UTILIZATION OF SOLAR ENERGY FOR COOLING

By

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FINAL REPORT

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CERTIFICATION OF APPROVAL

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Husam Eldeen Mohammed Ibrahim

ABSTRACT

Sudan is one of the largest countries in the African continent situated between latitudes of 3° N and 23° N and longitudes 21° 45 E and 39° E. The total daily sunshine hour is between 8 to 11 hours, and the average solar radiation received on the horizontal surface is between 20 to 24 MJm^{-2} day^{-1} as a result Sudan has very hot and dry weather. Air cooling is clearly needed in such weather, and the utilization of solar energy for this purpose is very appealing especially that grid supply is not available to several parts of the country, and where it is available it is usually very unstable in hot season. This report presents Hybrid Evaporative cooler powered by Stand-Alone Photovoltaic system. Steps taken to develop this cooler and a comprehensive review of several conventional and solar cooling techniques and the advantages of the new cooler are also presented. The hybrid evaporative cooler was found to have performance criteria suitable for Sudan and low power consumption what makes it economical when powered by Stand-Alone Photovoltaic system. This report also introduces sizing method for stand-alone photovoltaic system to power the cooler and a software tool to perform the sizing procedure. A full system was developed for the city of Khartoum to show the feasibility of the proposed system.

ACKNOWLEDGEMENTS

To
My Mother
My Family
My supervisor Dr. Balbir Singh Mahinder Singh
and to Universiti Teknologi PETRONAS

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LIST OF ABBREVIATIONS

COP: Coefficient of Performance.

PV: Photovoltaic.

db: dry-bulb temperature.

wb: wet-bulb temperature.

SAPV: stand-alone photovoltaic

Tae: Temperature of air entering evaporative cooler, in °C

Tal: Temperature of air leaving evaporative cooler, in °C

T*ae: Wet-bulb temperature of air entering evaporative cooler, in °C

I_O : Extraterrestrial global radiation

Gsc: Solar constant

Ø: latitude

δ: Declination angle

ω_1: Smallest hour angel

ω_2: Largest hour angle

θ: Zenth angle

T_b: Atmospheric transmittance for beam radiation

T_d: Transmittance coefficient for diffused radiation

I_g: Total ground radiation on horizontal surface

A_1,A_2,A_3: Standard atmosphere constants

D_T: Battery temperature derating factor

D_{ch}: Battery charge derating factor

disch : Battery charge derating factor

CHAPTER 1
INTRODUCTION

1.1 Background of Study

In hot seasons air cooling becomes an important issue. The look out for thermal comfort and cooling techniques is as old as the human civilization. Ancient Roman used aqueduct to circulate water through the walls of houses to cool them. Similar techniques in medieval Persia involved the use of cisterns and wind towers to cool buildings during the hot season. In today's world, the demand on cooling is even more and several technologies are employed to meet this demand. The life standard of people all over the world is improving and higher standers of thermal comfort are to be met. Moreover, global warming and the increasing summer temperature changed the need of air cooling from luxury to necessity.

The Republic of Sudan is one of the countries where the demand on air conditioning is increasing annually. Sudan is one of the largest countries in the African continent and has land area that is approximately 2.5 million km^2. It is situated between latitudes of 3° N and 23° N and longitudes 21° 45 E and 39° E. The total daily sunshine hour is between 8 to 11 hours, and the average solar radiation received on the horizontal surface is between 20 MJm^{-2} day^{-1} and 24 MJm^{-2} day^{-1} [10]. Sudan has very hot and dry weather and daily ambient temperature can exceed 40 °C in summer while the relative humidity is usually above 20%. A country that enjoys such high average solar radiation levels and such long sunshine duration is expected to have hot weather most of the year. Add to that the increasing summer temperature in recent years and the improving life stander in the country, the need for air cooling becomes very obvious.

The national grid power supply in Sudan is not stable during the summer and blackouts are frequent during day time, lack of power reached 15% during the summer of 2007. In addition to that, several parts of the country do not enjoy grid supply due to its remoteness from national grid. The utilization of solar energy for domestic cooling in Sudan is a very appealing proposition since the power supply is not available when most needed while solar energy is most available.

Conventional air conditioning (Vapor Compression) is one of the most common air coolers in Sudan due to the maturity of the technique. But the high initial and operation cost makes it out of reach to most domestic users and confines its use to offices and shops, add to that the low reliability of these coolers during the summer due to the lack of power supply. Powering these coolers using PV systems is not an economical idea due to the high cost of the overall resulting system.

Conventional evaporative coolers, operating on power supplied by the national grid, are quite common in Sudan. Its low cost and low energy requirements (typically ≥ 200Wh) make it more attractive to home users. However, this type of cooler has several short comings, whereby it fails to operate at nominal saturation efficiency in high temperature and that results in warm and humid air instead of cool and humid air, it lower temperature is governed by the relative humidity of the air in take, and it is also unreliable when powered from grid supply.

1.2 Problem Statement

The common conventional air coolers in Sudan are not able to meet users need due to the instability or lack of power supply in the summer, poor performance under local weather conditions and high initial operating cost. So therefore there is a need to develop a cooling system that is reliable under local weather, self powered and cost effective is needed.

1.3 Objectives & Scope of Work

This project is mainly aimed to design and develop an efficient and energy effective solar powered air cooling system for use in Sudan. The system should be able to:

- Perform optimally in hot and dry weather.
- Be operated by using photovoltaics.
- Operate at moderate initial cost, with minimum maintenance requirements.

To fulfill the goal of this project, good understanding about the available air cooling techniques must be gained. The available techniques must be evaluated based on two criteria, that is the level of thermal comfort and humidity it provides and the power consumption associated with these techniques.

After the evaluation is done, then a suitable cooling technique is to be selected accordingly, and modifications may be introduced to the selected technique to further improve its performance. The second part of the project is focused to the power supply. Since this project is intended to utilize the solar energy, good understanding about photovoltaic system must be gained. And then, according to the selected cooling system, Utility interactive or stand alone photovoltaic system will be selected to power the cooling system and a final design for the total cooling system will be developed for optimum performance in wither conditions of Sudan.

CHAPTER 2
LITERATURE REVIEW

2.1 Solar Energy in Sudan

Sudan is one of the largest countries in the African continent. Its area is approximately one million square miles (2.5 million km^2) extending between latitudes 3° N and 23° N; and longitudes 21° 45 E and 39° E. Sudan is relatively sparsely populated country. Sudan is one of the suitable countries in terms of potential in utilizing solar energy. Sunshine duration is ranging from 8.5 to 11 h per day, with high level of solar radiation on an average of 20 to 24 MJm^{-2} day^{-1} on the horizontal surface as shown in table 1 and figure 1[10].

Sudan already has well-established solar thermal applications such as industrial solar water heaters, solar dryers for peanut crops, solar stills, and solar driven cold stores to store fruits and vegetables, solar water desalination, and solar ovens. Photovoltaic systems are used for lighting, solar refrigeration to store vaccines for human and animal use, water pumping, communication network, microwave receiver stations and radio systems in airports [10]. Most of the applications are used in areas with relatively large population that does not enjoy fixed electricity supply due to its remoteness from national grid.

A country that enjoys such high average solar radiation levels and such long sunshine duration is expected to have hot weather most of the year. We take the city of Khartoum which is the capital city. The city is located in the northern part of the country and according to statistics for the last 16 years Khartoum experiences the pick temperature and the lower relative humidity levels in May[9], see figures 2 & 3.

Table 1 : Average values from different locations and cities in Sudan.

Station	Sunshine Duration (h/day)	Solar radiation (MJm^{-2} day^{-1})	Relative Humidity (%)	Latitude	
Port Sudan	9.0	20.87	65	19.58N	East
Shambat (Kh)	9.9	22.82	31	15.6 0N	Center
Wad Medani	9.8	22.84	40	14.40N	Center
Elfasher	9.6	22.8	33	13.61N	West
Juba	7.8	19.59	66	4.86N	South
Dongola	10.5	24.06	27	19.16N	North

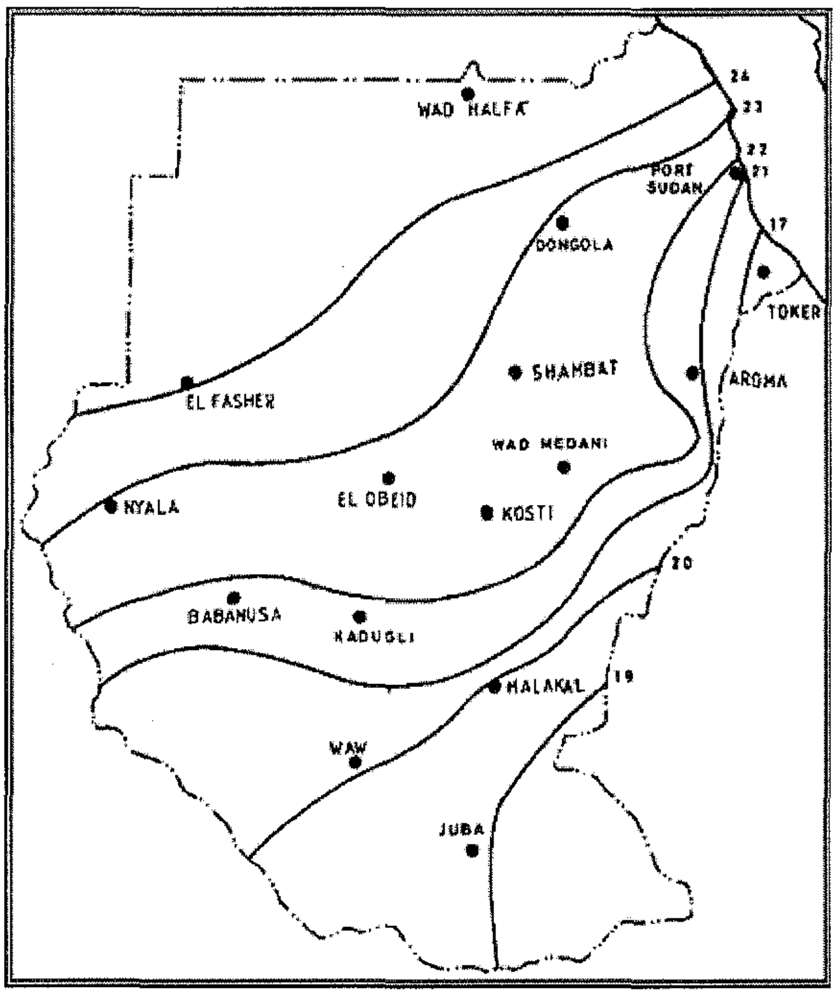


Figure 1 : Solar radiation in Sudan (MJm^{-2} day^{-1}). [10]

