/CU	828.34	27.1	20	2.58	2.15	17.63	17.60	41.60	50.1	45.95	37.32	9.8	0.067	0.057	0.13
10/16/02	PV/CU	822.43	26.2	30	2.68	2.13	17.32	17.65	36.93	49.8	46.78	37.77	5.5	0.069	0.056	0.09
10/17/02	PV/CU	835.25	27.1	30	2.70	2.17	17.63	17.59	35.84	48.6	47.42	38.31	5.8	0.070	0.057	0.09
10/22/02	PV/CU	865.01	27.5	30	2.82	2.22	17.94	17.80	36.60	51.5	49.88	39.58	5.7	0.071	0.056	0.09
10/25/02	PV/CU	856.21	26.9	40	2.99	2.23	17.66	17.69	34.10	49.2	52.80	39.52	4.0	0.076	0.057	0.07
10/29/02	PV/CU	870.36	27.1	40	3.16	2.28	17.68	17.54	35.50	50.2	55.68	40.21	3.8	0.078	0.056	0.07
10/31/02	PV/CU	856.00	26.7	40	2.89	2.22	17.68	17.51	33.60	47.4	51.30	38.91	3.9	0.077	0.057	0.08
1/14/03	PV/CPC	877.47	27.6	n/a	4.41	2.30	18.01	17.86	67.83	48.4	79.95	41.28	n/a	0.125	0.065	n/a
1/16/03	PV/CPC	854.00	28.2	n/a	4.29	2.22	17.93	17.77	65.20	47.5	76.93	39.45	n/a	0.125	0.064	n/a
1/17/03	PV/CPC	870.37	27.9	n/a	4.37	2.28	17.83	17.80	68.10	46.2	77.93	39.98	n/a	0.127	0.065	n/a
1/20/03	PV/CPC+CU	853.23	28.3	20	4.62	2.23	17.92	17.76	43.41	45.7	81.56	39.48	19.7	0.134	0.065	0.262
1/22/03	PV/CPC+CU	829.97	27.7	20	4.47	2.17	17.89	17.67	43.48	46.9	80.78	38.73	20.9	0.133	0.064	0.280
1/23/03	PV/CPC+CU	863.21	27.9	20	4.65	2.25	17.99	17.83	43.12	47.9	83.85	41.21	20.2	0.135	0.065	0.268
1/24/03	PV/CPC+CU	878.18	28.0	30	5.13	2.30	18.07	17.85	40.99	47.9	93.25	41.26	16.2	0.146	0.065	0.251
1/27/03	PV/CPC+CU	858.33	27.5	30	5.04	2.23	17.98	17.81	40.23	48.5	89.63	40.02	15.9	0.145	0.065	0.253
1/28/03	PV/CPC+CU	874.46	27.2	30	5.09	2.27	17.96	17.85	40.20	48.7	91.32	39.90	15.7	0.143	0.064	0.249
1/29/03	PV/CPC+CU	842.69	26.7	40	5.32	2.21	17.92	17.77	33.30	47.4	96.21	39.69	11.3	0.156	0.065	0.218
1/30/03	PV/CPC+CU	873.32	27.7	40	5.56	2.26	17.92	17.81	35.60	48.6	98.34	40.22	11.7	0.158	0.064	0.229
1/31/03	PV/CPC+CU	856.24	27.2	40	5.49	2.23	17.84	17.78	32.60	47.5	97.22	41.04	12.1	0.157	0.065	0.227

Note: M 1 = Module 1 (Test module), M 2 = Module 2 (Control), n/a = not applicable. (Av. Radiation = 824.57 W/m^2, mean deviation = 6%).
Av.Ambient Temperature = 26.9 °C. Mean deviation = 3.3%

5.2 Comparison of the Two PV Modules

The first step in the experimental study was to compare the performance of the two amorphous silicon PV modules. The tests were conducted under the same environmental conditions. This was done in order to establish their homogeneity in performance. The tests were done by mounting the two modules on the experimental rig and measuring their currents, voltages and back surface temperatures at the same time.

It can be noted in Table 5.1, that for the PV PLAIN experimental system the currents, voltages, temperature variations, and the computed electrical efficiencies of the two-identical modules (M1 and M2) are similar and follow the same pattern under the same radiation intensity and ambient temperature. From these results, the performance of the two PV modules can be compared without any correction factor required provided they were tested under the same weather conditions. Module 1 was used to study the performance of the different experimental systems while module 2 (PV Plain) was used as a control for all experiments.

5.3 Effects of the CPC on PV Module Temperature

Temperature variations were monitored for the different experimental systems by use of thermocouples that were fixed at the back surface of the PV modules. A comparison of PV module temperature with and without the CPC, the ambient temperature and solar radiation on a clear sky day is shown in Fig.5.1.

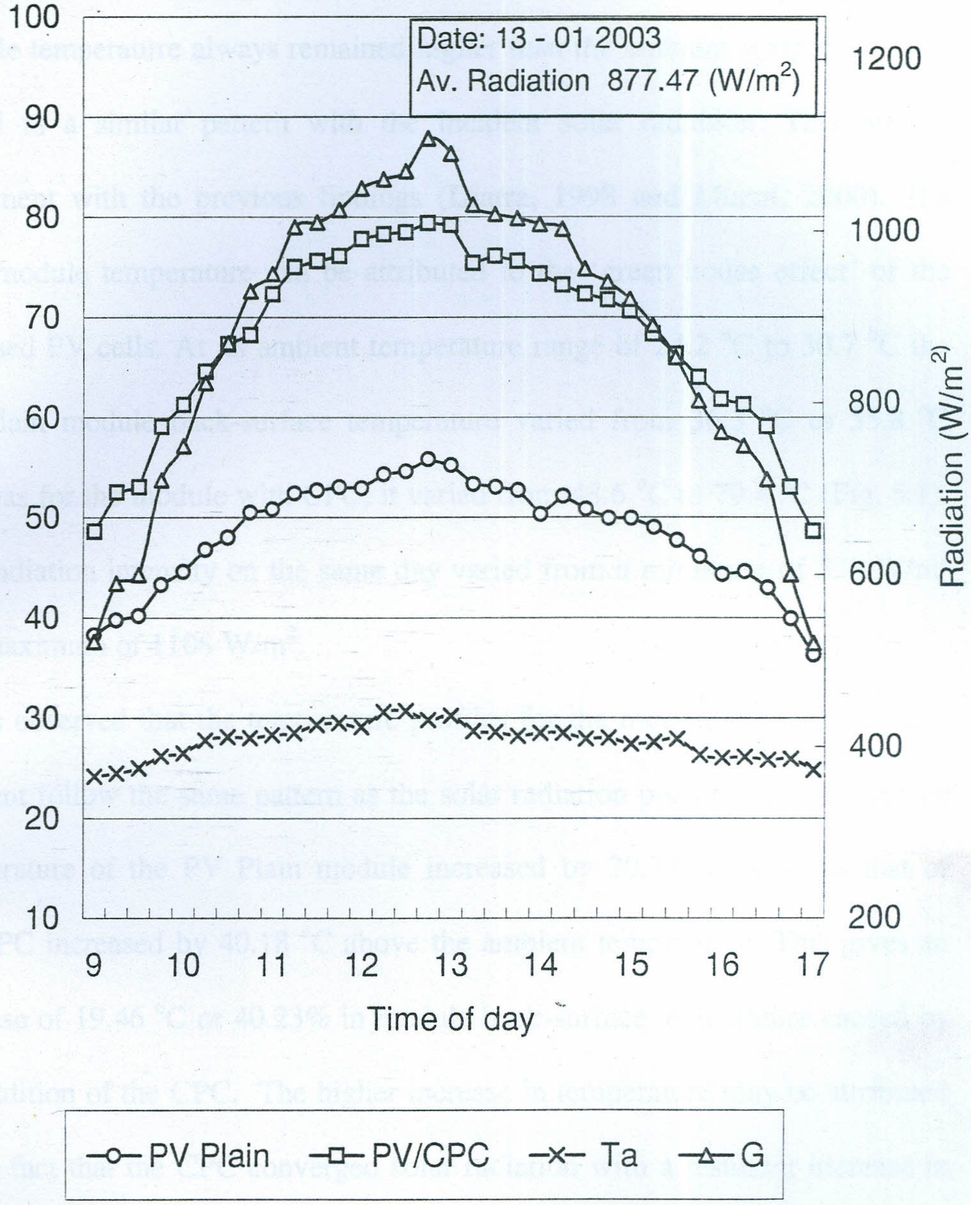

Fig.5.1 Comparison of solar radiation, ambient temperature and module temperatures for PV Plain and PV/CPC system on a clear sky day.

It was observed that in all the experiments done between 9 am and 5 pm, the module temperature always remained higher than the ambient temperature and varied in a similar pattern with the incident solar radiation. This was in agreement with the previous findings (Diarra, 1998 and Mueni, 2000). The high module temperature can be attributed to the 'green house effect' of the enclosed PV cells. At an ambient temperature range of 24.2 °C to 30.7 °C the PV Plain module back-surface temperature varied from 36.3 °C to 55.8 °C whereas for the module with CPC, it varied from 48.6 °C to 79.4 °C (Fig. 5.1). The radiation intensity on the same day varied from a minimum of 520 W/m^2 to a maximum of 1108 W/m^2.

It was observed that the temperature profiles for the module back surface and ambient follow the same pattern as the solar radiation profile. On average, the temperature of the PV Plain module increased by 20.72 °C whereas that of PV/CPC increased by 40.18 °C above the ambient temperature. This gives an increase of 19.46 °C or 40.23% in module back-surface temperature caused by the addition of the CPC. The higher increase in temperature may be attributed to the fact that the CPC converged solar radiation with a resultant increase in radiation per unit surface of the module.

5.4 Effect of CPC on Electrical Power Output

The electrical power output of the module was computed by multiplying the current and voltage it generated. Figure 5.2 shows power output for the PV Plain and PV/CPC modules and the corresponding solar radiation recorded on a clear sky day.

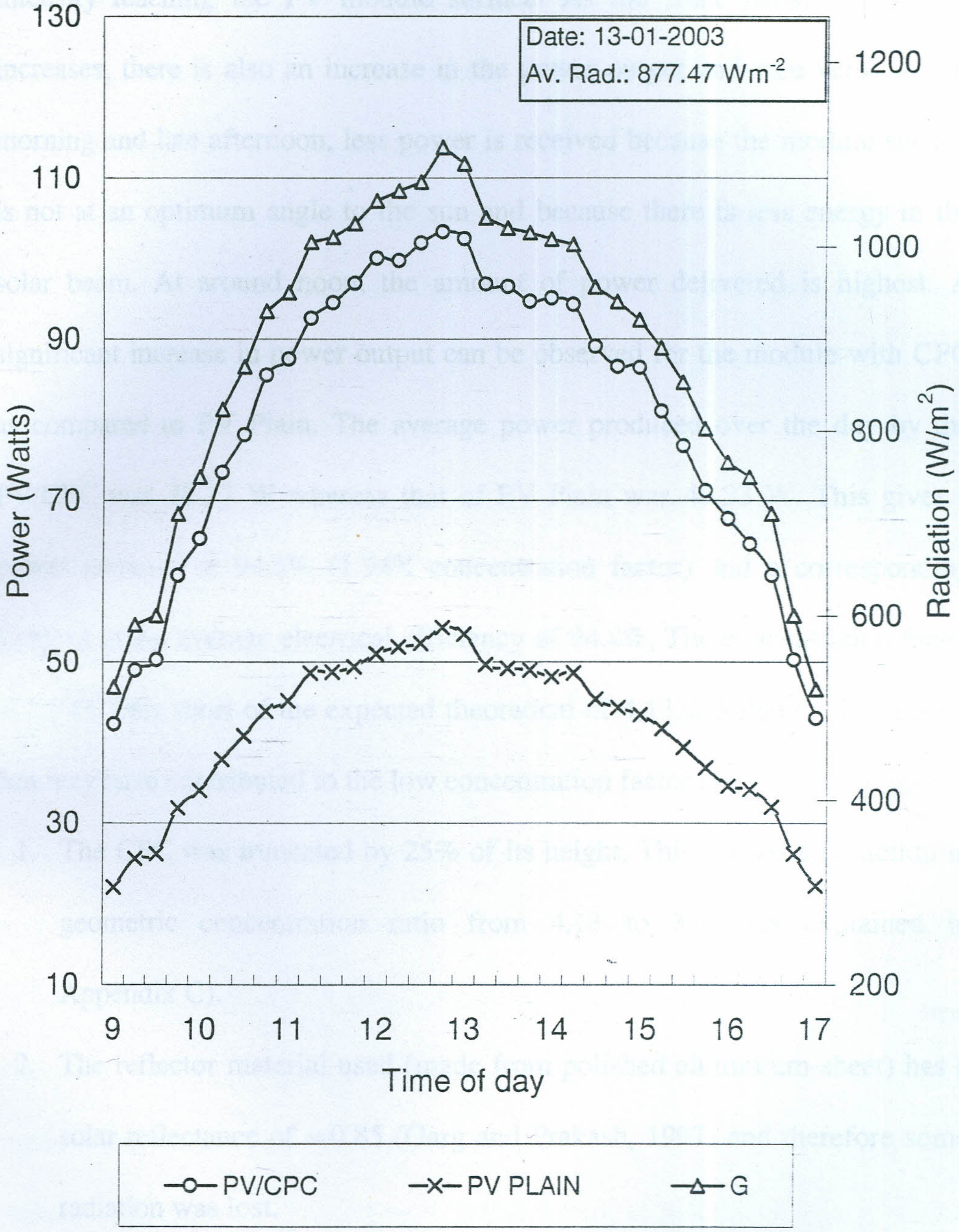

Fig. 5.2 Power output comparison for PV PLAIN and PV/CPC on a typical clear sky day

Figure 5.2 shows that power output is directly related to solar radiation intensity reaching the PV module surface. As the solar radiation intensity increases, there is also an increase in the power output and vice versa. In the morning and late afternoon, less power is received because the module surface is not at an optimum angle to the sun and because there is less energy in the solar beam. At around noon, the amount of power delivered is highest. A significant increase in power output can be observed for the module with CPC as compared to PV Plain. The average power produced over the day by the PV/CPC was 78.27 W whereas that of PV Plain was 40.23 W. This gives a power increase of 94.5% (1.94X concentration factor) and a corresponding increase in the average electrical efficiency of 94.4%. The concentration factor of 1.94X falls short of the expected theoretical of 4.13X. Some of the reasons that may have contributed to the low concentration factor are:

1. The CPC was truncated by 25% of its height. This caused a reduction in geometric concentration ratio from 4.13 to 3.09 (as explained in Appendix C).
2. The reflector material used (made from polished aluminium sheet) has a solar reflectance of ≈ 0.85 (Garg and Prakash, 1997) and therefore some radiation was lost.
3. Dust and small particles were deposited on the surface of the CPC; this caused a further reduction in the concentration factor. Dust has been reported to cause a reduction of up to 20% of electrical output (Lique, 1989).
4. Multiple reflection of light within the CPC cavity reduced the fraction of

light that finally reaches the surface of the module. Also, some light reaching the module is reflected away by the metal-covered parts of the cell and module, which totally reflects the light (Mueni, 2000). Overstraeten and Merterns (1986) place the loss due to reflection in an anti reflection –coated cell at between 5 – 10 % and that due to the metal- covered parts also at 5 – 10 % of the total amount of light reaching the cell.