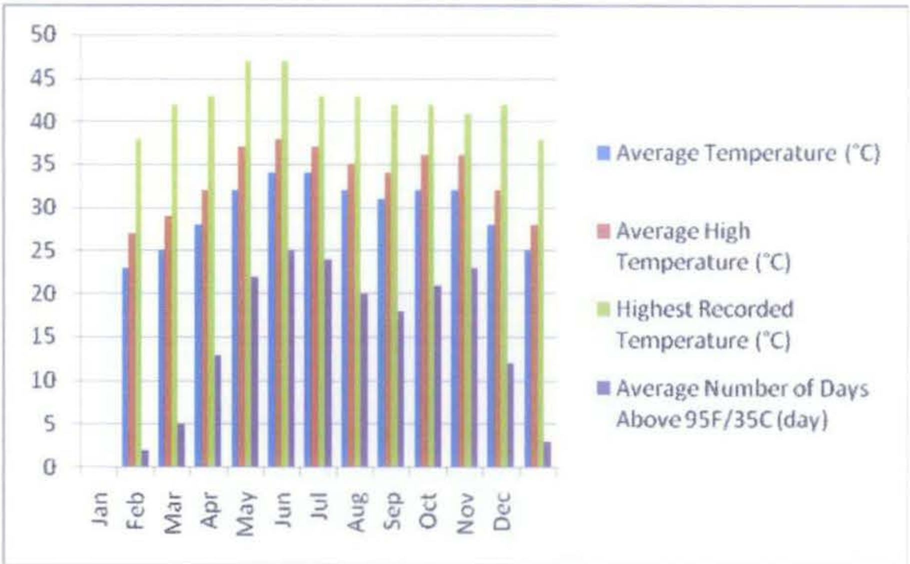


Figure 2 : Average temperature for the last 16 years in Khartoum city. [9]

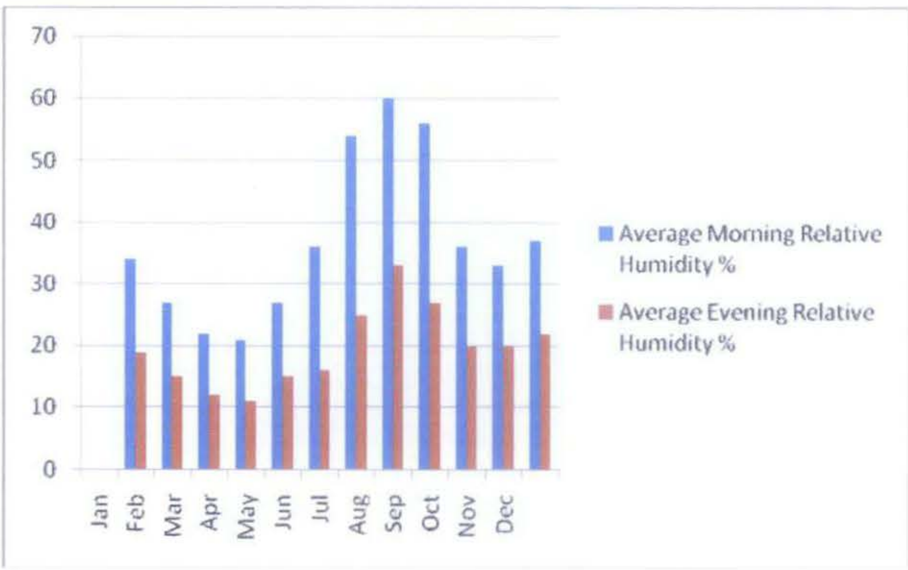


Figure 3 : Average relative humidity in Khartoum city. [9]

2.2 Air Cooling & Conditioning Techniques

Electrically and thermally driven cooling systems are available in the market to cover the cooling requirements of buildings and both forms of energy could be supplied form solar energy. Solar technology can supply photovolatically produced electricity for compression coolers or solar-thermally produced heat for absorption or desiccant coolers [2]. In the following few sections, several cooling techniques are described.

2.2.1 Vapor-Compression Refrigeration

Vapor-compression refrigeration is one of the many refrigeration cycles available for use. It is widely used method for air-conditioning of several buildings and automobiles, know as AC in general. Heat is transferred from a lower temperature source to a higher temperature heat sink in this system. Heat naturally flows in the opposite direction; therefore, work is required to move heat from cold to hot. This system is power consuming due to the work required to move heat in opposite to the natural heat flow [3].

This most common refrigeration cycle uses an electric motor to drive a compressor. Since evaporation occurs when heat is absorbed, and condensation occurs when heat is released, air conditioners are designed to use a compressor to cause pressure changes between two stages, and actively pump a refrigerant around. A refrigerant is pumped into the evaporator coil (low pressure side), where, despite the low temperature, the low pressure causes the refrigerant to evaporate, taking heat with it. In the condenser, the refrigerant vapor is compressed and forced through another heat exchange coil, condensing into a liquid, rejecting the heat previously absorbed from the cooled space (see figure 4,5). The heat exchanger in the condenser section is often cooled by a fan blowing outside air through it, or by other means such as water [3].

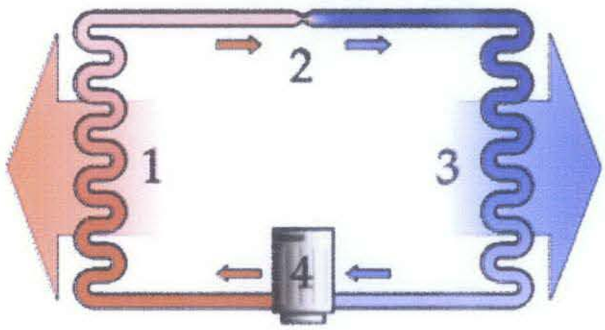


Figure 4 : A simple diagram of the refrigeration cycle: 1) Condensing coil, 2) Expansion valve, 3) Evaporator coil, 4) Compressor. [8]

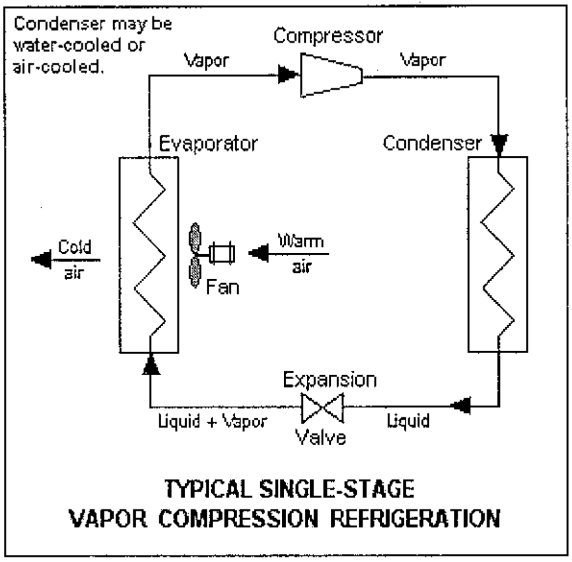


Figure 5 : Typical single-stage vapor compression refrigeration. [8]

The refrigerant is the fluid circulated in the refrigerant cooling systems. There is a number of refrigerants known and in use, yet the most common type is "Freon". Freon is known to be the most effective and widely used refrigerant and it is also known for its environmental impact on the Ozone (Ozone depletion). Different refrigerants has different levels of operating pressure, refrigerants with high operating pressure needs more expensive compressor and more energy consuming motor to derive the system [3].

This technology is very mature and advanced technology, yet, its environmental impact and the high operating cost and energy consumption are behind the efforts to replace this technology. Commercially available air conditioning units based on vapor compression refrigerant provide good performance besides the additional features such as air filtration and humidity control [1]. Unfortunately the use of this technology with photovoltaic as power source is unreasonable since it will require big and expensive photovoltaic system to drive it, and consequently high initial cost.

2.2.2 Solar Refrigeration and Air Conditioning

The idea of using solar energy for cooling to replace the use of electricity in areas where it is expensive or not possible to get electricity has been going on for decades.

Over the last four decades, several solar cooling and solar refrigeration techniques have been developed, but due to its complexity in concept and construction it is not know nor commercially spread [2]. Common solar cooling techniques are:

- Absorption cycle with several solid absorbents and liquid absorbents.
- Adsorption cycle using solid absorbents.
- Vapor compression cycle with solar powered Rankine engine.
- Vapor compression cycle with compressor driven by photovoltaic electricity.
- Passive cooling.
- Desiccant coolers.

Thermally driven cooling systems have developed very much in the last few decades and it have become quit reputable. Adsorption and absorption refrigeration are the most common and mature thermally driven cooling systems. The absorption refrigerator is a refrigerator that utilizes a heat source to provide the energy needed to drive the cooling system rather than being dependent on electricity to run a compressor. These refrigerators are popular where electricity is unreliable, costly, or unavailable, where noise from the compressor is problematic, or where surplus heat is available from turbine exhausts or industrial processes. An absorption refrigerator is similar to a regular compressor refrigerator in that the refrigeration takes place by evaporating a liquid with a very low boiling point. In both cases, when a liquid evaporates or boils, it takes some heat away with it, and can continue to do so either until the liquid is all boiled, or until everything has become so cold that the boiling point has been reached. Another technique usually related to solar cooling is desiccant cooling. The removal of moisture from the room air can help in providing comfortable environment spatially in highly humid places. Liquid and solid materials which have the property of attracting and holding water vapor known as desiccants and be used to dehumidify the air and thus be used for cooling spaces. Combining desiccant cooling with evaporative cooling appears to be promising for humid climate [2].

Performance of cooling system is evaluated using the coefficient of performance (COP). COP is the ratio of the amount of cooling produced and the energy supplied. The Rankin cycle driven cooling systems has a COP of 0.3 to 0.4 and it depends very much on the efficiency of the solar collectors, the solar Rankin vapor-compression cooling system can be used as a heat pump, and it can be used for electricity generation when cooling is not needed. The absorption cycle has COP of 0.1 to 0.2 depending on the solar collector efficiency as well, the system can be used with low heat and it is very quite but it requires auxiliary power to run the fans. The adsorption cycle has COP of 0.2 and it is very much like absorption cycle, but there is no commercial systems based on these techniques. Table 2 describes the efficiency of several solar cooling techniques [2]:

Table 2 : COP of several solar cooling techniques.

Solar cooling Technique	COP	Performance Remarks
Rankin cycle operated systems	0.3 to 0.4	Electricity generation when cooling is not needed
Vapor-compression with PV	0.25 to 0.35	Can be used as heat pump, high coast
Absorption cycle	0.1 to 0.2	Used low heat, very quiet
Adsorption cycle	0.2	Very quiet, need auxiliary power

2.2.3 Evaporative Cooling

The process of evaporation happens all the time. Human body for example perspires in hot weather; through evaporation the sweat dries and drops the body temperature. Whenever dry air passes over water, some of the water is absorbed by the air. That's why evaporative cooling naturally occurs near waterfalls, rivers, lakes and oceans, the hotter and drier the air, the more water that can be absorbed. Heat moves from the higher temperature of the air to the lower temperature of the water. As a result, the air is cooler. This cooling system is currently in application and it is available commercially (also well known in Sudan), it operates well in dry and hot climates and it requires low level of power to drive a fan and a water pump.

Wide range of evaporative coolers for several weathers and cooling loads are available. Evaporative cooling provides half the cooling load annually. Evaporative cooler are divided mainly into three types:

1. Direct Evaporative coolers.
2. Indirect Evaporative coolers.
3. Two stages evaporative coolers (Indirect- Direct).

To understand the concepts behind the three types of coolers, good understanding of wet air properties and cooling besides knowledge about the psychometric chart. In the following sub-sections, the concept, efficiency and heat transfer of the three types is further discussed.

2.2.4 Direct Evaporative Cooling

In this type of evaporative cooling, the air is cooled by passing through a wet medium or water spray (see figure 6). The water absorbs the air heat energy and evaporates reducing the air's temperature and increasing its relative humidity. The lower the relative humidity of the hot air passing through the lower its wet-bulb temperature and the better the cooling effect, therefore, direct evaporative cooling performs better in dry weather [1].

The performance of evaporative coolers is evaluated by its Saturation efficiency. Saturation efficiency is the ratio between the temperature difference between the hot air and cooled air and the difference between the dry-bulb temperature and wet-bulb temperature. It is give by the following equation [1]:

$$\varepsilon_{sat} = \frac{T_{ae} - T_{al}}{T_{ae} - T^{*}_{ae}}$$

T_{ae}, T_{al} = temperature of air entering and leaving direct evaporative cooler, in °C
T^{*}_{ac} = wet-bulb temperature of entering air, in °C

The performance of a direct evaporative cooler is affected by the following factors:

1. Velocity of air flowing through the wet medium.
2. Water-air ratio.
3. Type and configuration of the wet medium.

The water used in direct evaporative coolers is usually re-circulated and its temperature approaches the wb of the cooled air. The re circulation of water makes the operation less water consuming and more economical.

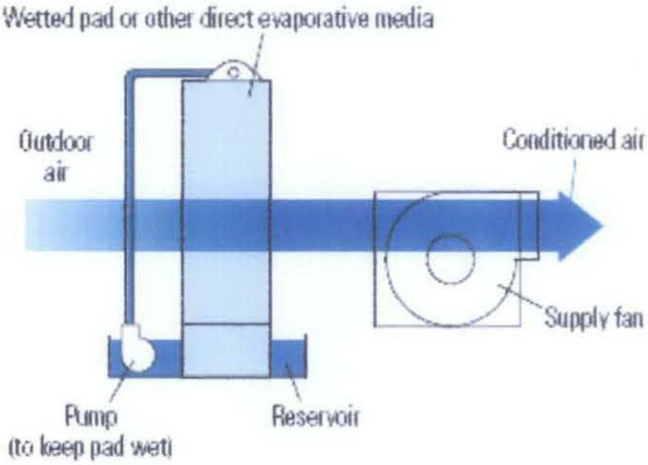


Figure 6 : Direct Evaporative Cooler model. [4]

2.2.5 Indirect Evaporative Cooling

In this type of evaporative cooling, the air to be cooled does not get directly in contact with the water; instead, it goes through a heat exchanger with the water on the other side of the exchanger (see figure 7). The air losses heat to the water and the water evaporates, a second air stream flows by the wet surface and its job is to cool the wet surface. The humidity of the cooled air stream is not affected since the air does not get in contact with the water and there for both dry bulb (db) and wet bulb (wb) are reduced. The heat process in this type of cooling takes place between the air to be cooled and the wet air [1]. This type of cooling is better than the direct evaporative cooling in cases where increment in relative humidity is not desired.

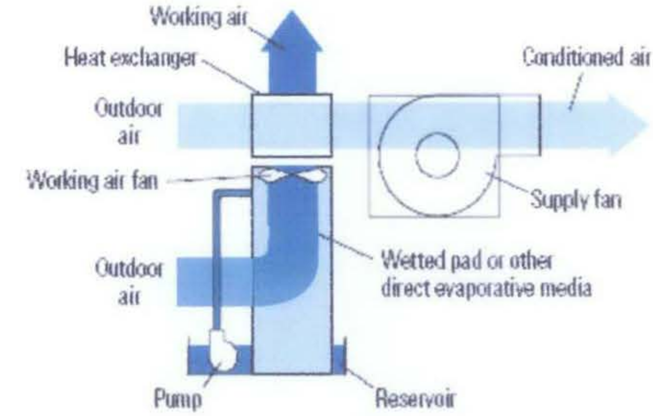


Figure 7 : Indirect Evaporative Cooler Model. [4]

2.2.6 Two Stages Evaporative cooling (Indirect-Direct)

In places where the air has relative humidity of 60% to 80% and wb of above 20 °C, a combination of indirect- direct evaporative cooling helps reducing the space heat despite the increment in relative humidity caused by the direct stage. The air to be cooled basses through the indirect cooler first, it losses some of its heat and a reduction in wb occurs without increasing the relative humidity and then the air goes to the second stage where it is directly cooled (see figure 8).

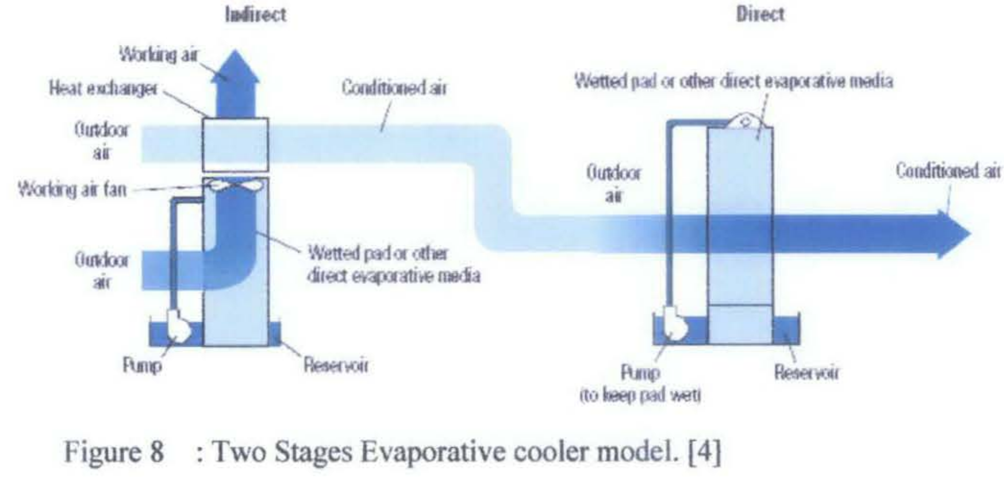


Figure 8 : Two Stages Evaporative cooler model. [4]

2.3 Photovoltaic System

Photovoltaic systems are the mean through which solar energy is converted to electrical energy. Solar cells are PN junction diodes that produce electrical current when exposed to sun light [7] and typically produces 3 watts at 0.5 volt dc. Assemblies of 36 cells form what is known as modules, modules have power output up to 300 watts. A group of connected modules is known as array, typically, arrays have output power of 100 to 1000 watts [6]. Photovoltaic system consists of several other components (figure 9) besides solar arrays, these components are known as balance of system (BOS) and they are mention bellow:

1. **Energy Storage Medium**: needed to store electrical energy produced by PV and supply the load when the PV can not provide maximum power or when it is off. Typically, rechargeable batteries are used for this purpose.

2. **Charge Controller**: in PV systems with batteries it typically utilizes a charge controller to prevent from overcharging or over-discharging.

3. **Maximum Power Tracker (MPT)**: it is important to operate the PV near the maximum power and that could be achieved using MPT. It changes the output dc voltage level.

4. **Inverter**: it is used to convert the dc voltage to ac when the load is ac operated or in grid connected system.

There are tow categories of photovoltaic systems namely utility interactive and stand-alone. Utility interactive system is useful to houses that already have grid supply; the system supports the loads in the house and uses the grid as storage. It exports power to the grid when there is balance and draws power from the grid when the load exceeds the system supply this way it reduces the cost of the utility. Stand-alone is suitable when grid supply is not available. Finally, it is very important to gather solar radiation data for the location where the PV system is intended to be installed.