5. Power loss due to the series resistance (I^2R_s) was considerably high due to the high amount of current produced under concentration.

Both modules with and without the CPC were monitored for a period of 8 hours per day and in that interval, PV PLAIN produced 199.5 Wh whereas the module with CPC produced 329.8 Wh of energy. The increase in the electrical energy as a result of concentration was 65.3%. These values were obtained by integrating power output over the number of hours of data collection. Mueni (2000) and Edmonds (1990) employed a similar method of calculating the total amount of energy generated. The increase in power and electrical energy generated as a result of concentration is mainly attributed to the light generated current. This current is proportional to the flux of photons with energy above the solar cell band-gap energy. By using a CPC the irradiance increases in the same proportion as the photon flux, this in turn generates a proportionately higher current.

5.5 Effect of Cooling on Module Temperature and Power Output

Tables 5.2 and 5.3 give comparisons of the average module power output and module temperature for the PV/CU and PV/CPC+CU systems respectively. These values were obtained by calculating the average values of three runs for each flow rate presented in Table 5.1.

Table 5.2 Comparison of the average electrical power output and efficiency with module temperature for the PV/CU systems.

System	Flow rate (l/hr)	Average module temp. (°C)	Average Power output (W)	Average Elec. Efficiency (%)
PV Plain	-	48.50	36.58	5.60
PV/CU	20	42.10	44.59	6.60
PV/CU	30	36.45	48.02	7.00
PV/CU	40	34.40	53.26	7.70

Table 5.3 Comparison of the average electrical power output and efficiency with module temperature for the PV/CPC+CU systems.

System	Flow rate (l/hr)	Average module temp. (°C)	Average Power output (W)	Average Elect.. Efficiency (%)
PV /CPC		67.04	78.27	12.50
PV/CPC+CU		53.33	82.06	13.40
PV/CPC+CU		40.47	91.40	14.40
PV/CPC+CU		33.80	97.25	15.70

From the tables, it can be noted that cooling of the PV module resulted in an increase in electrical power output and efficiency. For the PV/CU system, cooling of the PV module from 48.5 °C to 34.4 °C resulted in an increase of 45.5% and 37.5% in electrical power and efficiency respectively. Whereas for the PV/CPC+CU system there was an increase of 24.24% and 25.6% in electrical power and efficiency respectively by cooling the PV module from 67.04°C to 33.8°C. This observation clearly shows the negative effects of temperature rise on PV module electrical power output and conversion efficiency. As the temperature of the PV module increases, the electrical conversion efficiency and also the power output decreases. This can be attributed to the decrease in open circuit voltage and the fill factor with increase in temperature.

The extent of cooling of the module depended on the cooling water flow rate. When the flow rate was increased, there was an observed decrease in PV module temperature. This trend is also clearly shown in Fig. 5.3 for the PV/CPC+CU system. This can be explained by the fact that, increasing the cooling water flow rate increases the value of the inside heat transfer coefficient. Due to this, the heat removal factor increases, which means that the thermal energy that causes temperature rise in the module is removed at a faster rate. This results in low PV module/cell temperatures. The low cell temperature improves the electrical conversion efficiency and thereby increasing the electrical power output.

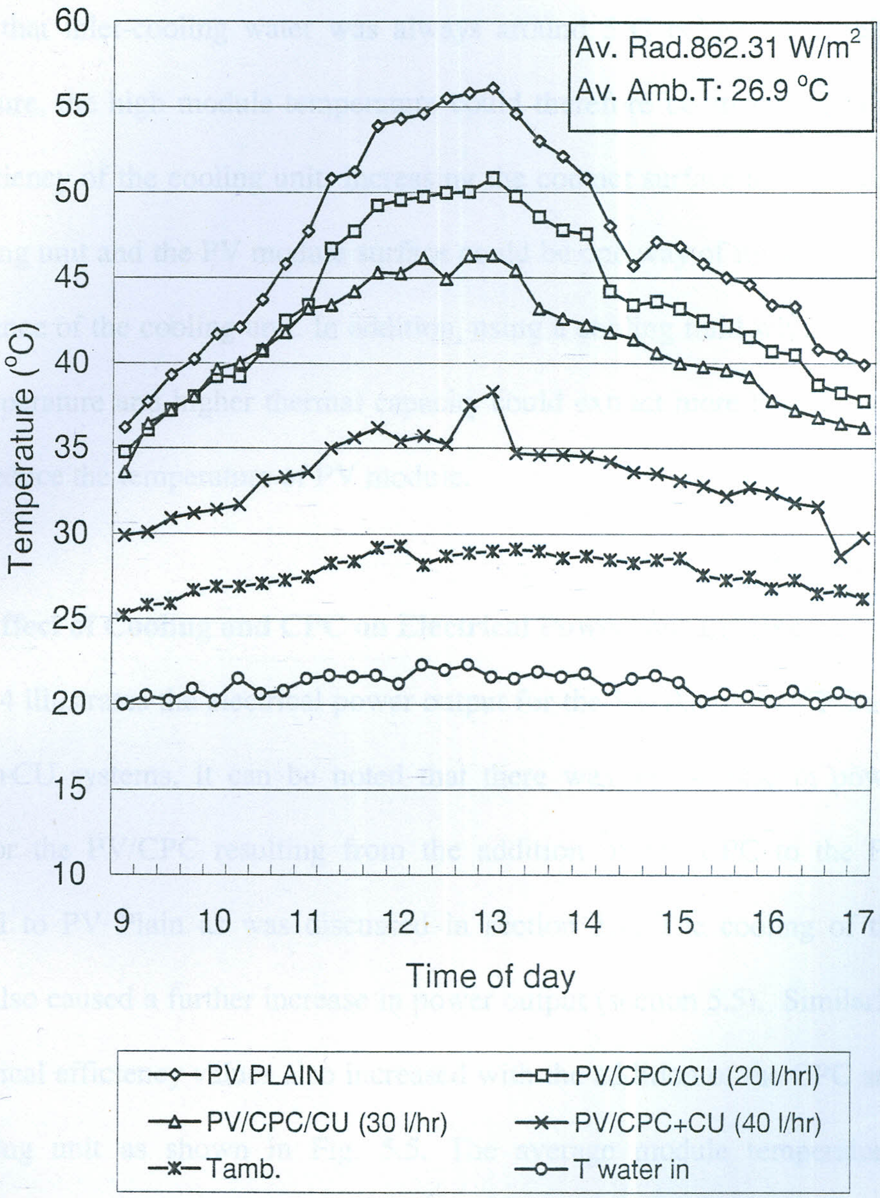

Fig. 5.3 Module temperature profiles for PV/CPC/CU at different cooling flow rates compared with PV PLAIN, inlet water and ambient temperatures on typical clear sky days.

It was also observed that for the three different water flow rates tested, the module temperature was still higher than the ambient temperature. Considering the fact that inlet-cooling water was always around 5^{o}C below the ambient temperature, the high module temperature could therefore be attributed to the low efficiency of the cooling unit. Increasing the contact surface area between the cooling unit and the PV module surface could be one way of improving the performance of the cooling unit. In addition, using a cooling fluid with a lower inlet temperature and higher thermal capacity could extract more heat and can further reduce the temperature of PV module.

5.6 Effect of Cooling and CPC on Electrical Power and Efficiency.

Figure 5.4 illustrates the electrical power output for the PV Plain, PV/CPC and PV/CPC+CU systems. It can be noted that there was an increase in power output for the PV/CPC resulting from the addition of the CPC to the PV compared to PV Plain as was discussed in section 5.4. The cooling of the module also caused a further increase in power output (section 5.5). Similarly, the electrical efficiency values also increased with the addition of the CPC and the cooling unit as shown in Fig. 5.5. The average module temperature, electrical power and efficiency for the PV Plain, PV/CPC and PV/CPC+CU systems are shown in Table 5.4. It was observed that the addition of the CPC to the PV caused a 94.5% increase in power output and 94.4% increase in efficiency. The cooling of the PV/CPC system resulted in further power increase of 24.24% and 25.6% electrical efficiency. The 24.24% and 25.6% power and electrical efficiency increases were as a result of 49.53% module

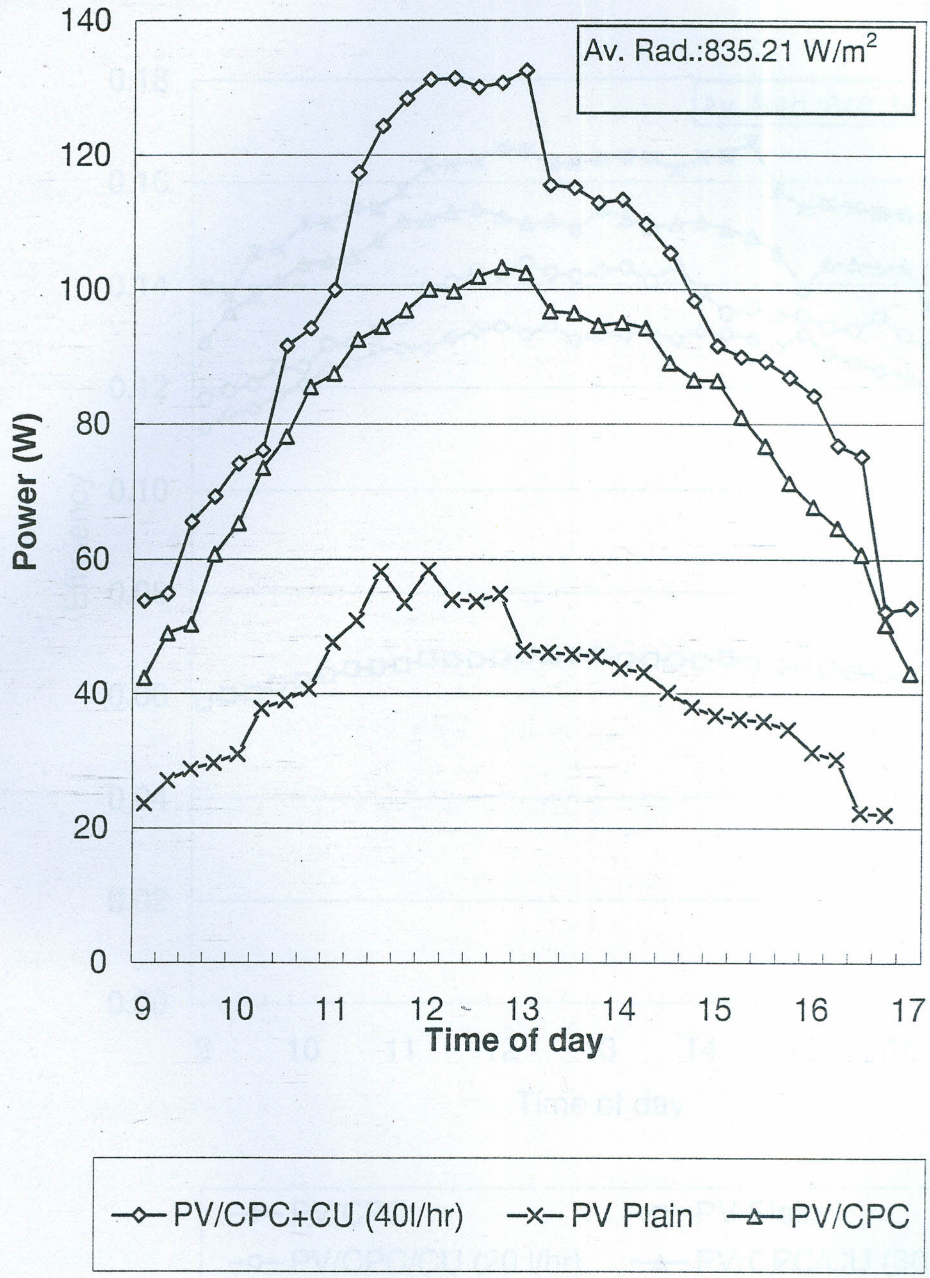

Fig. 5.4 Comparison of electrical power output for PV Plain, PV/CPC and PV/CPC+CU (40l/hr) systems on clear sky days.