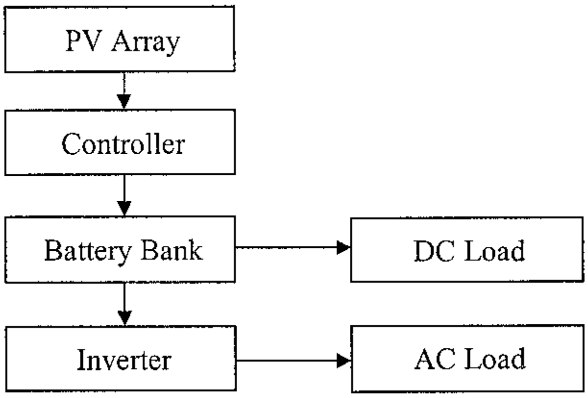


Figure 9 : Block diagram of stand alone PV system.

CHAPTER 3
METHODOLOGY

3.1 Overall Methodology

This project was started by intensive background study so that the objectives and the project scope could be identified clearly as mentioned in the first chapter. This background study proved very useful in conducting literature review since the solution criteria and the area of research were defined in this stage. The literature review included solar air cooling and refrigeration techniques, conventional air conditioning (vapor compression), evaporative cooling, and several passive cooling techniques to identify its fulfillment to the evaluation criteria mentioned in chapter 1 and explore potential improvements. Literature review was continued by studying Photovoltaic systems since it was found to be the best option for solar energy (see figure10).

Further research was needed to gather solar radiation data which lead to the proposition of solar estimation model due to the limited solar radiation data in Sudan. The model was developed and PV sizing technique was built on the estimation model. Software to size the photovoltaic system was developed using visual basic programming language.

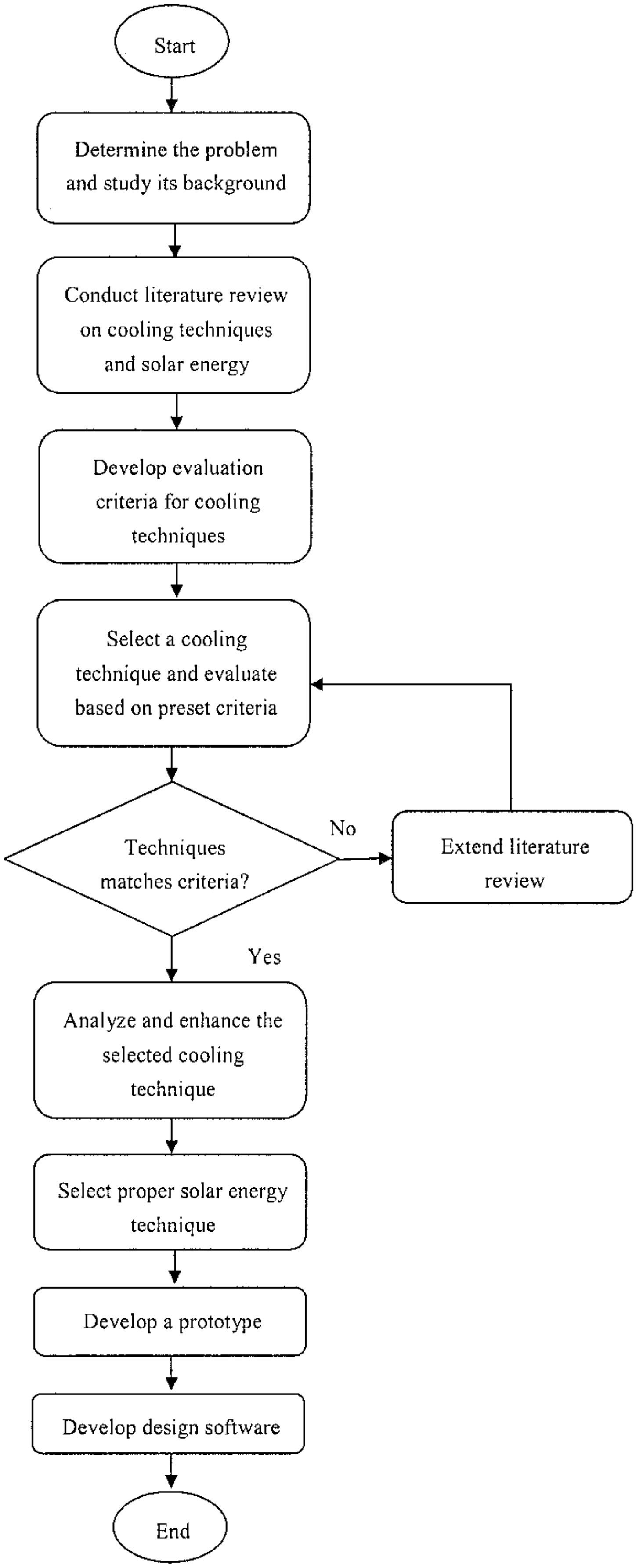


Figure 10 : Project over all flow chart.

3.2 Cooling Technique Selection

From the literature review on the different cooling technologies, evaporative cooling was found to be the most promising technology for the purpose of this project. Its low power requirements and good performance in dry weather since it increases the relative humidity of the air while cooling it besides its environmental friendly operation. These factors lead to selecting it as the subject of further study and searcher for potential improvements.

This coolers have several short comings, it fail to operate at nominal saturation efficiency in high temperature and that results in warm and humid air instead of cool and humid air, it lower temperature is governed by the relative humidity of the air in take, and it is also unreliable when powered from grid supply. This lead to experimental verification of the effect of water temperature on the performance of evaporative coolers as a mean of solving these problems.

3.3 Photovoltaic System Selection

Since the cooling system underdevelopment in this project is mainly designed to overcome the problem of cooling in the absence of grid supply, stand-alone photovoltaic (SAPV) system was selected to power the cooling system. SAPV systems are mainly used to provide electrical power for remote places where there is no electrical supply, the common factor here is the absence of grid supply. There are several methods for sizing SAPV systems and all of them require the presence of solar radiation data. Since this data is limited to only 16 stations across Sudan an estimate of this data is needed.

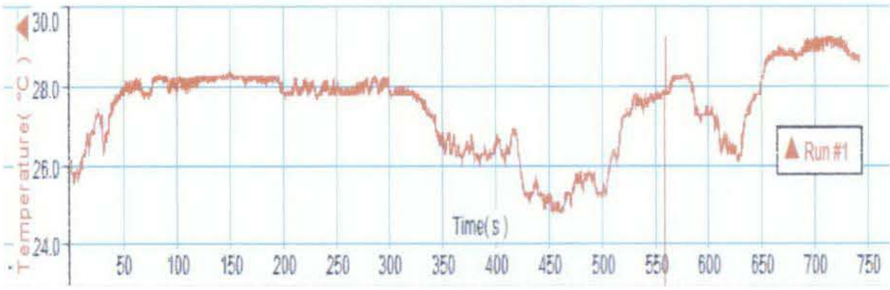
CHAPTER 4
RESULTS AND DISCUSSION

Evaporative coolers come second on the list. Its low cost and low power requirements (typically $\geq$ 200Wh) make it more attractive to home users. It produces high air volume flow rate which is a good feature since the buildings in Sudan do not have good insulation therefore the evaporative cooler will find the ventilation it needs and minimizes heat gains. This coolers have several short comings, it fail to operate at nominal saturation efficiency in high temperature and that results in warm and humid air instead of cool and humid air, it lower temperature is governed by the relative humidity of the air in take.

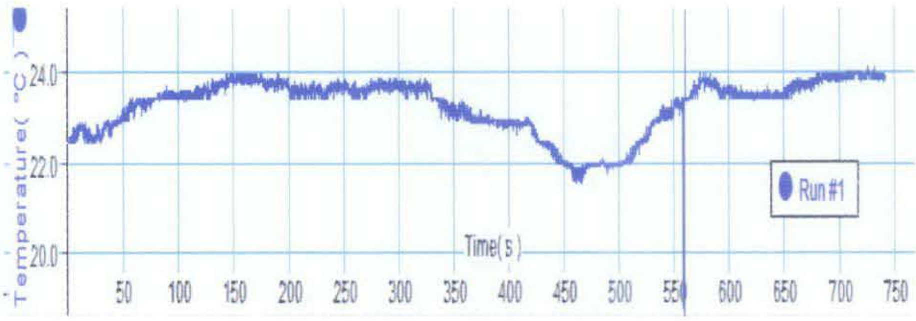
To compensate for these short comings, the effect of water temperature on the performance of the cooler was examined experimentally. The experiment was performed using an evaporative cooler prototype. The efficiency of the prototype was calculated and the water temperature was lowered to examine the effects on the produce cold air.

4.1 Water Temperature Effect on Evaporative Coolers

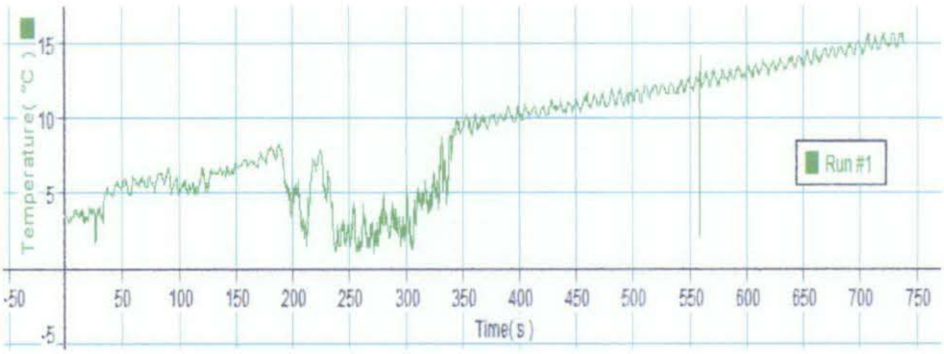
An evaporative cooler has saturation efficiency coefficient 0.21 which was evidently improved to 0.82 by lowering the water temperature to around 5 °C the relative humidity was 66% and the wet bulb temperature was 23.9 °C. As it could be seen from the graphs in figure 11, after 300 seconds, the hot air started losing temperature to the cold water be for going into the heat exchanger, what lead the cooled air temperature to reduce more. As the water started heating (after 400s) the cooled air started having higher temperature and the cooler would return to its normal operation as the water returns to the ambient temperature.



(a) Hot air



(b) Cooled air



(c) Water temperature

Figure 11 : Temperature of air streams and water during the experiment.

Form these results it is clear that the performance of evaporative coolers could be improved by reducing the water temperature. In practice, the lowest temperature the water can reach is the wet bulb temperature [1] which is a weather factor. We can lower and control the water temperature by lowering the water temperature what will ensure good temperature reduction in a controllable manner. That led to the introduction of Hybrid Evaporative Cooling.

4.2 Hybrid Evaporative Cooling (HEC)

The hybrid evaporative cooling system is based on the direct evaporative cooler that is coupled with the vapor compression system to reduce the temperature of the working fluid as in figure 12. The design of the hybrid system was innovated based on the ability to provide thermal comfort and the amount of power to be consumed by the system.

In order to provide thermal comfort, it was decided that the cooler should not only reduce the temperature of the air, but should be able increase the relative humidity as well. Since the ambient temperature is high in Sudan, relying on natural evaporation to cool off the temperature of the working fluid will not translate to effective cooling system. Therefore, the usual refrigeration system is used to reduce the temperature of the working fluid. The whole cooling part is powered by using a photovoltaic system, with capacity for storing electrical energy.

In conventional evaporative coolers, the air temperature drops due to the increase in moisture content of the air – increase relative humidity – and gradually it gradually cools down the water [1]. This along side with heat gains from the surrounding environment explains the bad performance of conventional evaporative coolers in high temperature. The hybrid evaporative cooler on the other hand cools down the water far below the intake air temperature – typically above 5 °C to avoid from freezing – and as a result a heat exchange between the air and the water takes place simultaneously with the evaporation effect. These simultaneous processes result in lower air temperature and since the water temperature is lower than the air's the air will not suffer heat gains. In addition to that, the hybrid evaporative cooler operates much better in humid and hot environment compared to conventional evaporative coolers.

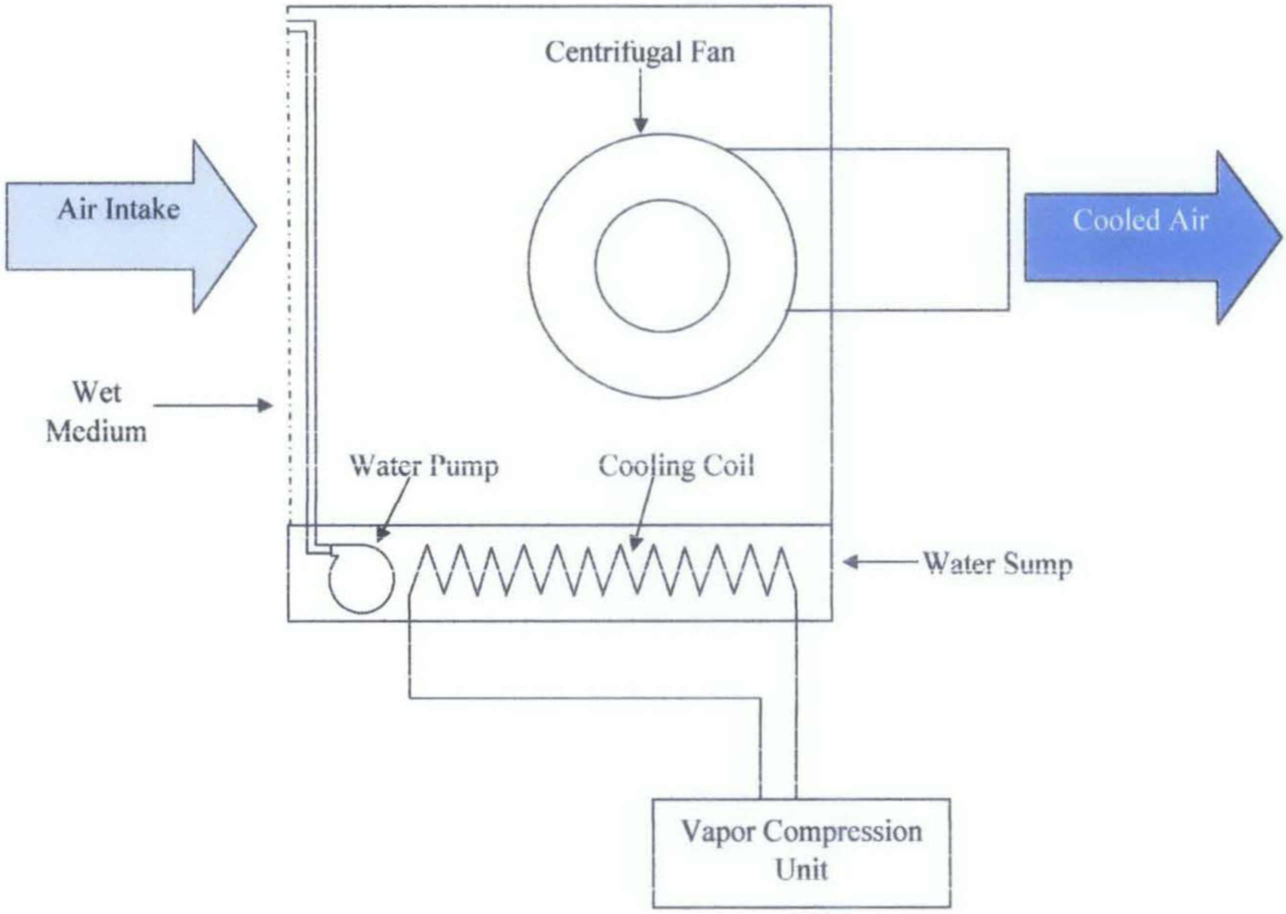


Figure 12 : Sketch of a Hybrid Evaporative Cooler.

To help understand the performance of the hybrid evaporative cooler consider a conventional evaporative cooler with saturation efficiency of 0.7 operating in ambient temperature of 45 °C and relative humidity of 20%. As shown in figure 13, the conventional evaporative cooler can achieve cool air temperature of 30 °C point b. The introduction of heat exchange at this point will result in cool air temperature on the curve b-c depending on the effectiveness of the exchange process.

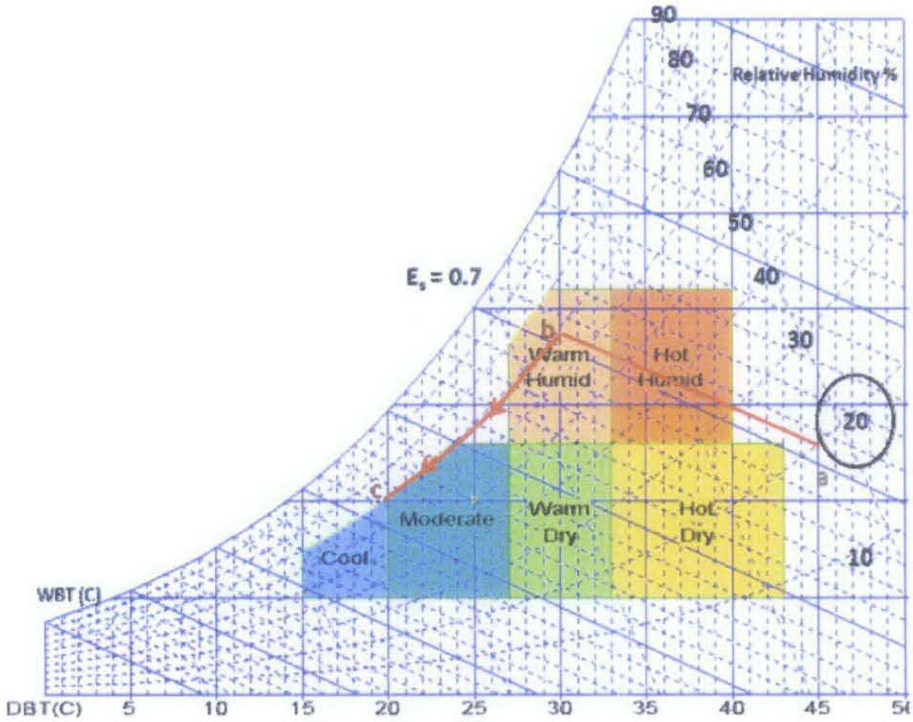


Figure 13 : performance of HEC on Psychometric chart

A prototype of hybrid evaporative cooler was built and its performance was verified experimentally, the cooler's saturation efficiency improved by 0.3 for every 5 °C reduction in water temperature as in table 3. The experiment was conducted in ambient temperature 30 °C, relative humidity of 70%, and wet bulb temperature of 25.5 °C.

Table 3 : Experimental result for HEC prototype.

Water Temperature	Cool Air Temperature	Saturation Efficiency
27	28.5	0.3
20	27	0.6
15	26	0.8

The vapor compression unit used to cool the water should overcome heat gains form the following sources:

1. Natural convection around the cooler. Given by:

$$Q= h\,A\,(T_a - T_w) \qquad (1)$$

2. Heat exchange between the air and the water in the cooler. Given by:

$$Q=\acute{\varepsilon}\,Q_{max} = \acute{\varepsilon}\,C_{min}\,(T_a - T_w) \qquad (2)$$

3. Heat gains from solar radiation since the cooler is typically installed outdoors.

The only desirable heat gain is that due to heat exchange between the air and the water, it is always best if the heat gain due solar radiation and natural convection is minimized. This can be achieved by shading the cooler to minimize solar radiation heat gains and passively cooling the surroundings of the cooler through trees to minimize heat gains due natural convection and also improving the overall performance of the cooler by reducing the temperature of the intake air.

4.3 Power Requirements of Hybrid Evaporative Cooler

The hybrid evaporative cooler consists of three electrical powered parts (1) Centrifugal fan motor, (2) water pump, (3) vapor compression unit. The fan motor and the water pump typically have rated power of 200W for AC power. For the vapor compression unit there are a handful of choices we could derive the required cooling power using equation 1 & 2 in the previous section but the lack of heat exchange effectiveness data for evaporative coolers prevents from that. Therefore, we limit the unit's power rating of to 1000 W per day (House refrigerator compressor) so the cost of the SAPV system used stays economical. Most preferred are the 12 V DC vapor compression units used in new DC refrigerators, it consumes 200 – 500 W per day but it is usually more costly.