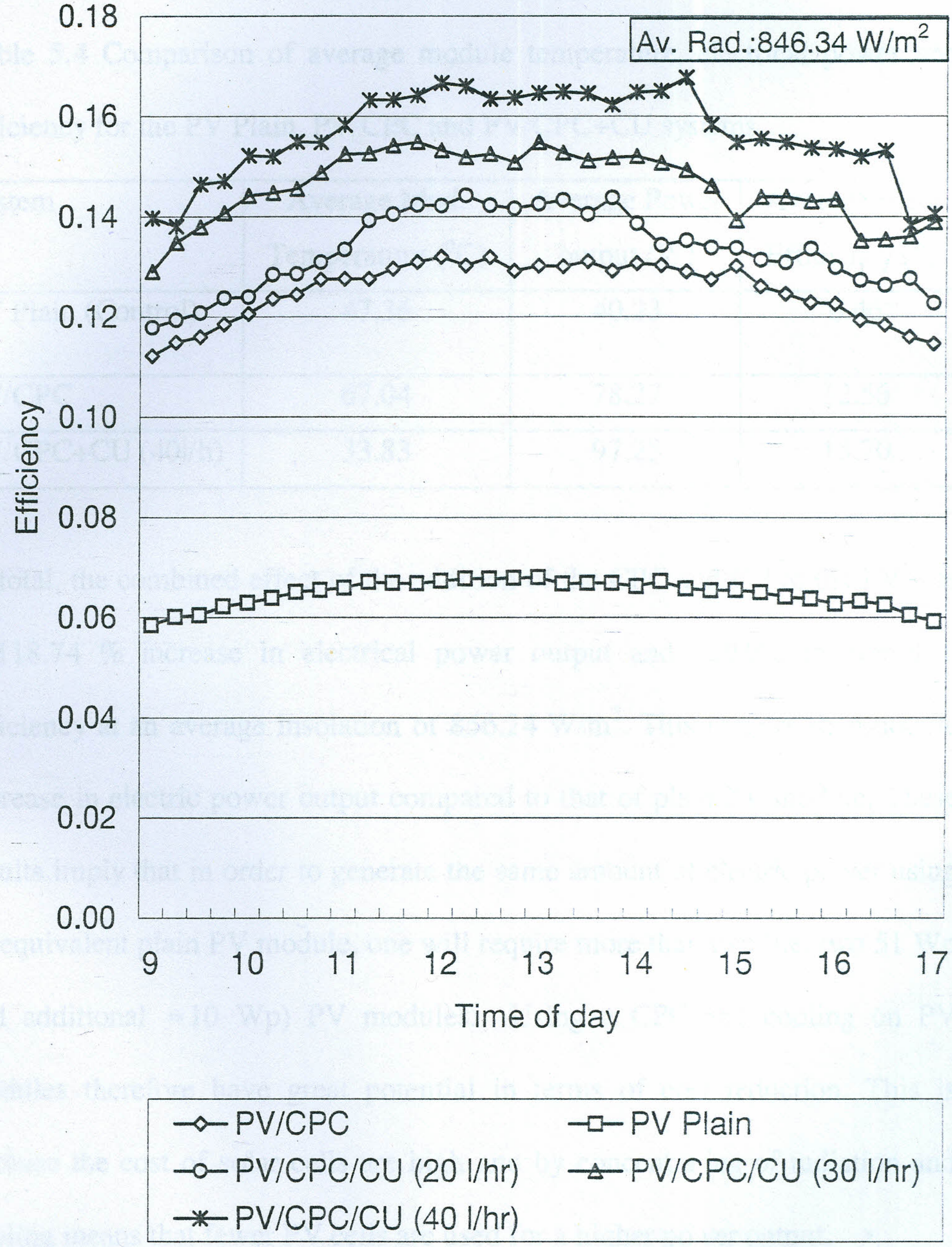

Fig. 5.5 Electrical efficiency variation with concentration and cooling at different flow rates on typical clear sky days.

temperature reduction from 67.04 °C to 33.83 °C.

Table 5.4 Comparison of average module temperature, electrical power and efficiency for the PV Plain, PV/CPC and PV/CPC+CU systems.

System	Average Mod. Temperature (°C)	Average Power output (W)	Average Elect. Efficiency (%)
PV Plain (Control)	47.36	40.23	6.46
PV/CPC	67.04	78.27	12.56
PV/CPC+CU (40l/h)	33.83	97.25	15.70

In total, the combined effect of the addition of the CPC and CU to the PV was a 118.74 % increase in electrical power output and 120.0% in electrical efficiency at an average insolation of 856.24 W/m^2. This is more than double increase in electric power output compared to that of plain PV module. These results imply that in order to generate the same amount of electric power using an equivalent plain PV module, one will require more than two (i.e. two 51 Wp and additional ≈10 Wp) PV modules. Using a CPC and cooling on PV modules therefore have great potential in terms of cost reduction. This is because the cost of solar cells are high and by concentrating of radiation and cooling means that fewer PV cells are used for a higher power output.

5.7 Effect of CPC and flow rate on thermal energy output.

The cooling water temperature was measured at the inlet and outlet of the heat exchanger unit. The change in water temperature was calculated by considering the difference between the outlet and inlet water temperatures.

Table 5.5 gives a comparison of water temperature rise and thermal efficiency variations at different water flow rates for the PV/CU and the PV/CPC+CU systems. These values were obtained by computing the average of three runs for each system.

It was observed that the water temperature rise decreased with increase in flow rate. Figure 5.5 shows the effect of flow rate on the cooling water temperature for the PV/CPC+CU system.

On clear sky days, with an average insolation of 826.47 W/m^2, the outlet cooling water temperature for the PV/CPC+CU system increased by an average of 20.2 °C, 15.9 °C and 11.7 °C for 20l/hr, 30l/hr and 40l/hr flow rates respectively. Whereas for the PV/CU system it increased by 9.6 °C, 5.6 °C and 3.9 °C for the three flow rates respectively.

Table 5.5 Comparison of water temperature rise and thermal efficiency variations with flow rates for the PV/CU and PV/CPC+CU systems

System	Flow Rate (l/hr)	Water Temp. Rise (°C)	Thermal Efficiency (%)
PV/CU	20	9.6	12.6
	30	5.6	9.0
	40	3.9	7.3
PV/CPC/CU	20	20.2	27.0
	30	15.9	25.1
	40	11.7	21.8

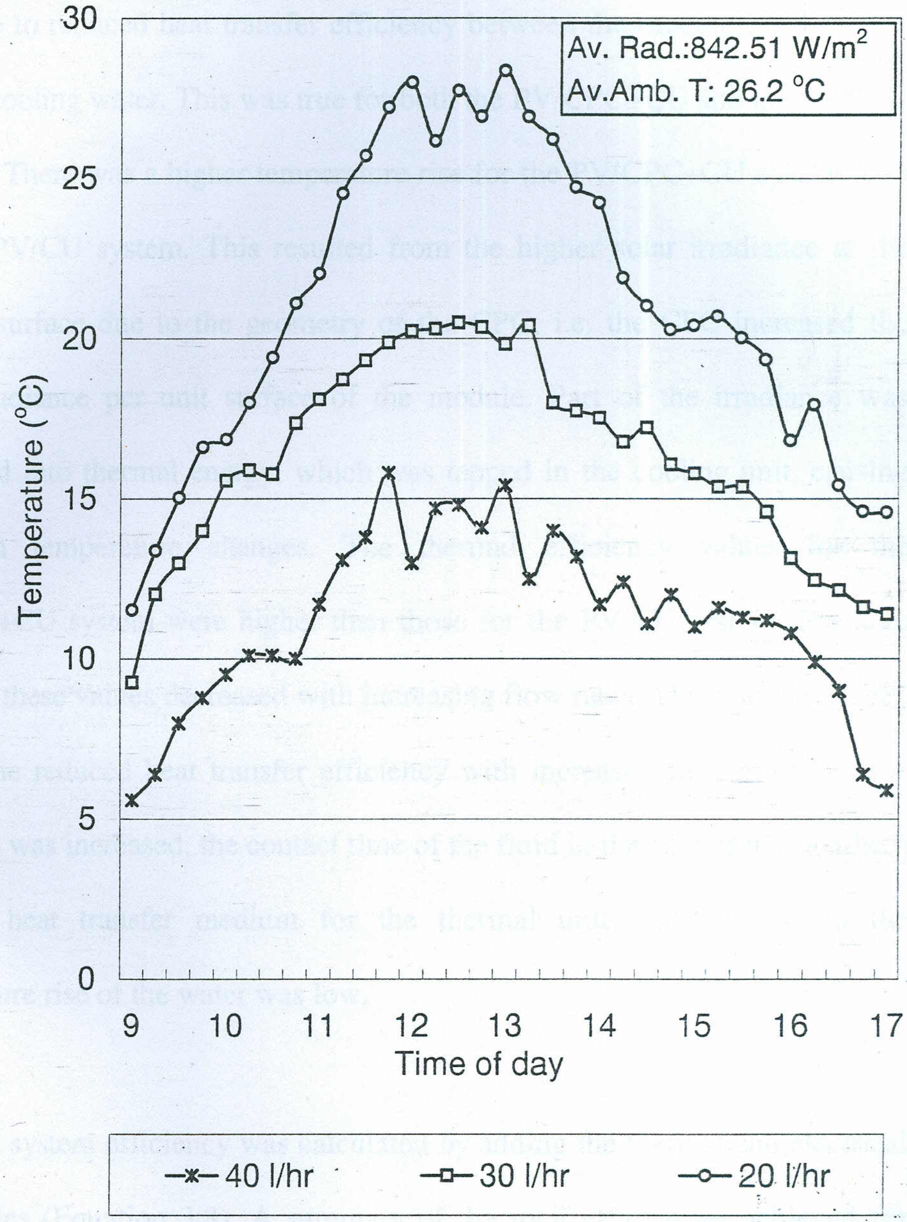

Fig 5.6 Comparison of water temperature rise with time for different flow rates for the PV/CPC+CU set up on clear sky days

The decrease in water temperature rise with increased flow rates may have been due to reduced heat transfer efficiency between the module back surface and the cooling water. This was true for both the PV/CPC+CU and the PV/CU systems. There was a higher temperature rise for the PV/CPC+CU system than for the PV/CU system. This resulted from the higher solar irradiance at the module surface due to the geometry of the CPC, i.e. the CPC increased the solar irradiance per unit surface of the module. Part of the irradiance was converted into thermal energy, which was tapped in the cooling unit, causing the high temperature changes. The thermal efficiency values for the PV/CPC+CU system were higher than those for the PV/CU system. For both systems, these values decreased with increasing flow rates. This may have been due to the reduced heat transfer efficiency with increased flow rates. As the flow rate was increased, the contact time of the fluid in the copper tubes, which acted a heat transfer medium for the thermal unit reduced and so the temperature rise of the water was low.

The total system efficiency was calculated by adding the thermal and electrical efficiencies (Equation 3.8). A summary of the total efficiencies achieved for the PV/CU and PV/CPC+CU experimental systems with the different flow rates are given in Table 5.6. It can be observed from Table 5.7 that the addition of CPC caused a substantial increase in both thermal and electrical efficiencies of the system. The PV/CPC+CU system with cooling water flow rate of 20 l/h had the highest total system efficiency, which was mainly contributed by the high thermal efficiency.

Table 5.6 Total system efficiencies for PV PLAIN, PV/CU PV/CPC and PV/CPC+CU systems.

System	Flow Rate (l/hr)	Electrical efficiency (%)	Thermal efficiency (%)	Total system efficiency (%)
PV PLAIN	-	5.6	-	5.6
PV/CU	20	6.6	12.6	19.2
	30	7.0	9.0	16.0
	40	7.7	7.3	15.0
PV/CPC	-	12.5	-	12.5
PV/CPC+CU	20	13.4	27.0	40.4
	30	14.4	25.1	39.5
	40	15.7	22.4	38.1

The high thermal efficiency resulted from high water temperature rise observed at the same flow rate of 20 l/h. This is because thermal efficiency increases with increase in water temperature rise.

5.8 Total Energy from the CHP System.

The total energy for the different systems was calculated by adding the electrical and thermal energy values. The electrical and thermal energy values were obtained by calculating the product of the power outputs and the average sunshine hours. The value of sunshine hours was taken to be 5.45 hours, which corresponds to the national average (Hankins, 1991). Table 5.7 gives a comparison of total system energy for the experimental systems.

The addition of a cooling unit to the PV plain module made it possible to harness the thermal energy from the system. This increased the amount of energy available. The addition of the CPC further increased this energy. For the PV/CU system it was observed that the total energy was higher at lower flow rates than at higher flow rates. At a flow rate of 20 l/hr, the energy available increased by 565% from 0.219 KWh/day to 1.458 KWh/day. At 30 l/hr the increase was 505% from 0.219 KWh/day to 1.325 KWh/day while at 40 l/hr the increase was 483% from 0.219 KWh/day to 1.277 KWh/day.

Table 5.7 Comparison of total system energy for the experimental systems.

System	Flow Rate (l/hr)	Electrical Energy (KWh/day)	Thermal Energy (KWh/day)	Total Daily Energy (KWh/day)	Total Annual Energy (KWh/yr)
PV Plain	-	0.219		0.219	79.94
PV/CU	20	0.243	1.215	1.458	532.17
	30	0.262	1.063	1.325	483.16
	40	0.290	0.987	1.277	466.11
PV/CPC	-	0.426	-	0.426	155.49
PV/CPC+CU	20	0.447	2.557	3.004	1096.46
	30	0.498	3.018	3.516	1283.34
	40	0.530	2.962	3.492	1274.58

For the PV/CPC+CU system, the total energy increased by 605% from 0.426 KWh/day to 3.004 KWh/day at 20l/hr, 725% from 0.426 KWh/day to 3.516

KWh/day at 30 l/hr and 719% from 0.426 KWh/day to 3.492 KWh/day at 40 l/hr. Considering the PV/CPC+CU system, it appears that the optimum flow rate at which there is maximum thermal energy is 30 l/hr. However more experiments at different flow rates high and below 30 l/hr need to be done so as to verify the observation.

5.9 Financial Evaluation.

5.9.1 Introduction

Economic and financial considerations are important factors to be considered when examining and evaluating the viability of investment in renewable energy projects. Life cycle costing (LCC) is considered to be one of the most complete approaches to economic appraisal (Markvat, 1994). In this method, the initial costs and all future costs of the entire operational life of the renewable energy system are considered. Detailed description of LCC methodology is given in Appendix D.

5.9.2 Life cycle costing of the experimental systems

The LCC of four systems were computed and compared for a domestic household situation. These systems were; PV PLAIN and PV/CPC for electricity while PV/CU and PV/CPC+CU for both electricity and heated water. For the PV/CU and PV/CPC+CU experiments, flow rates of 20 l/h and 30 l/hr were chosen respectively because these flow rates gave the highest amount of total energy for each of the systems.The cost data given in Appendix E was used in the calculation of the life cycle cost as shown in Table 5.8.

Table 5.8 Life cycle cost comparisons for the different systems investigated.

Item/ Experimental Set up	**PV PLAIN**	**PV/CU**	**PV/CPC**	**PV/CPC+CU**
1.Capital cost				
Complete PV kit with 6 lamps (Ksh.)	41600	41600	41600	41600
Cooling Unit		21000		21000
CPC			9000	9000
Installation & accessories (10 % of above)	4160	6260	5060	7160
Total Capital Cost	**45760**	**68860**	**55660**	**78760**
Add operation and maintenance (2% of Capital)	915	1377	1113	1575
Add Replacement				
1.Batteries (at year 5, 10 & 15)	11160	11160	11160	11160
2.Solar lamps (at year 4,8,12&16)	11952	11952	11952	11952
3.Charge controller (at year 10)	2622	2622	2622	2622
Total replacement cost	25734	25734	25734	25734
Total Life Cycle cost (LCC)	**72409**	**95971**	**82435**	**106069**
Annualised Life Cycle Cost (ALCC) (Ksh/yr)	8508.70	11277.40	9686.80	12464
Total Electricity generated per year (KWh/yr)	79.94	88.69	155.49	181.77
Total thermal energy annually (kWh/yr)	0.0	443.47	0.0	1101.57
Total Energy generated (kWh/yr)	79.94	532.17	155.49	1283.34
Levelized Energy Cost (LEC) (Ksh./kWh)	**106.44**	**21.19**	**62.29**	**9.71**

Note. Cost values are in Kenya Shillings; other units are indicated in item/experiment set up column.

5.9.3 Comparisons of capital costs.

Comparison of the capital cost for each system is given in Fig. 5.7. It can be observed that the addition of the cooling unit increased the capital cost by 50% while the CPC increased the capital cost further by 22%. For the PV/CPC+CU system in which both the CPC and the cooling unit were added, the capital cost increased by 72%. The high increase, which can be observed for the case of PV/CU and PV/CPC+CU systems, was mainly attributed to the cost of the insulated hot water storage tank.

However, capital costs do not include operation and maintenance and component replacement costs over the lifetime of the system. It doesn't also take into considerations the energy available from the system.

5.9.4 LCC Comparisons

The PV/CPC+CU system had the highest LCC of Ksh.106069 (U$1359.9) followed by the PV/CU with Ksh.95971 (U$1230.4) then PV/CPC with Ksh.82435 (U$1056.9). The PV PLAIN system had the lowest LCC of Ksh.72409 (U$928.3). However, this method does not still take into consideration the amount of energy harvested from the system. The annualised life cycle cost (ALCC) and the Levelized Energy Cost (LEC) are therefore utilised to give a more intelligent expression of the cost of the renewable energy system.

5.9.5 Comparison of the ALCC and the LEC of the different systems

The PV/CPC+CU system had the highest ALCC whereas the PV PLAIN had

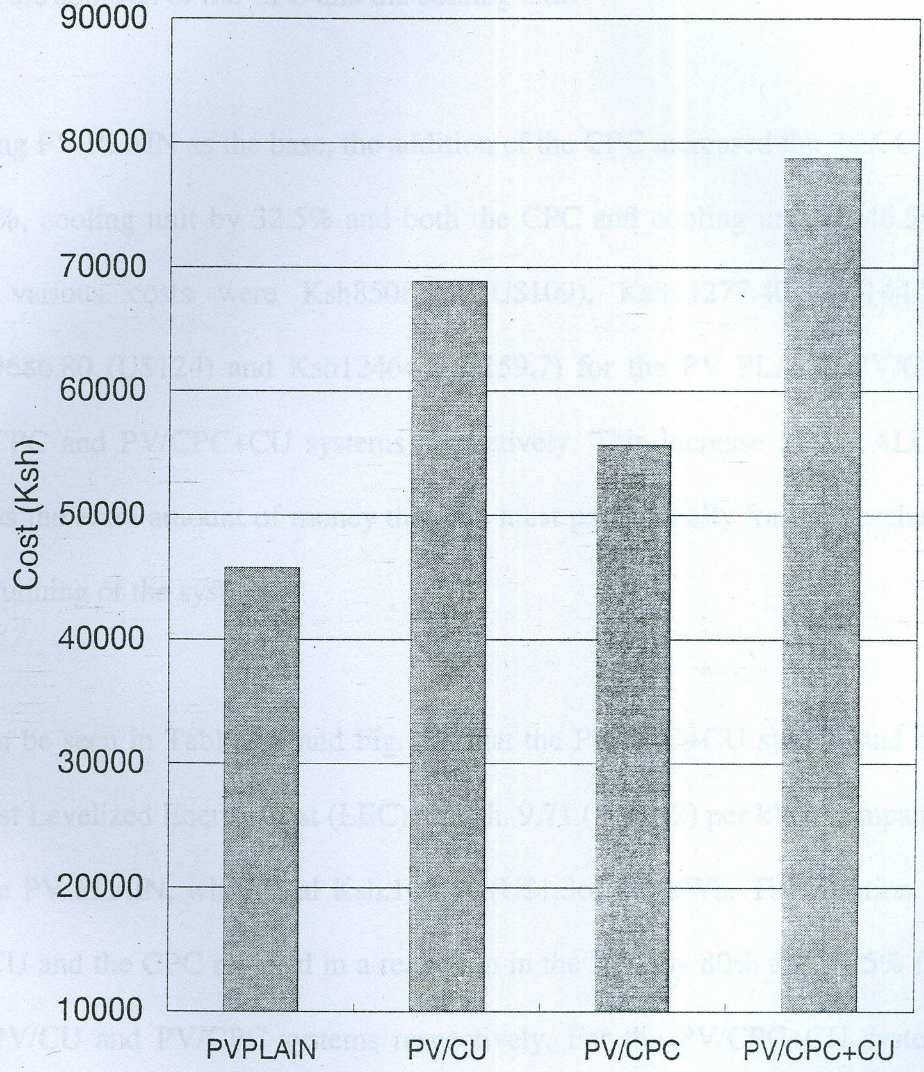

Fig. 5.7 Comparison of the Initial Capital cost of the diferent experimental systems.

the lowest. Since the replacement costs were constant for all the systems, the increase in ALCC was because of the initial increase in capital cost resulting from the addition of the CPC and the cooling unit.

Taking PV PLAIN as the base, the addition of the CPC increased the ALCC by 13.8%, cooling unit by 32.5% and both the CPC and cooling unit by 46.5%. The various costs were Ksh8508.70 (U$109), Ksh11277.40 (U$144.5), Ksh9686.80 (U$124) and Ksh12464 (U$159.7) for the PV PLAIN, PV/CU, PV/CPC and PV/CPC+CU systems respectively. This increase in the ALCC shows the extra amount of money that one must pay annually for the purchase and running of the systems.

It can be seen in Table 5.8 and Fig. 5.8 that the PV/CPC+CU system had the lowest Levelized Energy Cost (LEC) of Ksh. 9.71 (U$0.12) per kWh compared to the PV PLAIN, which had Ksh.106.44 (U$1.36) per kWh. The addition of the CU and the CPC resulted in a reduction in the LEC by 80% and 41.5% for the PV/CU and PV/CPC systems respectively. For the PV/CPC+CU system where both the CU and the CPC were added, the LEC reduced by 90.9%. This means that in the long run, it is much cheaper to operate a CHP system with an added CPC compared to a PV PLAIN, although the initial capital and the ALCC are higher for the PV/CPC+CU than for the PV PLAIN.

In addition to the reduced unit cost of energy, the addition of CPC and CU generated more electrical energy, For example the PV/CPC+CU system

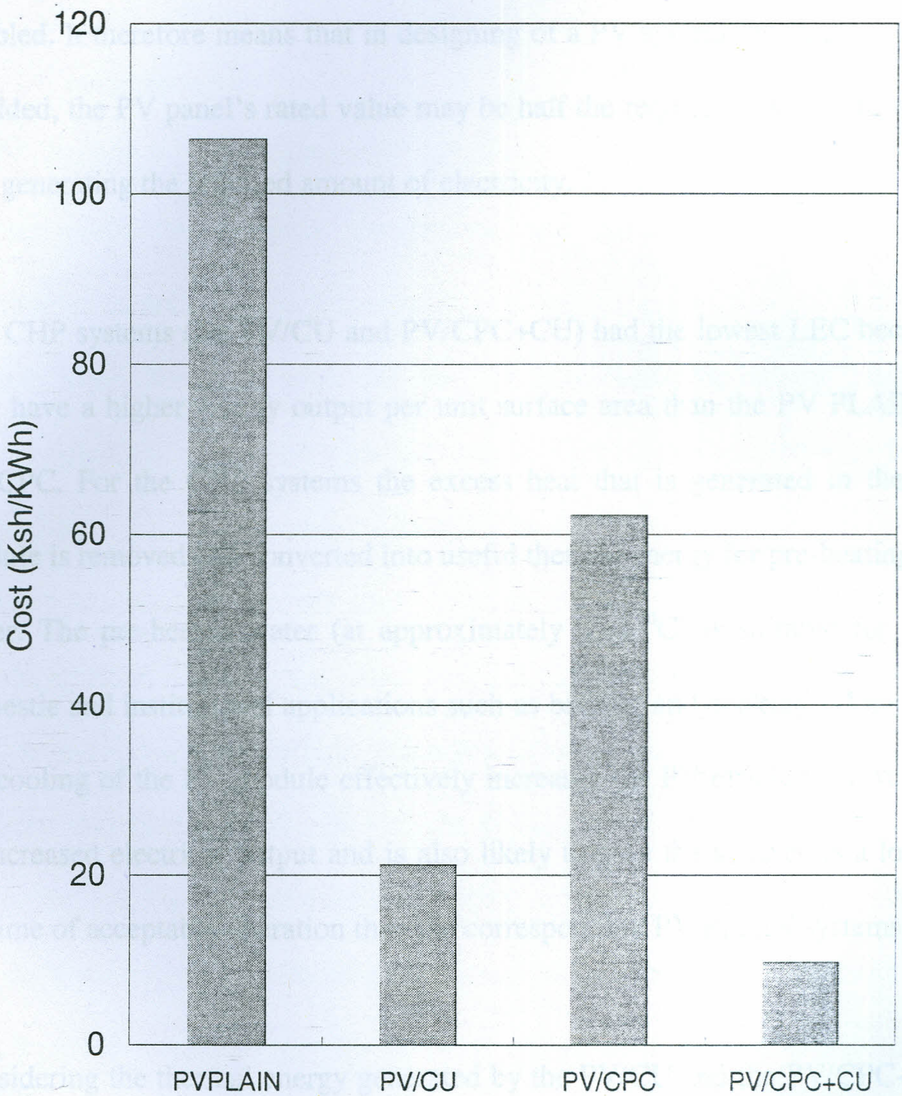

Fig. 5.8 Levelized energy ccst of the different experimental systems.

generates an extra 106.96 kWh/yr, which translates to 293.04 Wh/day of electricity. This shows that the electrical energy from the system more than doubled. It therefore means that in designing of a PV system, when a CPC/CU is added, the PV panel's rated value may be half the required design size while still generating the required amount of electricity.

The CHP systems (i.e. PV/CU and PV/CPC+CU) had the lowest LEC because they have a higher energy output per unit surface area than the PV PLAIN or PV/CPC. For the CHP systems the excess heat that is generated in the PV module is removed and converted into useful thermal energy for pre-heating water. The pre-heated water (at approximately 43.2 ^{o}C) is suitable for both domestic and institutional applications such as bathing and cooking. Moreover, the cooling of the PV module effectively increases the PV efficiency resulting in increased electrical output and is also likely to give the solar cells a longer lifetime of acceptable operation than the corresponding PV PLAIN systems.

Considering the thermal energy generated by the PV/CU and the PV/CPC+CU systems, an equivalent quantity of wood fuel that can produce the same amount of energy, can be calculated. Taking the average calorific value of wood to be 18.6 MJ/kg, and if a fuelwood combustion stove of 30% efficiency is used to heat water then the equivalent quantity of wood fuel PV/CU system is 286 kg/year whereas for the PV/CPC+CU is 710 kg per year.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

A PV system with an integrated compound parabolic concentrator and a cooling unit was designed, constructed and tested at the Appropriate Technology centre (ATC) in Kenyatta University.

In this work, the main objective was to investigate the effects of solar concentration and cooling on a photovoltaic module power production and heat generation. A 51 Wp amorphous silicon PV module with an active surface area of 0.768 m^2 was used in the study. For the cooling of the module, a heat exchanger made from copper tubes was coupled to the back surface of the module to form a CHP system. Water was used as the cooling fluid and the flow rate was kept at 20 l/hr, 30 l/hr and 40 l/hr. These flow rates were chosen arbitrarily. For the concentration, a 2D CPC with an acceptance angle of 14^o was designed and made with polished aluminium sheets. The concentrator was then attached on to the lengthwide sides of the module. Life cycle costing technique was used to evaluate the economics of the different systems for an average household application for both lighting and warm water requirements.