4.4 Stand-Alone Photovoltaic (SAPV) System

Since the cooling system is mainly designed to overcome the problem of cooling in the absence of grid supply, stand-alone photovoltaic system is the ideal choice. To be able to size SAPV system regardless of the method used we need solar radiation data. Unfortunately Sudan has only solar radiation data of 16 stations only what leaves big parts of the country without this information.

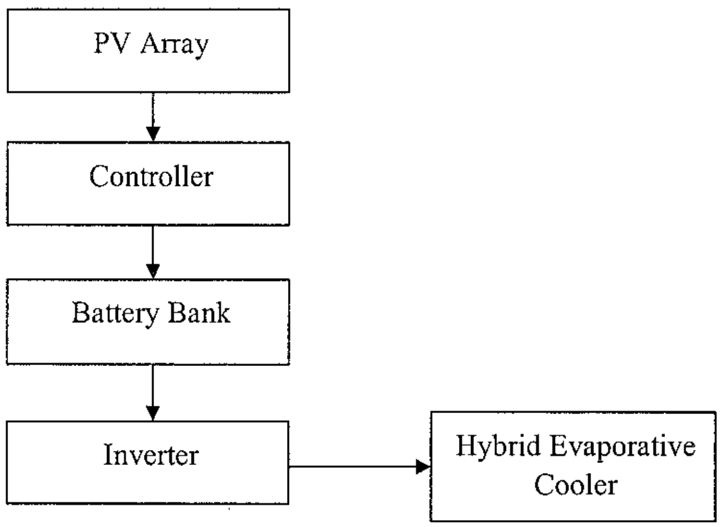


Figure 14 : SAPV powered Hybrid Evaporative Cooler.

An estimation model based on clear sky analysis [13] was developed to provide radiation data for the task of SAPV system sizing. This model is accurate enough to be used for parts of the country that falls north to latitude 10° N with error margin not more than10% [12] as in table 3. Most of the over estimation happens in the months of June to October due to clouds in the rainy season. The following set of equations was used in the estimation model:

$$I_o = \frac{24 \times 3600 \times Gsc}{\pi}(1 + 0.033 \cos \frac{360n}{365}) \times [\cos\phi \cos\delta(\sin\omega 2 - \sin\omega 1) + \frac{\pi(\omega 2 - \omega 1)}{180} \sin\phi \sin\delta]$$

$$T_b = A_o + A_1 \exp(-A_2 / \cos\theta)$$

$$T_d = 0.271 - 0.2939 T_b$$

$$I_g = T_b I_o + T_d I_o$$

$$A_1 = 0.4237 - 0.00821(6 - altitude(Km))^2$$

$$A_2 = 0.5055 + 0.00595(6.5 - altitude(Km))^2$$

$$A_3 = 0.2711 + 0.01858(2.5 - altitude(Km))^2$$

The system's load is not constant through the year since it will be used for 20 to 24 hours a day in April, May, and June and 10 to 15 hours in November, December, January, and February, clearly from figure 14 the highest demand coincides with the highest radiation levels as in figure 14. The following relation can be used to produce the optimum size of the SAPV system:

$\text{Max}\ (Q_t - P_t) \leq 0$

Where

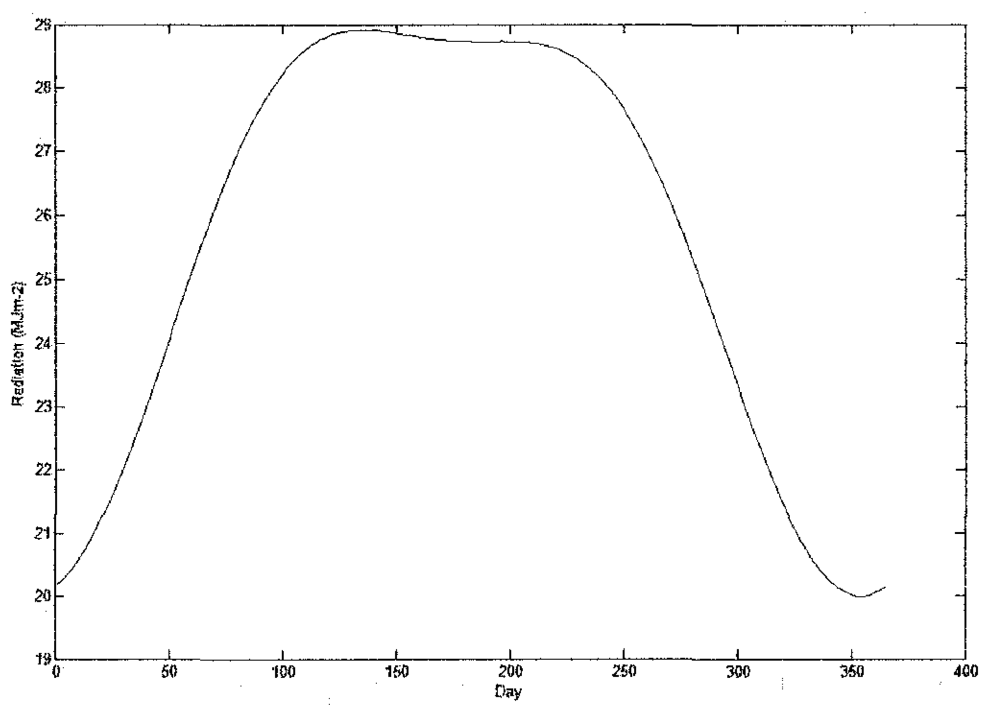
Q_t is the load at any time t

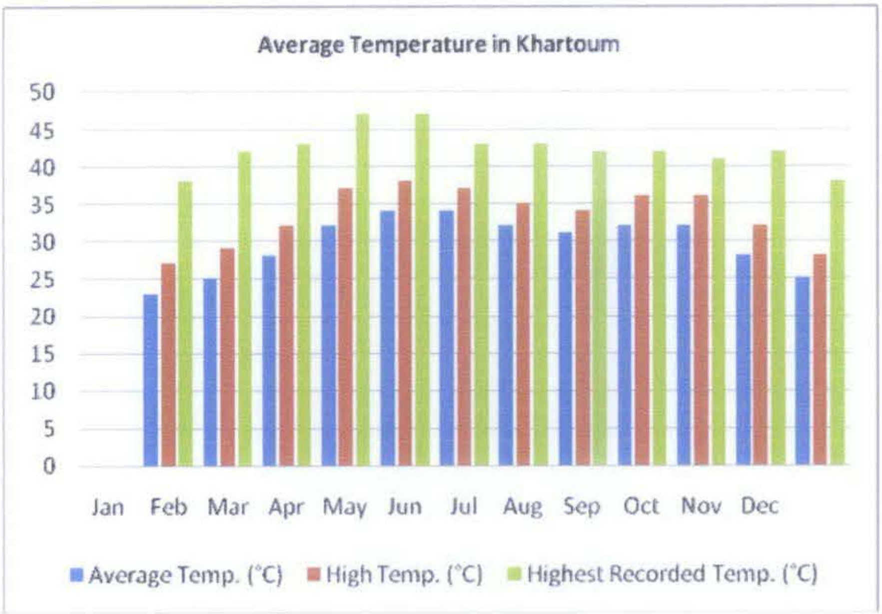
P_t is the power from the PV system at any time t

Since the estimation model has error margin, one would expect under-sizing to happen. This could be ruled out because the over estimation occurs for the rainy moths (June - October) where the ambient temperature drops and consequently the vapor compression unit will be off more often and the operation hours of the cooler are expected to be shorter compared to the summer season.

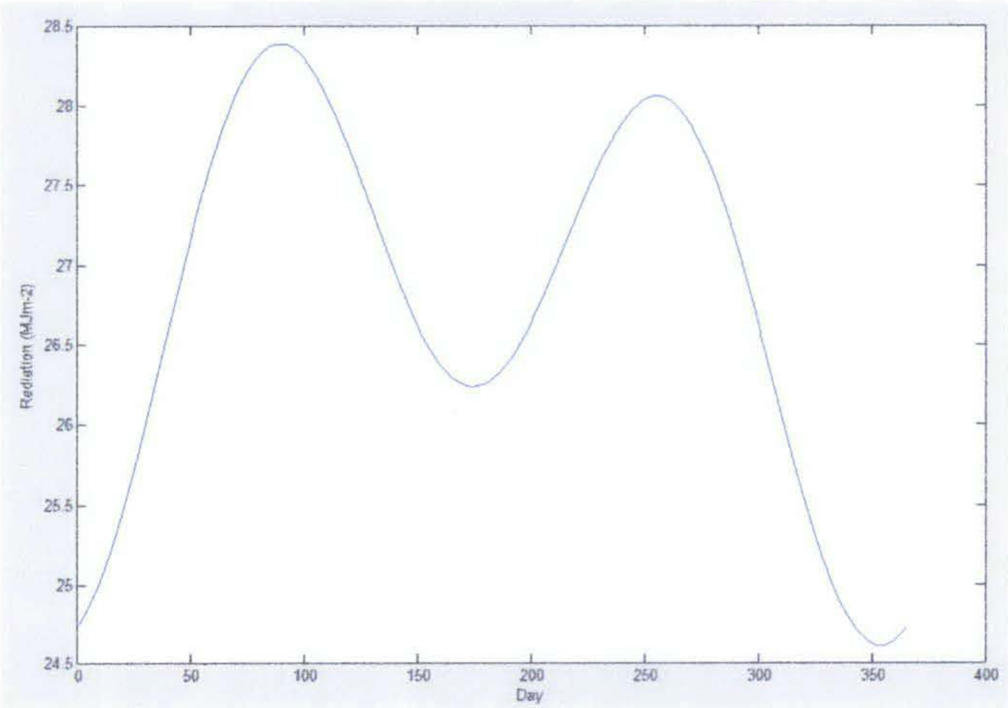
Table 4 : Actual VS Estimated Average Solar Radiation.

City	Measured Solar radiation (MJm^{-2} day^{-1})	Estimated Solar radiation (MJm^{-2} day^{-1})	
Port Sudan	20.87	24.18	East
Khartoum	22.82	25.63	Center
Wad Medani	22.84	25.84	Center
Elfasher	22.8	26.56	West
Juba	19.59	26.79	South
Dongola	24.06	24.75	North





(a) Annual Radiation and Temperature for Khartoum



(b) Annual Radiation and Temperature for Juba

Figure 15 : Estimated Annual radiation and annual average temperature for Khartoum & Juba.

Even though the error in radiation estimation for location south to 10° N is higher than 10%, it is still acceptable to use the estimated radiation under the following relation:

$Q_{Max} < P_{Min}$

Where

Q_{Max} is the maximum load

P_{Min} is the minimum power from the PV system

The system calculated using this relation may still be under-sized. To overcome this problem the system must be oversized by 15%. The estimation model produces radiation estimates radiation received on horizontal surface. It is acceptable to install PV modules horizontally since the received radiation will be highest when the demand is highest as in figure 14.

4.5 Hybrid Evaporative Cooler for the City of Khartoum

Khartoum is the capital city of Sudan situated at latitude 15.6 N longitude 32.54 E and altitude of 382 m above see level. SAPV sizing for Hybrid Evaporative Cooler comprising of 200 W fan motor and water pump and 1000W per day vapor compression unit in the city of Khartoum was performed based on the following inputs:

Table 5 : Anticipated Operation profile for HEC in the city of Khartoum.

	Month	Operation Hours
High demand	March, April, May, June	15 h
Medium demand	July, August, September, October	11 h
Low demand	November, December, January, February	8 h

The batteries used are 6V 220Ah Flooded lead-acid batteries that cost approximately USD 90 and has 5-years life cycle. The inverter used is 12V inverter with conversion efficiency of 0.9. The PV module used are 4.4A 50W with rated voltage of 12V and cost USD 350.

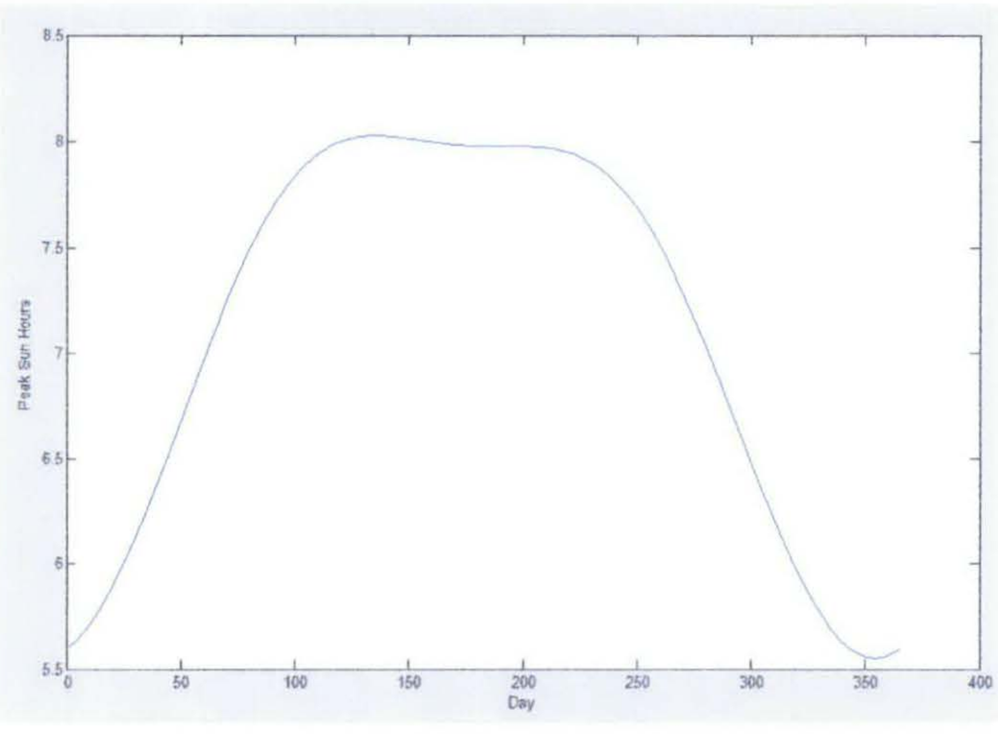


Figure 16 : Estimated Peak Sun Hours for one year in Khartoum.

The corrected load considering wiring loses of 0.2 and inverter efficiency 0.9 and battery efficiency of 0.8.

For high demand is 428 Ah per day

For medium demand is 314 Ah per day

For low demand 228.3 Ah per day

The battery duration is given by $D_{non} = -0.48 T_{\min peakhour} + 4.58$ since the system is treated as non critical system.

Table 6 : Required battery size.

	Minimum peak sun Hours	Required battery duration	Required battery size
High demand	7 h	1.2 day	512.6 Ah
Medium demand	6.3 h	1.5 day	471 Ah
Low demand	5.6 h	1.9 day	433.8 Ah

We take the highest required size that the system will supply which is 512.6 Ah to determine the number of batteries needed.

Number of batteries = Required battery size (Ah) / Battery capacity (Ah)

The required number of batteries was rounded down to 2 batteries at cost of $ 180. Since the system runs on (12 V) the 2 batteries will be connected in series.

The system will require 12 modules connected in series to provide the required power at cost of $4200 and PV system total cost $ 4380.

Sizing a PV system using DC parts with equivalent performance to that of the AC parts will result in smaller and less expensive system due to the energy efficiency of DC parts. SAPV sizing for Hybrid Evaporative Cooler comprising of 100 W DC fan motor and water pump and 490Wh per day DC vapor compression unit .Using same batteries an PV modules used in the AC system and under the same operation profile requires 2 batteries and 6 PV modules only as in table 7.

Table 7 : PV system for DC hybrid evaporative cooler

	Number of batteries	Cost of batteries	Number of PV modules	Cost of PV modules
12 V DC system	2	$180	6	$2100

4.6 SAPV Sizing Tool

These concepts were all used to develop sizing software. The software obtains the specifications of the batteries and PV arrays used through a graphical interface (see figure 17). It also requires the designer to enter the anticipated operation hours for maximum demand, medium demand, and minimum demand. Maximum demand is anticipated to happen in the months of March, April, May, and June where the medium demand is expected in the moths of July, August, September, and October. The minimum demand is expected for the rest of the year.

The design tool minimizes over sizing for locations north to 10° N while minimizing under sizing for location south of 10° N buy following the sizing relationships mentioned earlier. The design tool is capable of performing PV system sizing for AC and DC systems since DC systems may be used due to its low power requirements. This tool also has built in rated values for battery, it uses 6V 220A flooded lead-acid when the designer chooses rated values.

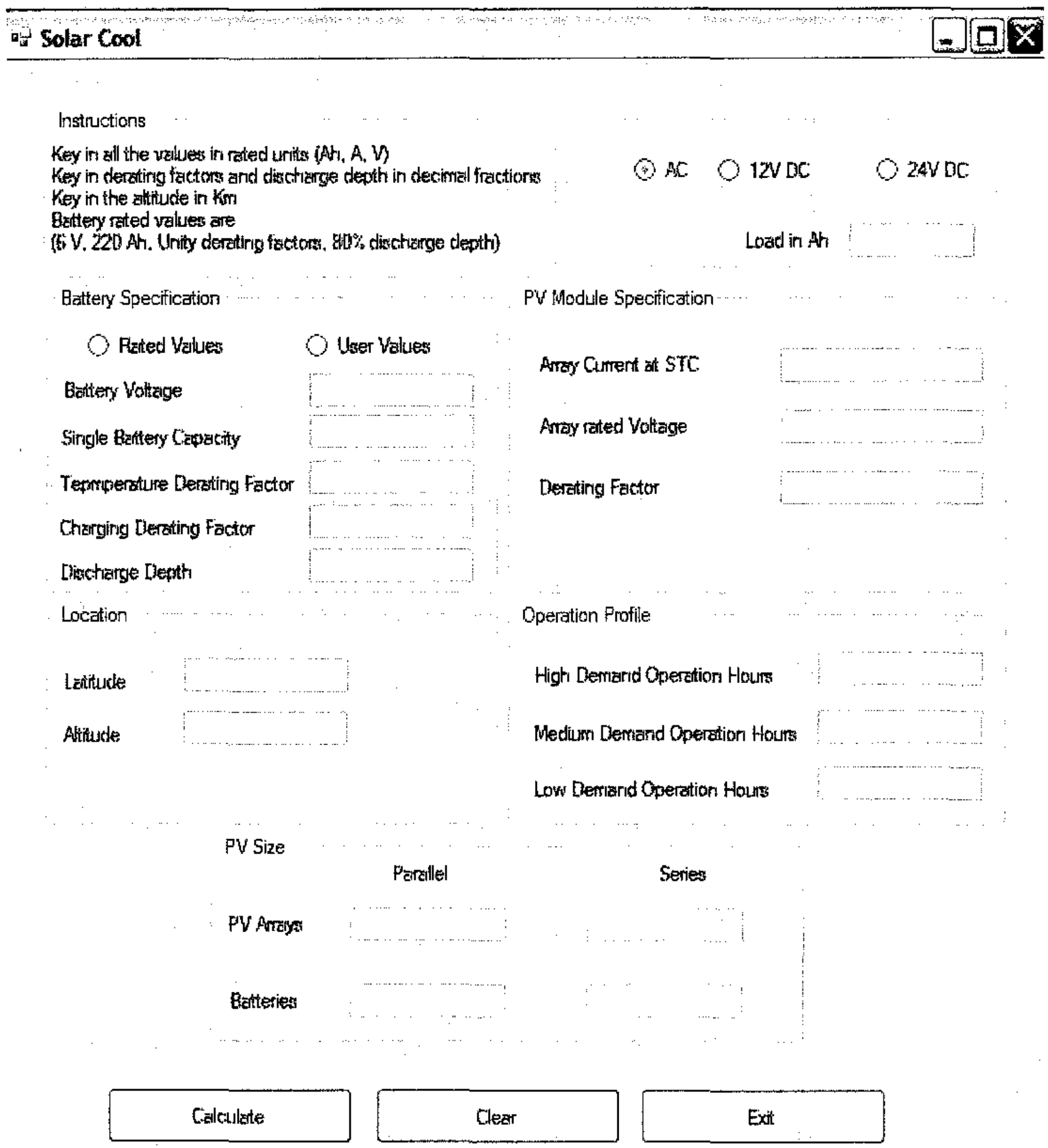


Figure 17 : Graphical interface for the design tool.