The main conclusions arrived at are the following:

1. Cooling water flow rate play an important role in of cooling of the PV module. For the PV/CU system the PV module was cooled by an average of 14 ^oC from 48.5 ^oC to 34.4 ^oC, which caused an increase in

electrical power and efficiency by 45.6% and 37.5% respectively, whereas for the PV/CPC+CU system, cooling of the PV module from 67.04°C to 33.8°C increased the electrical power and efficiency by 24.2% and 25.6% respectively.

2. Using 2D CPC with an acceptance angle of 14° coupled to a 51 Wp amorphous silicon PV module with an area of $0.768m^2$ caused the module temperature to increase by an average of 40.23% above that of a plain PV module with the same area and hence cooling is required.
3. A 25% truncated CPC with a theoretical concentration factor of 4.13 will increase the module power output by about 1.9X. The concentration factor of 1.9X obtained is lower than the expected 4.13 because of the effect of truncation, dust and the low reflectance value of ≈ 0.85 of the aluminium material used.
4. A 25% truncated 2D CPC with an acceptance angle of 14° increases the electrical efficiency of a 51 Wp amorphous PV module with an active area of 0.768 m^2 by 95.3%.
5. Solar concentration using a 25% truncated CPC and cooling on a 51Wp PV module results in a 118.74% increase in electrical power and 120.1% increase in electrical efficiency.
6. The addition of 25% truncated CPC to a CHP PV module raises the thermal energy and efficiencies. The changes are dependent on the cooling water flow rate. At a flow rate of 30 l/hr. the outlet cooling water temperature-rise changed from an average of 5.6 °C to 15.9 °C, with a corresponding increase in thermal efficiency from 9% to 25.1%.

At the same time, the thermal energy output increased from 1.063KWh/day to 3.018KWh/day

7. The use of CHP systems have great potential of reducing the water heating bills and can also contribute to the conservation of forests and the environment as a whole.
8. For an average household, it is more economical to run a CHP system with a CPC than for a plain PV module.

From the results obtained and discussed in this study, it is concluded that coupling a truncated 2D CPC with an acceptance angle of 14° to a CHP PV system is a viable option of improving the efficiency of a photovoltaic module and lowering the cost per unit of energy generated. The CHP PV system with the CPC have great potential of meeting the ever increasing energy demands in Kenya and other developing countries, especially in the rural and remote areas where the extension of the grid electricity is not economical.

6.2 Recommendations for further work.

The results obtained in this work can be further improved and complemented with the following research suggestions:

1. More work should be done to determine the optimum cooling water flow rate for the CHP - PV systems.
2. Develop suitable models and standardized method of assessing the energy performance of the PV/T systems with added CPC.

3. Further work need to be done to compare the thermal output of CHP PV systems using modules with different surface areas.
4. More work needs to be done to compare the performance of different PV module types for CHP systems.

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APPENDIX A

SAMPLE DATA SHEETS FOR THE VARIOUS EXPERIMENTAL SYSTEMS

Table A-1 Sample Data sheet for PV Plain Experimental system.

Date: 26-09-02

Time (Hrs)	G (W/m^2)	Ta (^oC)	I M1 (A)	I M2 (A)	V M1 (V)	V M2 (V)	T M1 (^oC)	T M2 (^oC)	P M2 (W)	PM2 (W)	E_{eff} M1	E_{eff} M2
9.00	230.21	20.2	0.57	0.57	15.34	15.32	28.4	28.3	8.74	8.73	0.049	0.049
9.15	108.96	19.9	0.25	0.24	14.88	14.87	24.6	24.5	3.72	3.57	0.044	0.043
9.30	770.33	21.6	2.01	2.00	17.46	17.47	40.2	40.2	35.09	34.94	0.059	0.059
9.45	772.48	22.0	2.02	2.02	17.46	17.46	41.3	40.9	35.27	35.27	0.059	0.059
10.00	708.28	22.3	1.84	1.84	17.23	17.23	42.3	42.3	31.70	31.70	0.058	0.058
10.15	886.54	23.0	2.31	2.30	17.92	17.91	49.0	48.9	41.40	41.19	0.061	0.061
10.30	825.40	22.6	2.15	2.16	17.65	17.64	46.8	46.7	37.95	38.10	0.060	0.060
10.45	269.31	21.2	0.68	0.68	15.49	15.50	29.6	30.0	10.53	10.54	0.051	0.051
11.00	801.48	24.1	2.09	2.09	17.56	17.54	46.1	46.2	36.70	36.66	0.060	0.060
11.15	732.19	23.2	1.91	1.90	17.30	17.30	43.9	43.5	33.04	32.87	0.059	0.058
11.30	741.68	23.0	1.93	1.94	17.34	17.36	44.3	44.2	33.47	33.68	0.059	0.059
11.45	773.73	24.0	2.02	2.03	17.46	17.46	43.8	43.6	35.27	35.44	0.059	0.060
12.00	819.03	24.9	2.13	2.13	17.65	17.65	46.8	46.5	37.59	37.59	0.060	0.060
12.15	714.73	24.2	1.86	1.87	17.27	17.28	43.7	42.9	32.12	32.31	0.059	0.059
12.30	265.01	22.1	0.66	0.66	15.46	15.49	29.5	29.7	10.20	10.22	0.050	0.050
12.45	820.37	23.1	2.14	2.14	17.00	17.63	45.2	45.1	36.38	37.73	0.058	0.060
13.00	388.57	21.2	1.00	1.01	15.95	15.90	35.3	35.2	15.95	16.06	0.053	0.054
13.15	880.63	22.6	2.30	2.31	17.88	17.86	47.5	47.6	41.12	41.26	0.061	0.061
13.30	705.77	22.4	1.83	1.83	17.03	17.03	43.0	43.0	31.16	31.16	0.057	0.057
13.45	671.51	21.9	1.75	1.75	17.00	17.01	42.1	42.5	29.75	29.77	0.058	0.058
14.00	650.62	22.2	1.69	1.69	16.95	16.99	40.5	40.7	28.65	28.71	0.057	0.057
14.15	206.15	20.3	0.50	0.57	15.22	15.23	30.0	30.2	7.61	8.68	0.048	0.055
14.30	721.53	22.8	1.88	1.87	17.20	17.25	40.7	40.6	32.34	32.26	0.058	0.058
14.45	724.58	21.3	1.89	1.88	17.21	17.21	42.1	42.1	32.53	32.35	0.058	0.058
15.00	666.47	23.2	1.72	1.73	17.01	17.20	41.9	41.9	29.26	29.76	0.057	0.058
15.15	539.87	22.5	1.40	1.41	16.50	16.46	37.5	37.4	23.10	23.21	0.056	0.056
15.30	610.20	22.9	1.58	1.58	16.82	16.83	40.5	40.4	26.58	26.59	0.057	0.057
15.45	530.70	21.8	1.37	1.37	16.50	16.52	38.5	38.6	22.61	22.63	0.055	0.056
16.00	435.57	21.3	1.11	1.12	16.11	16.11	34.6	34.7	17.88	18.04	0.053	0.054
16.15	642.92	22.6	1.67	1.67	16.92	16.92	40.2	40.2	28.26	28.26	0.057	0.057
16.30	490.59	22.6	1.26	1.25	16.30	16.42	37.2	37.2	20.54	20.53	0.055	0.054
16.45	388.57	21.2	1.01	1.01	15.72	15.72	33.4	33.5	15.88	15.88	0.053	0.053
17.00	437.72	22.8	1.12	1.12	16.15	16.10	33.6	33.6	18.09	18.03	0.054	0.054

Table A-2 Sample Data Sheet for PV/CU Experimental system with cooling water flow rate of 20 l/hr.

Date: 03.10.02

Time (Hrs)	G (W/m^2)	T_a (°C)	I M1 (A)	I M2 (A)	V M1 (V)	V M2 (V)	T M1 (°C)	T M2 (°C)	T_i °C	T_o °C	T_o-T_i °C	P M1 (W)	P M2 (W)	E_{eff} M1	E_{eff} M2	T_{eff}
9.00	550.22	22.6	1.68	1.42	16.93	16.07	34.2	39.1	22.7	27.5	4.80	28.44	22.82	0.063	0.051	0.09
9.15	602.56	22.3	1.85	1.56	17.00	16.77	38.2	39.9	19.9	26.1	6.20	31.45	26.16	0.064	0.053	0.11
9.30	647.13	23.5	1.98	1.65	17.17	16.96	38.8	43.3	19.7	27.6	7.90	34.00	27.98	0.064	0.053	0.13
9.45	657.88	24.2	2.02	1.70	17.19	17.00	40.4	44.5	21.5	29.9	8.40	34.72	28.90	0.065	0.054	0.14
10.00	683.12	25.0	2.08	1.77	17.29	17.11	41.4	44.2	19.6	29.0	9.40	35.96	30.28	0.064	0.054	0.15
10.15	697.18	24.4	2.15	1.82	17.38	17.19	42.6	44.3	20.7	30.2	9.50	37.37	31.29	0.066	0.055	0.15
10.30	697.18	24.4	2.15	1.82	17.38	17.19	44.1	44.3	20.7	29.2	8.50	37.37	31.29	0.066	0.055	0.13
10.45	715.98	24.8	2.20	1.88	17.48	17.27	44.8	43.9	20.2	29.3	9.10	38.46	32.47	0.066	0.055	0.14
11.00	758.21	25.2	2.33	1.97	17.51	17.38	44.9	47.3	22.6	30.8	8.20	40.80	34.24	0.066	0.055	0.12
11.15	774.52	24.9	2.37	2.01	17.63	17.46	45.3	47.3	22.6	31.9	9.30	41.78	35.09	0.066	0.055	0.13
11.30	774.52	24.9	2.37	2.01	17.63	17.46	46.7	47.3	22.6	32.9	10.30	41.78	35.09	0.066	0.055	0.14
11.45	841.34	25.6	2.60	2.21	18.01	17.73	47.2	48.1	23.5	31.9	8.40	46.83	39.18	0.068	0.057	0.11
12.00	882.33	27.5	2.74	2.31	18.20	17.88	48.2	52.1	21.5	31.0	9.50	49.87	41.30	0.069	0.057	0.12
12.15	997.54	27.2	3.12	2.61	18.63	18.19	47.7	53.6	23.1	33.2	10.10	58.13	47.48	0.071	0.058	0.11
12.30	1024.90	26.5	3.19	2.94	18.70	18.81	47.8	54.2	22.5	32.9	10.40	59.65	55.30	0.071	0.066	0.11
12.45	1121.30	27.3	3.51	2.95	18.67	18.76	47.6	59.3	23.2	35.4	12.20	65.53	55.34	0.072	0.060	0.12
13.00	1054.24	28.6	3.25	2.75	18.77	18.86	46.3	57.5	23.2	36.6	13.40	61.00	51.87	0.071	0.060	0.14
13.15	993.62	28.0	3.09	2.59	18.52	18.31	46.5	54.3	23.5	34.1	10.60	57.23	47.42	0.070	0.058	0.12
13.30	988.27	26.9	3.07	2.57	18.59	18.20	46.5	53.2	22.9	33.1	10.20	57.07	46.77	0.071	0.058	0.11
13.45	900.56	28.5	2.81	2.35	18.30	17.96	45.3	52.3	23.4	32.2	8.80	51.42	42.21	0.070	0.057	0.11
14.00	895.11	27.9	2.76	2.34	18.20	18.92	46.4	50.9	24.0	33.6	9.60	50.23	44.27	0.069	0.061	0.12
14.15	885.23	27.5	2.74	2.31	18.20	17.88	45.7	52.1	21.5	31.0	9.50	49.87	41.30	0.069	0.057	0.12
14.30	880.53	27.7	2.75	2.31	17.90	17.88	44.8	51.5	23.2	34.0	10.80	49.23	41.30	0.068	0.057	0.13
14.45	853.71	26.2	2.60	2.23	17.99	17.77	45.1	49.7	22.6	33.5	10.90	46.77	39.63	0.067	0.057	0.14
15.00	830.72	30.1	2.59	2.17	17.69	17.70	43.6	49.2	22.7	32.5	9.80	45.82	38.41	0.067	0.057	0.13
15.15	815.22	27.5	2.51	2.12	17.63	17.39	43.8	46.8	22.0	32.3	10.30	44.25	36.87	0.066	0.055	0.14
15.30	784.52	24.9	2.42	2.01	17.63	17.46	43.1	47.3	22.2	31.9	9.70	42.66	35.09	0.067	0.055	0.13
15.45	655.20	29.0	2.02	1.69	17.13	16.97	41.8	39.3	22.5	28.3	5.80	34.60	28.68	0.065	0.054	0.10
16.00	650.11	29.0	2.00	1.68	17.03	16.96	41.8	39.2	22.1	28.2	6.10	34.06	28.49	0.064	0.054	0.10
16.15	599.22	27.2	1.83	1.57	17.00	16.77	40.8	40.7	21.6	27.1	5.50	31.11	26.33	0.064	0.054	0.10
16.30	590.00	27.2	1.79	1.53	16.73	16.73	38.9	45.6	23.0	29.0	6.00	29.95	25.60	0.062	0.053	0.11
16.45	787.45	24.9	2.41	2.05	17.63	17.46	37.0	47.3	22.6	29.9	7.30	42.49	35.79	0.066	0.056	0.10
17.00	540.31	28.4	1.63	1.40	16.74	16.53	35.0	40.5	23.6	29.5	5.90	27.29	23.14	0.062	0.052	0.12

Table A-3 Sample Data Sheet for PV/CU Experimental system with cooling water flow rate of 30 l/hr.

DATE: 15-10-02

Time (Hrs)	G (W/m^2)	Ta (^oC)	IM 1 (A)	IM 2 (A)	VM 1 (V)	VM 2 (V)	TM 1 (^oC)	TM 2 (^oC)	T_i (^oC)	T_o (^oC)	T_o-T_i (^oC)	P M1 (w)	P M2 (w)	E_{eff} M1	E_{eff} M2	T_{eff}
9.00	486.63	23.5	1.52	1.23	16.41	16.33	33.13	38.70	21.8	24.9	3.10	24.94	20.09	0.063	0.051	0.09
9.15	524.30	25.1	1.65	1.34	16.25	16.08	35.50	39.00	21.5	24.2	2.70	26.81	21.55	0.063	0.050	0.07
9.30	568.51	23.8	1.80	1.47	16.53	16.71	35.60	41.60	22.1	25.4	3.30	29.75	24.56	0.064	0.053	0.08
9.45	570.21	24.3	1.82	1.48	16.83	16.67	36.80	43.00	21.9	25.5	3.60	30.63	24.67	0.066	0.053	0.09
10.00	612.21	24.6	1.96	1.58	16.86	16.83	36.50	45.70	21.2	25.8	4.60	33.05	26.59	0.066	0.053	0.10
10.15	695.23	24.9	2.24	1.82	17.34	17.15	37.30	46.70	21.5	26.4	4.90	38.84	31.21	0.068	0.055	0.10
10.30	735.47	25.8	2.36	1.90	17.51	17.20	38.20	48.00	21.7	26.6	4.90	41.32	32.68	0.069	0.054	0.09
10.45	766.51	26.4	2.36	1.99	17.55	17.40	39.00	47.40	21.4	26.9	5.50	41.42	34.63	0.066	0.055	0.10
11.00	820.51	25.3	2.68	2.14	17.32	17.65	38.95	49.80	21.3	26.8	5.50	46.42	37.77	0.069	0.056	0.09
11.15	833.29	26.2	2.69	1.17	17.63	17.59	38.86	49.80	21.7	27.2	5.50	47.42	20.58	0.070	0.030	0.09
11.30	860.51	26.5	2.81	2.24	17.43	17.51	39.45	52.20	22.1	27.9	5.80	48.98	39.22	0.070	0.056	0.09
11.45	867.41	27.5	2.55	2.17	17.68	17.77	40.60	55.10	22.6	27.8	5.20	45.08	38.56	0.064	0.054	0.08
12.00	903.23	25.6	2.95	2.36	17.99	17.87	40.20	55.30	21.9	27.9	6.00	53.07	42.17	0.072	0.057	0.09
12.15	926.51	27.0	2.98	2.39	17.86	17.97	41.00	57.60	22.3	28.5	6.20	53.22	42.95	0.070	0.057	0.09
12.30	940.63	27.2	3.08	2.44	18.36	18.11	40.36	56.60	22.3	28.2	5.90	56.55	44.19	0.074	0.057	0.09
12.45	993.26	27.1	3.26	2.58	18.44	18.13	41.00	58.00	21.7	28.6	6.90	60.11	46.78	0.074	0.058	0.09
13.00	993.58	27.3	3.25	2.58	18.22	18.31	40.28	57.40	21.6	27.6	6.00	59.22	47.24	0.073	0.058	0.08
13.15	1020.50	27.3	3.36	2.67	17.83	17.98	40.36	57.40	21.8	28.8	7.00	59.91	48.01	0.072	0.058	0.09
13.30	869.01	27.5	2.51	2.17	17.68	17.77	40.44	57.30	22.6	27.8	5.20	44.38	38.56	0.062	0.054	0.08
13.45	860.53	26.6	2.78	2.22	17.94	17.81	40.60	57.80	22.9	27.7	4.80	49.87	39.54	0.071	0.056	0.08
14.00	725.53	27.8	1.87	1.75	16.97	16.93	40.60	55.80	22.7	27.3	4.60	31.73	29.63	0.054	0.050	0.09
14.15	789.22	26.1	2.50	1.99	17.46	17.42	38.80	50.96	21.9	27.0	5.10	43.94	34.82	0.068	0.054	0.09
14.30	721.53	27.8	1.86	1.75	16.97	16.93	40.60	55.80	22.7	27.3	4.60	31.56	29.63	0.054	0.050	0.09
14.45	720.28	26.1	1.91	1.80	17.53	17.27	39.70	53.70	22.0	26.1	4.10	33.48	31.09	0.057	0.053	0.08
15.00	681.56	27.2	1.74	2.07	17.03	17.07	38.90	50.10	21.6	26.8	5.20	29.63	35.33	0.053	0.063	0.10
15.15	672.53	27.3	1.58	1.63	16.83	16.75	36.30	49.90	21.8	26.5	4.70	26.59	27.30	0.048	0.050	0.10
15.30	598.21	26.1	1.62	1.51	16.83	16.73	37.10	49.60	21.9	25.3	3.40	27.26	25.26	0.056	0.052	0.08
15.45	596.21	26.1	1.62	1.51	16.83	16.73	37.10	49.60	21.9	25.3	3.40	27.26	25.26	0.056	0.052	0.08
15.00	560.51	26.5	1.72	1.41	16.96	16.20	34.10	46.70	21.5	24.9	3.40	29.17	22.84	0.064	0.050	0.08
16.15	533.58	26.3	1.69	1.29	16.55	16.50	35.80	43.90	21.6	25.2	3.60	27.97	21.29	0.064	0.049	0.09
14.00	520.56	26.7	1.48	1.39	16.39	16.37	33.80	38.70	21.0	24.0	3.00	24.26	22.75	0.057	0.053	0.08
16.45	492.35	26.2	1.31	1.24	16.15	16.24	32.50	36.50	21.2	23.8	2.60	21.16	20.14	0.053	0.050	0.07
17.00	455.30	25.2	1.22	1.10	16.03	16.19	32.40	34.20	21.7	24.2	2.50	19.56	17.81	0.053	0.048	0.07

Table A-4 Sample Data Sheet for PV/CU Experimental system with cooling water flow rate of 40 l/hr.

Date: 24.10.02

Time (Hrs)	G (W/m^2)	T_a (°C)	I M1 (A)	I M2 (A)	V M1 (V)	V M2 (V)	T M1 (°C)	T M2 (°C)	T_i °C	T_o °C	T_o-T_i °C	P M1 (W)	P M2 (W)	E_{eff} M1	E_{eff} M2	T_{eff}
9.00	268.86	19.30	0.81	0.67	16.51	16.19	26.1	29.6	19.0	20.0	1.0	13.37	10.85	0.061	0.049	0.06
9.15	287.22	20.50	0.95	0.73	16.67	16.27	26.2	29.8	19.2	20.1	0.9	15.84	11.88	0.067	0.051	0.05
9.30	308.17	20.60	1.01	0.78	15.80	15.67	26.9	30.9	20.2	21.4	1.2	15.96	12.22	0.063	0.049	0.06
9.45	438.52	21.50	1.48	1.13	16.20	16.15	28.7	33.6	19.9	21.6	1.7	23.98	18.25	0.067	0.051	0.06
10.00	545.87	22.30	1.85	1.40	16.53	16.31	30.1	37.2	20.1	22.6	2.5	30.58	22.83	0.069	0.051	0.07
10.15	554.83	21.90	1.89	1.41	16.52	16.47	30.5	38.3	20.1	22.1	2.0	31.22	23.22	0.069	0.051	0.06
10.30	607.47	23.20	2.11	1.57	16.83	16.60	30.8	39.2	20.1	22.4	2.3	35.51	26.06	0.072	0.052	0.06
10.45	692.88	24.50	2.40	1.80	17.19	17.05	32.8	42.7	21.6	24.5	2.9	41.26	30.69	0.073	0.054	0.07
11.00	725.83	23.90	2.51	1.88	17.20	17.02	33.0	43.3	20.2	22.9	2.7	43.17	32.00	0.073	0.054	0.06
11.15	755.21	25.50	2.62	1.96	17.53	17.38	33.6	44.6	20.5	24.0	3.5	45.93	34.06	0.074	0.055	0.08
11.30	778.00	25.40	2.68	2.07	17.21	17.07	35.0	44.7	22.1	24.8	2.7	46.12	35.33	0.073	0.056	0.06
11.45	795.93	26.30	2.63	2.06	17.63	17.54	34.6	45.8	23.0	25.2	2.2	46.37	36.13	0.071	0.056	0.05
12.00	812.68	26.90	2.84	2.13	17.65	17.61	35.7	46.5	23.2	26.3	3.1	50.13	37.51	0.075	0.056	0.06
12.15	845.17	26.50	2.95	2.19	17.91	17.73	35.4	47.4	21.7	26.4	4.7	52.83	38.83	0.076	0.056	0.09
12.30	854.93	26.80	2.99	2.23	17.66	17.77	36.4	47.7	21.5	25.5	4.0	52.80	39.63	0.076	0.057	0.08
12.45	869.00	27.10	3.16	2.28	17.64	17.59	36.5	47.6	21.4	25.2	3.8	55.74	40.11	0.078	0.056	0.07
13.00	910.53	27.20	3.21	2.37	17.98	17.83	36.4	48.5	21.3	25.8	4.5	57.72	42.26	0.078	0.057	0.08
13.15	953.00	26.30	3.46	2.59	17.95	17.86	36.6	52.1	21.5	26.1	4.6	62.11	46.26	0.080	0.059	0.08
13.30	977.00	26.10	3.28	2.55	17.66	17.57	35.9	47.7	21.5	25.5	4.0	57.92	44.80	0.073	0.056	0.07
13.45	967.30	26.20	3.39	2.52	18.22	18.08	35.5	51.1	22.0	25.9	3.9	61.77	45.56	0.078	0.058	0.07
14.00	960.00	25.90	3.20	2.51	17.63	17.54	36.1	45.8	23.0	26.2	3.2	56.42	44.03	0.072	0.056	0.05
14.15	958.43	25.50	3.38	2.51	18.15	18.06	33.8	50.1	21.9	26.0	4.1	61.35	45.33	0.078	0.058	0.07
14.30	944.64	25.50	3.32	2.47	18.23	18.11	32.8	50.5	21.8	25.9	4.1	60.52	44.73	0.078	0.058	0.07
14.45	940.08	24.90	3.30	2.46	17.93	17.73	32.5	50.4	21.7	25.3	3.6	59.17	43.62	0.077	0.057	0.06
15.00	938.74	25.10	3.29	2.45	18.03	17.91	30.9	50.5	21.4	25.9	4.5	59.32	43.88	0.077	0.057	0.08
15.15	899.88	24.40	3.16	2.35	17.99	17.96	30.9	49.3	21.5	25.7	4.2	56.85	42.21	0.077	0.057	0.08
15.30	857.00	24.30	2.87	2.23	17.43	17.34	30.0	44.3	20.9	25.0	4.1	50.02	38.67	0.071	0.055	0.08
15.45	799.81	23.40	2.81	2.08	17.96	17.57	29.8	46.1	21.5	25.3	3.8	50.47	36.55	0.077	0.056	0.08
16.00	650.28	23.40	2.25	1.68	17.06	16.96	30.0	41.5	21.2	24.0	2.8	38.39	28.49	0.072	0.054	0.07
16.15	522.36	23.10	1.78	1.34	16.46	16.26	29.8	37.4	20.6	23.0	2.4	29.30	21.79	0.069	0.051	0.08
16.30	420.81	22.00	1.41	1.07	16.52	16.11	29.3	35.8	21.5	22.9	1.4	23.29	17.24	0.068	0.050	0.05
16.45	348.00	21.40	1.19	0.86	16.41	16.38	30.5	34.2	21.2	22.5	1.3	19.53	14.09	0.069	0.050	0.06
17.00	310.00	21.10	0.98	0.76	16.33	16.24	28.9	36.5	21.2	22.2	1.0	16.00	12.34	0.063	0.049	0.05

Table A-5 Sample Data sheet for PV/CPC Experimental system.

Date: 14-01-2003

Time (Hrs)	G (W/m²)	T_a (°C)	I M1 (A)	I M 2(A)	VM1(V)	VM2 (V)	Tm1 °C	Tm2 °C	P M1(W)	P M2(W)	E_{eff} M1	E_{eff} M2
9.00	522.61	24.20	2.53	1.34	16.72	16.46	48.60	38.30	42.30	22.06	0.112	0.058
9.15	590.28	24.50	2.90	1.53	16.88	16.73	52.50	39.80	48.95	25.60	0.115	0.060
9.30	600.23	25.00	2.95	1.56	17.03	16.77	53.00	40.20	50.24	26.16	0.116	0.060
9.45	710.11	26.20	3.53	1.85	17.20	17.23	59.10	43.30	60.72	31.88	0.118	0.062
10.00	750.23	26.50	3.75	1.96	17.41	17.38	61.30	44.60	65.29	34.06	0.121	0.063
10.15	823.55	27.80	4.12	2.15	17.83	17.65	64.60	46.80	73.46	37.95	0.124	0.064
10.30	870.22	28.10	4.38	2.29	17.84	17.84	67.30	48.00	78.14	40.85	0.124	0.065
10.45	930.23	28.00	4.73	2.43	18.09	18.08	68.20	50.50	85.57	43.93	0.127	0.065
11.00	950.54	28.30	4.81	2.49	18.20	18.15	72.30	50.80	87.54	45.19	0.128	0.066
11.15	1005.24	28.50	5.06	2.65	18.30	18.34	75.00	52.40	92.60	48.60	0.128	0.067
11.30	1010.51	29.30	5.12	2.65	18.46	18.38	75.60	52.70	94.52	48.71	0.130	0.067
11.45	1025.32	29.50	5.23	2.68	18.53	18.42	76.10	53.00	96.91	49.37	0.131	0.067
12.00	1050.23	29.10	5.34	2.75	18.73	18.54	77.80	52.90	100.02	50.99	0.132	0.067
12.15	1060.83	30.60	5.39	2.79	18.50	18.58	78.30	54.30	99.72	51.84	0.130	0.068
12.30	1070.53	30.70	5.44	2.81	18.73	18.61	78.50	54.60	101.89	52.29	0.132	0.068
12.45	1108.01	29.80	5.52	2.90	18.71	18.70	79.40	55.80	103.28	54.23	0.129	0.068
13.00	1090.23	30.20	5.47	2.86	18.73	18.69	79.20	55.20	102.45	53.45	0.130	0.068
13.15	1031.26	28.70	5.23	2.70	18.51	18.38	75.40	53.30	96.81	49.63	0.130	0.067
13.30	1020.13	28.60	5.18	2.67	18.63	18.42	76.10	53.00	96.50	49.18	0.131	0.067
13.45	1015.22	28.20	5.12	2.66	18.49	18.40	75.60	52.70	94.67	48.94	0.129	0.067
14.00	1008.00	28.50	5.09	2.63	18.68	18.31	74.30	50.30	95.08	48.16	0.131	0.066
14.15	1002.52	28.50	5.08	2.65	18.56	18.34	73.20	52.10	94.28	48.60	0.130	0.067
14.30	956.24	27.90	4.81	2.50	18.52	18.15	72.30	50.80	89.08	45.38	0.129	0.066
14.45	940.52	28.00	4.75	2.45	18.23	18.11	71.70	49.90	86.59	44.37	0.128	0.065
15.00	920.53	27.40	4.63	2.41	18.68	18.04	70.60	49.90	86.49	43.48	0.130	0.065
15.15	890.26	27.60	4.49	2.33	18.05	17.92	68.30	49.00	81.04	41.75	0.126	0.065
15.30	853.21	27.90	4.28	2.22	17.93	17.77	66.30	47.70	76.74	39.45	0.125	0.064
15.45	802.51	26.30	4.02	2.10	17.71	17.57	64.00	46.10	71.19	36.90	0.123	0.064
16.00	765.83	26.00	3.80	1.99	17.83	17.42	61.80	44.30	67.75	34.67	0.123	0.063
16.15	750.22	26.10	3.75	1.97	17.23	17.38	61.30	44.60	64.61	34.24	0.119	0.063
16.30	710.53	25.80	3.53	1.86	17.20	17.23	59.10	43.00	60.72	32.05	0.118	0.062
16.45	600.21	25.90	2.95	1.56	17.03	16.77	53.00	39.90	50.24	26.16	0.116	0.060
17.00	520.30	24.80	2.53	1.35	17.01	16.46	48.60	36.30	43.04	22.22	0.115	0.059

Table A-6 Sample Data for PV/CPC/CU Experimental system with cooling water flow rate of 20 l/hr.

Date: 22-01-2003

Time (Hrs)	G (w/m²)	Ta (°C)	I M1 (A)	I M 2(A)	VM1 (V)	VM2 (V)	Tm1 (°C)	Tm2 (°C)	Tfi (°C)	Tfo (°C)	P M1	P M2	E_{eff} M1	E_{Eff} M2	T_{eff}	Tfo-Tfi (°C)
9.00	482.31	25.2	2.46	1.25	16.68	16.43	34.76	36.2	20.0	31.53	41.03	20.54	0.118	0.059	0.260	11.5
9.15	530.83	25.8	2.75	1.38	16.63	16.50	36.03	37.7	20.5	33.88	45.73	22.77	0.119	0.059	0.274	13.4
9.30	583.23	25.9	3.04	1.50	16.72	16.69	37.25	39.3	20.2	35.23	50.83	25.04	0.121	0.059	0.281	15.0
9.45	610.23	26.7	3.21	1.59	16.98	16.80	38.03	40.2	20.9	37.5	54.51	26.71	0.124	0.061	0.296	16.6
10.00	655.10	26.9	3.44	1.70	17.03	16.96	39.21	41.7	20.2	37.04	58.58	28.83	0.124	0.061	0.280	16.8
10.15	660.00	26.9	3.50	1.76	17.48	17.00	39.20	42.1	21.5	39.50	61.18	29.92	0.128	0.063	0.297	18.0
10.30	720.53	27.1	3.85	1.89	17.36	17.27	40.70	43.7	20.6	40.01	66.84	32.64	0.129	0.063	0.293	19.4
10.45	793.55	27.3	4.26	2.07	17.60	17.54	42.50	45.8	20.8	41.9	74.98	36.31	0.131	0.063	0.289	21.1
11.00	856.23	27.5	4.60	2.24	17.92	17.77	43.40	47.7	21.5	43.52	82.43	39.80	0.133	0.064	0.280	22.0
11.15	950.23	28.3	5.18	2.49	18.43	18.15	46.70	50.8	21.7	46.22	95.47	45.19	0.139	0.066	0.281	24.5
11.30	996.28	28.4	5.43	2.60	18.60	18.31	47.70	51.2	21.6	47.31	101.00	47.61	0.140	0.066	0.281	25.7
11.45	1052.36	29.2	5.76	2.74	18.76	18.50	49.23	53.9	21.7	48.92	108.06	50.69	0.142	0.067	0.282	27.2
12.00	1068.23	29.3	5.82	2.79	18.83	18.58	49.55	54.3	21.2	49.19	109.59	51.84	0.142	0.067	0.285	28.0
12.15	1070.32	28.2	5.88	2.82	18.94	18.61	49.73	54.6	22.3	48.46	111.37	52.48	0.144	0.068	0.266	26.2
12.30	1100.32	28.7	6.02	2.90	18.76	18.72	49.96	55.5	22.0	49.73	112.94	54.29	0.142	0.068	0.274	27.7
12.45	1106.83	28.9	6.01	2.91	18.82	18.71	50.02	55.8	22.3	49.23	113.11	54.45	0.142	0.068	0.265	26.9
13.00	1120.51	29.0	6.08	2.94	18.95	18.81	50.83	56.1	21.6	49.95	115.22	55.30	0.142	0.068	0.275	28.4
13.15	1070.53	29.1	5.88	2.83	18.82	18.60	49.75	54.6	21.5	48.42	110.66	52.64	0.143	0.068	0.274	26.9
13.30	1025.22	29.0	5.59	2.68	18.59	18.42	48.53	53.0	21.9	48.11	103.92	49.37	0.140	0.067	0.278	26.2
13.45	990.58	28.6	5.42	2.60	18.96	18.31	47.76	52.1	21.6	46.32	102.76	47.61	0.144	0.067	0.272	24.7
14.00	988.10	28.7	5.36	2.56	18.44	18.27	47.52	50.8	21.8	46.03	98.84	46.77	0.139	0.066	0.267	24.2
14.15	865.10	28.5	4,66	2.26	17.99	17.81	44.20	48.0	20.9	42.79	83.83	40.25	0.134	0.064	0.275	21.9
14.30	850.23	28.3	4.62	2.23	17.96	17.77	43.41	45.7	21.5	42.52	82.98	39.63	0.135	0.065	0.269	21.0
14.45	827.56	28.5	4.48	2.16	17.84	17.70	43.61	47.1	21.7	41.98	79.92	38.23	0.134	0.064	0.267	20.3
15.00	820.21	28.6	4.44	2.14	17.83	17.68	43.20	46.8	21.3	41.72	79.17	37.84	0.134	0.064	0.271	20.4
15.15	791.53	27.6	4.26	2.06	17.62	17.54	42.50	45.8	20.2	40.90	75.06	36.13	0.131	0.063	0.285	20.7
15.30	780.23	27.3	4.20	2.05	17.55	17.50	42.20	45.0	20.6	40.63	73.71	35.88	0.131	0.064	0.279	20.0
15.45	750.54	27.5	4.03	1.97	17.96	17.38	41.54	44.6	20.5	39.84	72.38	34.24	0.134	0.063	0.280	19.3
16.00	715.23	26.8	3.82	1.87	17.56	17.23	40.71	43.4	20.2	37.01	67.08	32.22	0.130	0.062	0.256	16.8
16.15	712.56	27.3	3.79	1.86	17.28	17.23	40.50	43.3	20.8	38.74	65.49	32.05	0.127	0.062	0.274	17.9
16.30	623.21	26.5	3.30	1.63	17.22	16.88	38.73	40.8	20.1	35.52	56.83	27.51	0.126	0.061	0.269	15.4
16.45	620.52	26.7	3.28	1.61	17.43	16.84	38.25	40.5	20.7	35.31	57.17	27.11	0.128	0.061	0.256	14.6
17.00	600.53	26.2	3.16	1.56	16.83	16.77	37.75	39.9	20.2	34.77	53.18	26.16	0.123	0.060	0.264	14.6

Table A-7 Sample Data sheet for PV/CPC/CU Experimental system with cooling water flow rate of 30 l/hr.

Date: 24-01-2003

Time (Hrs)	G (W/m²)	Ta (°C)	I M1 (A)	I M 2 (A)	VM1 (V)	VM2 (V)	Tm1 °C	Tm2 °C	T_i (°C)	T_o (°C)	P M1	P M2	T_o-T_i (°C)	E.E M1	E.E M2	T.E
9.00	520.60	25.30	2.90	1.35	16.72	16.47	33.60	37.40	20.20	29.46	48.49	22.23	9.26	0.129	0.059	0.242
9.15	650.53	25.20	3.72	1.70	17.01	16.96	36.43	41.60	20.30	32.32	63.28	28.83	12.02	0.135	0.061	0.251
9.30	694.23	25.70	3.98	1.81	17.36	17.15	37.22	42.70	21.60	34.60	69.09	31.04	13.00	0.138	0.062	0.255
9.45	740.54	25.90	4.29	1.94	17.53	17.34	38.00	44.30	21.30	35.30	75.20	33.64	14.00	0.141	0.063	0.257
10.00	823.57	26.00	4.79	2.14	17.88	17.65	39.64	46.80	22.00	37.56	85.65	37.77	15.56	0.144	0.064	0.257
10.15	835.20	26.10	4.86	2.18	17.94	17.69	40.00	41.70	21.40	37.28	87.19	38.56	15.88	0.145	0.064	0.259
10.30	875.86	26.20	5.12	2.29	17.96	17.85	40.80	48.50	22.40	38.16	91.96	40.88	15.76	0.145	0.065	0.245
10.45	920.53	27.00	5.42	2.41	18.23	18.06	41.80	50.00	21.90	39.26	98.81	43.52	17.36	0.149	0.066	0.257
11.00	990.21	26.90	5.87	2.59	18.56	18.32	43.20	52.50	21.70	39.81	108.95	47.45	18.11	0.152	0.066	0.249
11.15	1003.23	26.80	5.93	2.64	18.63	18.34	43.40	52.40	22.30	41.02	110.48	48.42	18.72	0.153	0.067	0.254
11.30	1040.55	26.70	6.18	2.73	18.73	18.50	44.20	53.60	22.60	41.92	115.75	50.51	19.32	0.154	0.067	0.253
11.45	1080.25	26.80	6.40	2.84	18.86	18.66	45.30	55.00	22.90	42.78	120.70	52.99	19.88	0.155	0.068	0.250
12.00	1093.24	28.50	6.42	2.86	18.83	18.69	45.25	55.10	23.50	43.73	120.89	53.45	20.23	0.153	0.068	0.252
12.15	1105.22	27.00	6.42	2.90	18.86	18.74	46.15	55.50	22.60	42.90	121.08	54.35	20.30	0.152	0.068	0.250
12.30	1106.51	28.30	6.41	2.90	18.99	18.73	44.93	45.30	23.10	43.60	121.73	54.32	20.50	0.152	0.068	0.252
12.45	1110.56	27.20	6.43	2.91	18.79	18.78	46.26	54.90	22.80	43.15	120.82	54.65	20.35	0.151	0.068	0.249
13.00	1087.53	27.90	6.40	2.85	18.98	18.68	46.28	54.90	23.70	43.53	121.47	53.24	19.83	0.155	0.068	0.248
13.15	1082.03	27.30	6.40	2.83	18.63	18.61	45.42	54.70	22.90	43.30	119.23	52.67	20.40	0.153	0.067	0.257
13.30	993.52	27.40	5.87	2.60	18.46	18.31	43.20	52.10	22.80	40.80	108.36	47.61	18.00	0.151	0.066	0.247
13.45	960.53	27.50	5.68	2.52	18.52	18.19	42.60	51.10	22.40	40.14	105.19	45.84	17.74	0.152	0.066	0.251
14.00	950.21	27.30	5.62	2.49	18.55	18.15	42.22	50.80	22.40	39.92	104.25	45.19	17.52	0.152	0.066	0.251
14.15	920.68	27.50	5.42	2.42	18.47	18.05	41.80	49.50	22.50	39.26	100.11	43.68	16.76	0.151	0.066	0.248
14.30	903.26	27.60	5.31	2.35	18.32	17.96	41.40	48.30	22.60	39.82	97.28	42.21	17.22	0.149	0.065	0.259
14.45	860.58	27.50	5.05	2.25	17.96	17.81	40.60	47.80	21.90	37.96	90.70	40.07	16.06	0.146	0.065	0.254
15.00	830.53	26.80	4.85	2.17	17.21	17.69	40.00	41.70	22.50	38.28	83.47	38.39	15.78	0.139	0.064	0.259
15.15	822.22	27.60	4.79	2.15	17.83	17.66	39.80	46.80	22.70	38.06	85.41	37.97	15.36	0.144	0.064	0.254
15.30	820.00	27.60	4.79	2.14	17.78	17.54	39.60	46.80	22.70	38.06	85.17	37.54	15.36	0.144	0.063	0.255
15.45	790.53	27.50	4.62	2.06	17.66	17.34	39.20	45.80	22.80	37.40	81.59	35.72	14.60	0.143	0.063	0.251
16.00	720.58	26.80	4.16	1.88	17.93	17.15	37.80	42.70	22.70	35.86	74.59	32.24	13.16	0.143	0.062	0.249
16.15	683.42	26.70	3.91	1.79	17.05	17.05	37.22	42.60	22.50	34.97	66.67	30.52	12.47	0.135	0.062	0.248
16.30	670.88	25.90	3.83	1.74	17.12	16.98	36.80	42.00	22.60	34.76	65.57	29.55	12.16	0.135	0.061	0.247
16.45	652.43	26.30	3.70	1.69	17.31	16.88	36.44	41.80	22.70	34.32	64.05	28.53	11.62	0.136	0.061	0.242
17.00	640.27	25.50	3.66	1.66	17.53	16.92	36.20	41.30	22.70	34.10	64.16	28.09	11.40	0.139	0.061	0.242

Table A-8 Sample Data Sheet for PV/CPC/CU Experimental system with cooling water flow rate of 40 l/hr.

Date: 29-01-2003

Time (Hrs)	G (w/m^2)	Ta (°c)	I M1 (A)	I M 2 (A)	VM1 (V)	VM2 (V)	TM 1 °C	TM2 °C	T_i (°C)	T_o (°C)	P M1	P M2	T_o-T_i (°C)	E_{eff} M1	E_{eff} M2	T_{eff}
9.00	533.53	6.50	3.26	1.38	16.50	16.55	29.90	37.80	20.00	25.60	53.79	22.84	5.60	0.140	0.059	0.171
9.15	550.53	25.5	3.29	1.43	16.67	16.57	30.10	38.00	20.50	26.90	54.84	23.70	6.40	0.138	0.060	0.190
9.30	620.33	24.6	3.87	1.61	16.93	16.84	30.90	40.60	20.20	28.20	65.52	27.11	8.00	0.146	0.061	0.211
9.45	652.52	24.6	4.07	1.70	17.01	16.96	31.20	41.50	20.90	29.69	69.23	28.83	8.79	0.147	0.061	0.220
10.00	675.23	26.7	4.21	1.74	17.61	17.07	31.40	42.00	21.50	31.00	74.14	29.70	9.50	0.152	0.061	0.230
10.15	693.83	26.7	4.34	1.81	17.53	17.15	31.70	42.70	21.20	31.30	76.08	31.04	10.10	0.152	0.062	0.238
10.30	820.20	26.1	5.23	2.14	17.53	17.65	33.10	46.80	22.40	32.50	91.68	37.77	10.10	0.155	0.064	0.201
10.45	843.76	26	5.35	2.20	17.62	17.72	33.30	47.60	21.90	31.90	94.27	38.98	10.00	0.155	0.064	0.194
11.00	875.22	26.50	5.57	2.28	17.95	17.84	33.60	48.30	21.70	33.40	99.98	40.68	11.70	0.158	0.064	0.218
11.15	996.53	27.90	6.38	2.60	18.40	18.31	35.00	53.00	22.30	35.40	117.39	47.61	13.10	0.163	0.066	0.215
11.30	1055.21	27.10	6.70	2.75	18.56	18.50	35.60	53.60	22.60	36.40	124.35	50.88	13.80	0.163	0.067	0.214
11.45	1083.21	28.90	6.75	3.07	19.02	18.96	36.20	57.10	21.70	37.50	128.39	58.21	15.80	0.164	0.074	0.238
12.00	1090.73	27.60	6.92	2.86	18.96	18.70	35.40	55.10	22.90	35.90	131.20	53.48	13.00	0.167	0.068	0.195
12.15	1096.53	28.30	6.93	3.09	18.96	18.90	35.70	57.00	21.20	35.90	131.39	58.40	14.70	0.166	0.074	0.219
12.30	1102.51	27.20	6.85	2.88	18.99	18.73	35.20	55.20	23.10	37.90	130.08	53.94	14.80	0.163	0.068	0.219
12.45	1106.13	27.80	6.97	2.87	18.75	18.72	37.50	55.50	22.60	36.70	130.69	53.73	14.10	0.164	0.067	0.208
13.00	1115.23	28.50	6.99	2.93	18.96	18.71	38.30	55.80	22.80	38.20	132.53	54.82	15.40	0.165	0.068	0.225
13.15	970.53	26.60	6.20	2.55	18.63	18.20	34.70	51.20	20.60	33.10	115.51	46.41	12.50	0.165	0.066	0.210
13.30	969.26	28.20	6.18	2.53	18.63	18.23	34.60	51.40	21.90	35.90	115.13	46.12	14.00	0.165	0.066	0.236
13.45	963.28	27.90	6.12	2.52	18.44	18.19	34.60	51.10	21.70	34.90	112.85	45.84	13.20	0.162	0.066	0.224
14.00	952.67	28.80	6.11	2.50	18.55	18.20	34.50	50.80	21.50	33.20	113.34	45.50	11.70	0.165	0.066	0.201
14.15	920.51	27.30	5.91	2.42	18.56	18.06	34.20	50.20	20.90	33.30	109.69	43.71	12.40	0.165	0.066	0.220
14.30	870.23	27.80	5.56	2.29	18.95	18.83	33.60	47.70	21.30	32.40	105.36	43.12	11.10	0.168	0.069	0.208
14.45	860.54	27.30	5.50	2.25	17.88	17.84	33.50	46.30	20.20	32.20	98.34	40.14	12.00	0.158	0.065	0.228
15.00	820.31	28.90	5.23	2.15	17.52	17.65	33.10	46.80	20.50	31.50	91.63	37.95	11.00	0.155	0.064	0.219
15.15	801.62	29.10	5.09	2.09	17.68	17.57	32.80	46.00	20.80	32.40	89.99	36.72	11.60	0.156	0.063	0.236
15.30	799.33	28.30	5.04	2.06	17.72	17.57	32.20	46.10	20.20	31.50	89.31	36.19	11.30	0.155	0.063	0.231
15.45	783.79	28.80	4.96	2.05	17.53	17.50	32.70	45.00	20.50	31.70	86.95	35.88	11.20	0.154	0.063	0.233
16.00	760.52	28.90	4.80	1.99	17.55	17.42	32.40	44.90	20.70	31.50	84.24	34.67	10.80	0.153	0.063	0.232
16.15	700.55	27.70	4.41	1.82	17.42	17.20	31.80	43.00	20.60	30.50	76.82	31.30	9.90	0.152	0.062	0.231
16.30	680.32	26.50	4.28	1.77	17.57	17.11	31.60	42.30	20.20	29.20	75.20	30.28	9.00	0.153	0.062	0.216
16.45	523.21	26.30	3.20	1.35	16.32	16.50	28.70	36.50	20.80	27.20	52.22	22.28	6.40	0.138	0.059	0.200
17.00	520.73	27.60	3.19	1.34	16.55	16.46	29.80	37.40	20.50	26.40	52.79	22.06	5.90	0.140	0.059	0.185

APPENDIX B

EFFICIENCY OF SOME PV CELLS/MODULES.

Table. B-1 Efficiency of some PV cells/modules (Green, 1999).

Type of Cell	Symbol	Characteristic	Efficiency (Percent)	
			Laboratory cells	Commercial Modules
Single crystalline silicon	Sc-Si	Wafer type	24	13-15
Multicrystalline silicon	mc-Si	Wafer type	19	12-24
Crystalline silicon films on ceramics	f-Si	Wafer type	17	(8-11)
Crystalline silicon films on glass	-	Thin films	13	-
Amorphous silicon	a-Si	Thin films	13	6-9
Copper Indium/gallium diselenide	CIGS	Thin films	18	(8-11)
Cadmium telluride	-	Thin films	16	(7-10)
Organic cells	-	Thin films	11	-
High efficiency tendem cells	III-V	Wafer and thin films	30	-
High efficiency concentrator cells	III-V	Wafer and thin films	33 (tendem) 28 (single)	-

Note: Numbers in parentheses are results from pilot production or first commercial production.

APPENDIX C

CALCULATION OF CPC GEOMETRIC FACTORS

Calculation showing the height and the concentration factor of the untruncated and truncated 14^0 CPC.

The subscript T represents the truncated CPC

For the 2D CPC with acceptance angle of 14^0:

$$\theta_a = 14^0$$

$$C = 1/\sin\theta_a$$

$$b = 68\ cm$$

$$W = b/\sin\theta_a = 281cm$$

$$H = (b+W)/2 + \tan\theta_a = 155\text{cm}$$

After truncating to approximately three quarters of its height, we obtain:

$$H_T = 116.25\text{ cm}$$

$$b = 68\text{ cm (constant)}$$

$$W_T = 210.75\text{ cm}$$

$$C_T = W_T/b = 210.75/68 = 3.09$$

Using this concentration factor to calculate the acceptance angle we obtain

$$3.09 = 1/\sin\theta_T \Rightarrow \theta_T = 18.88$$

This means that truncation in this case increased the acceptance angle of the CPC to 18.88 and reduced the height by a quarter while lowering its concentration factor to 3.09.

APPENDIX D

LIFE CYCLE COSTING

Life Cycle Costing and Discounting Methodology.

The Life Cycle Costs (LCC) is the sum of all costs associated with the initial purchase, installation, operation and maintenance of the system throughout its operational life. To make a meaningful comparison, all future costs and benefits have to be discounted to their equivalent value in today's economy, called the present worth (PW). To achieve this, each future cost is multiplied by a discount factor, calculated from the discount rate. All calculations are done relative to the general inflation, so that all costs are expressed in today's money. The illustration given in Table D-1 outlines the methodology of life cycle costing.

Calculation of Present Worth (PW)

There are two types of calculations used in LCC to express a future cost at its present worth. These include:

a) Single Payment

This is applicable for a single future cost (Cr), payable in n year's time for example replacement cost of a battery the present value is given by:

$$PV = Cr.\mathrm{Pr} \qquad \text{D-1}$$

where, $\mathrm{Pr} = \left(\frac{1+i}{1+d}\right)^n$

Table D-1 Life cycle costing methodology

PERFORMANCE DATA	INPUTS: COST DATA	INPUTS: ECONOMIC PARAMETERS
System specification ⇩ Performance Estimate ⇩ Net useful Energy	1.Capital costs • Hardware • Design overheads 2.Operation and maintenance 3.Component replacement costs	• Period of analysis • Discount rate • Inflation

⇩

OUTPUTS

Economic Indicators

Life Cycle Cost

⇩

Annualised Project Cost

⇩

Levelized unit Cost of Energy

and d = discount rate

i = commodity specific inflation rate (above general inflation)

n = year of incurred cost.

b) Annual payment

For a payment (Ca) occurring annually for a period of n years, the present worth (PW) is given by:

$$PV = Ca.\,Pa \qquad \text{D-2}$$

Where $$Pa = \left(\frac{1+i}{1+d}\right)\left(\left|\frac{1+i}{1+d}\right|^{N} - 1\right) \Big/ \left(\frac{1+i}{1+d} - 1\right)$$

For each of the payments to be made during the life of the system, the present Value can therefore be determined using the discount factors Pr and Pa. The sum of all present value of all costs gives the total life cycle cost of the system.

Replacement Costs

The lifetime of the battery, solar lamps and the charge controller given by the manufacturers as 5, 4 and 10 years respectively were used to calculate the replacement costs. Replacement costs were calculated for these components over the analysis period and discounted in order to express them in their present worth.

Period of analysis

An analysis period of 20 years was chosen, which corresponds to the useful lifetime of the PV modules given by the manufacturers. A discount rate of 10% was also chosen, as this is usually considered typical for developing countries (Garg and Prakash, 1997).

Economic Indicators.

There are two ways that the LCC is commonly used to provide more intelligible expression of system cost, namely;

I) Annualized Life Cycle Cost

II) Levelized Energy Cost

(i) Annualized life cycle cost (ALCC)

The ALCC is the LCC expressed in terms of a constant cost per year. It's the annual expenditure require to pay for the system over its lifetime and include the cost of repayments on borrowed capital.

ALCC = LCC/ Pa (n)

Where Pa is the annualization factor.

ii) Levelized Energy Cost (LEC)

This is the most useful figure for comparing two energy technologies. It expresses the average cost of generating each useful unit of energy during the lifetime of the system. For a system generating electricity, the LEC can be determined from the ALCC as follows:

$$LEC = \frac{ALCC(Ksh/\,year.)}{Electricity\,\text{sup}\,pliedperyear(KWh/\,year)} \quad \text{(D-3)}$$

For a combined heat and power system:

$$LEC = \frac{ALCC}{TotalEnergy(KWh/\,year)} \quad \text{(D-4)}$$

Where total energy is the sum of electric and thermal energies

APPENDIX E

Table E-1 Cost Data of Experimental Components.

1. PV Lighting Kit

Item	Ksh
51W PV module	18500
100Ah Battery	9000
15 AMPS charge controller	6900
6 x 11 watts solar lights	7200
Total	**41600**

2. CPC

Polished aluminium sheet 4'x8'	7000
Support structure	2000
Total CPC cost	**9000**

3. Cooling Unit

Copper pipes (15 m)	5000
250l Hot water storage tank	15000
500l Cold water tank	1000
Total	**21000**

4. Replacement Costs

(i) Battery at Ksh. 9000

At yr.	Factor Pr	PW
5	0.62	5580
10	0.38	3420
15	0.24	2160
Total		**11160**

(ii) Solar Lamps

At yr.	Factor Pr	PW
4	0.68	4896
8	0.46	3312
12	0.31	2232
16	0.21	1512
Total		**11952**

(iii) Charge controller at Ksh. 6900

At yr.	Factor Pr	PW
10	0.38	**2622**