The program starts by determining the number of batteries and PV modules needed to be used in series. Then estimated peak sun hours are calculated for the high, medium, and low demand periods. After that the corrected load is calculated to account for wire and inverter loses and the battery storage duration is determined using the following equation.

$$D_{non} = -0.48T_{\min peakhour} + 4.58$$

The required battery capacity is then determined using the following equation:

$$Battery(Ah) = correctedload(\frac{D_{non}}{D_T D_{ch}(disch)})$$

And dividing the battery capacity by the single battery capacity, the number of batteries in parallel needed is found. The corrected load and the rated PV module voltage and STC current along with the peak sun hours are used to find the number of parallel PV modules to be used.

The tool displays the number of modules and batteries needed in parallel and series. The total number of needed batteries and PV modules is the product multiplying the number in parallel by the number in series.

CHAPTER 5
CONCLUSION & RECOMMENDATION

5.1 Hybrid Evaporative Cooler

The hybrid evaporative cooler can provide thermal comfort in the weather of Sudan through out the year. Its ability to overcome conventional evaporative coolers problem which was demonstrated in this report makes it the best choice. This cooler is also easy to manufacture and install. Over all the cooling system has proven to be effective and there is potential for commercialization. Although the cost is very much dependent on the cooling load, but the relative cost is much lower as compared to the conventional cooling system. Perhaps to be more cost effective, the cooler can be installed in a common area where all the household occupants can enjoy the benefit of this cooling system. Additional on site testing will help in sizing the vapor compression unit much accurately and it will also help determining the heat exchange effectiveness of wet medium

5.2 Stand-Alone Photovoltaic system

SAPV system was found to be the most suitable solar energy system for the purpose of this project. The sizing method discussed in this report can provide good performance system but if a more accurate estimation module can be used, then the SAPV size could be minimized so the cost will stay minimum. DC parts and equipments are preferred because of the high energy efficiency and the smaller size of required PV system. Due to the relatively high cost of the PV system currently, it is recommended to limit the operation hours to 15 hours per day so the needed system cost could be recovered over the system's useful life. Economical break even analysis can also be used to select the best operation period. Yet the system could eventually recover its cost in terms of power cost savings.

The increasing demand on PV system will soon lead to cost reduction of the system components. So in the near future this system could very well be the best for of electrical power supply in terms of cost and environmental impact.

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[13] John A. Duffie, William A. Beckman, Solar Engineering of Thermal Process, Wiley-Interscience , 1991.

APPENDICES

APPENDIX A

RADIATION ESTIMATION MODEL (MATLAB)

```
lat= ;
alt= ;
a1=0.4237-0.00821*((6-alt)^2);
a2=0.5055+0.00595*((6.5-alt)^2);
a3=0.2711+0.01858*((2.5-alt)^2);
Iavg=0;
for n= 1:365
   a=360*(284+n)/365;
   declin=23.45*sin(a*pi/180);
   b=-1*tan(lat*pi/180)*tan(declin*pi/180);
   sunshineangle =180*acos(b)/pi;
   sunshinehour = 12-(sunshineangle/15);
   daylight = (48/360)*sunshineangle;
   hourangle1 = 15*(12-(daylight+sunshinehour));
   hourangle2 = 15*(12-sunshinehour);
   I(n)=
(12*3600*1367/3.142)*((1+0.033*cos((360*n/365)*pi/180))*(cos(lat*pi/180)*cos(d
eclin*pi/180)*(sin(hourangle2*pi/180)-
sin(hourangle1*pi/180))+6.284*((hourangle2-
hourangle1)/360)*sin(lat*pi/180)*sin(declin*pi/180)));
   Tb=a1+a2*exp(-1*a3/cos((lat-declin)*pi/180));
   Td=0.271-0.2939*Tb;
   Ig(n)=Tb*I(n)+Td*I(n);
   Ig(n)=Ig(n)/1000000;
   Iavg= Iavg+Ig(n);
end
plot (Ig);
xlabel('Day');
ylabel('Radiation (MJm-2)');
Iavg=Iavg/365
```

APPENDIX BRADIATION ESTIMATION MODEL

```
lat= ;
alt= ;
a1=0.4237-0.00821*((6-alt)^2);
a2=0.5055+0.00595*((6.5-alt)^2);
a3=0.2711+0.01858*((2.5-alt)^2);
Iavg=0;
for n= 1:365
   a=360*(284+n)/365;
   declin=23.45*sin(a*pi/180);
   b=-1*tan(lat*pi/180)*tan(declin*pi/180);
   sunshineangle =180*acos(b)/pi;
   sunshinehour = 12-(sunshineangle/15);
   daylight = (48/360)*sunshineangle;
   hourangle1 = 15*(12-(daylight+sunshinehour));
   hourangle2 = 15*(12-sunshinehour);
   I(n)=
(12*3600*1367/3.142)*((1+0.033*cos((360*n/365)*pi/180))*(cos(lat*pi/180)*cos(d
eclin*pi/180)*(sin(hourangle2*pi/180)-
sin(hourangle1*pi/180))+6.284*((hourangle2-
hourangle1)/360)*sin(lat*pi/180)*sin(declin*pi/180)));
   Tb=a1+a2*exp(-1*a3/cos((lat-declin)*pi/180));
   Td=0.271-0.2939*Tb;
   Iw(n)=Tb*I(n)+Td*I(n);
   Iw(n)=Ig(n)/1000000;
   Iavg= Iavg+Ig(n);
end
plot (Ig);
xlabel('Day');
ylabel('Irradiance (Wm-2)');
Iavg=Iavg/365
```

APPENDIX C

SAPV SYSTEM SIZING TOOL (CODE & INTERFACE)

```
Public Class Solar
    Dim coolerloade As Decimal
    Dim highload, mediumload, lowload, Batterydurationlow,
Batterydurationmedium, Batterydurationhigh, daylightmedium, Igmedium
As Decimal
    Dim a1, a2, a3, a, b, declin, sunshineangle, sunshinehour,
daylight, hourangle1, hourangle2 As Decimal
    Dim radiation, T, Td, Ig, daylightarry, c, daylightlow1, Iglow1,
daylightlow2, Iglow2, daylightlow, Iglow, daylighthigh, Ighigh,
Batterysizelow, Batterysizemedium, Batterysizehigh, Batterysize,
Batteryseries, Batteryparallel, PV As Decimal
    Dim PVseries, PVparallel, PVlow, PVmedium, PVhigh, Igs,
daylights, Peakhour, Peakhourlow, Peakhourmedium, Peakhourhigh As
Decimal
    Private Sub Label4_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Label4.Click
    End Sub

    Private Sub TextBox2_TextChanged(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles TextBox2.TextChanged

    End Sub

    Private Sub GroupBox2_Enter(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles GroupBox2.Enter

    End Sub

    Private Sub RBrated_CheckedChanged(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RBrated.CheckedChanged
        Me.Select()
        RBuser.Enabled = True
        TextBox1.Enabled() = False
        TextBox2.Enabled() = False
        TextBox3.Enabled() = False
        TextBox4.Enabled() = False
        TextBox6.Enabled() = False

    End Sub

    Private Sub TextBox1_TextChanged(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles TextBox1.TextChanged

    End Sub

    Private Sub RBAC_CheckedChanged(ByVal sender As System.Object,
ByVal e As System.EventArgs)
        'Me.Select()
        ' TextBox5.Enabled = False


    End Sub
```

```
    Private Sub RB12DC_CheckedChanged(ByVal sender As System.Object,
ByVal e As System.EventArgs)
        '  Me.Select()
        ' TextBox5.Enabled = True


    End Sub

    Private Sub RB12_CheckedChanged(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles RB12.CheckedChanged
        Me.Select()
        TextBox5.Enabled = True
    End Sub

    Private Sub RB24_CheckedChanged(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles RB24.CheckedChanged
        Me.Select()
        TextBox5.Enabled = True
    End Sub

    Private Sub RBAC_CheckedChanged_1(ByVal sender As System.Object,
ByVal e As System.EventArgs) Handles RBAC.CheckedChanged
        Me.Select()
        TextBox5.Enabled = True

    End Sub

    Private Sub Button1_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Butt_cal.Click

        If RBAC.Checked Then
            coolerloade = TextBox5.Text
            PVseries = 12 / TextBox12.Text
            If RBrated.Checked Then
                Batteryseries = 2
            ElseIf RBuser.Checked Then
                Batteryseries = 12 / TextBox6.Text
            End If

        ElseIf RB12.Checked Then
            coolerloade = TextBox5.Text
            PVseries = 12 / TextBox12.Text
            If RBrated.Checked Then
                Batteryseries = 2
            ElseIf RBuser.Checked Then
                Batteryseries = 12 / TextBox6.Text
            End If
        ElseIf RB24.Checked Then
            coolerloade = TextBox5.Text
            PVseries = 24 / TextBox12.Text
            If RBrated.Checked Then
                Batteryseries = 4
            ElseIf RBuser.Checked Then
                Batteryseries = 24 / TextBox6.Text
            End If
        End If
        highload = (coolerloade * TBhigh.Text) / 0.98
        mediumload = (coolerloade * TBmedium.Text) / 0.98
        lowload = (coolerloade * TBlow.Text) / 0.98

        If RBAC.Checked Then
```

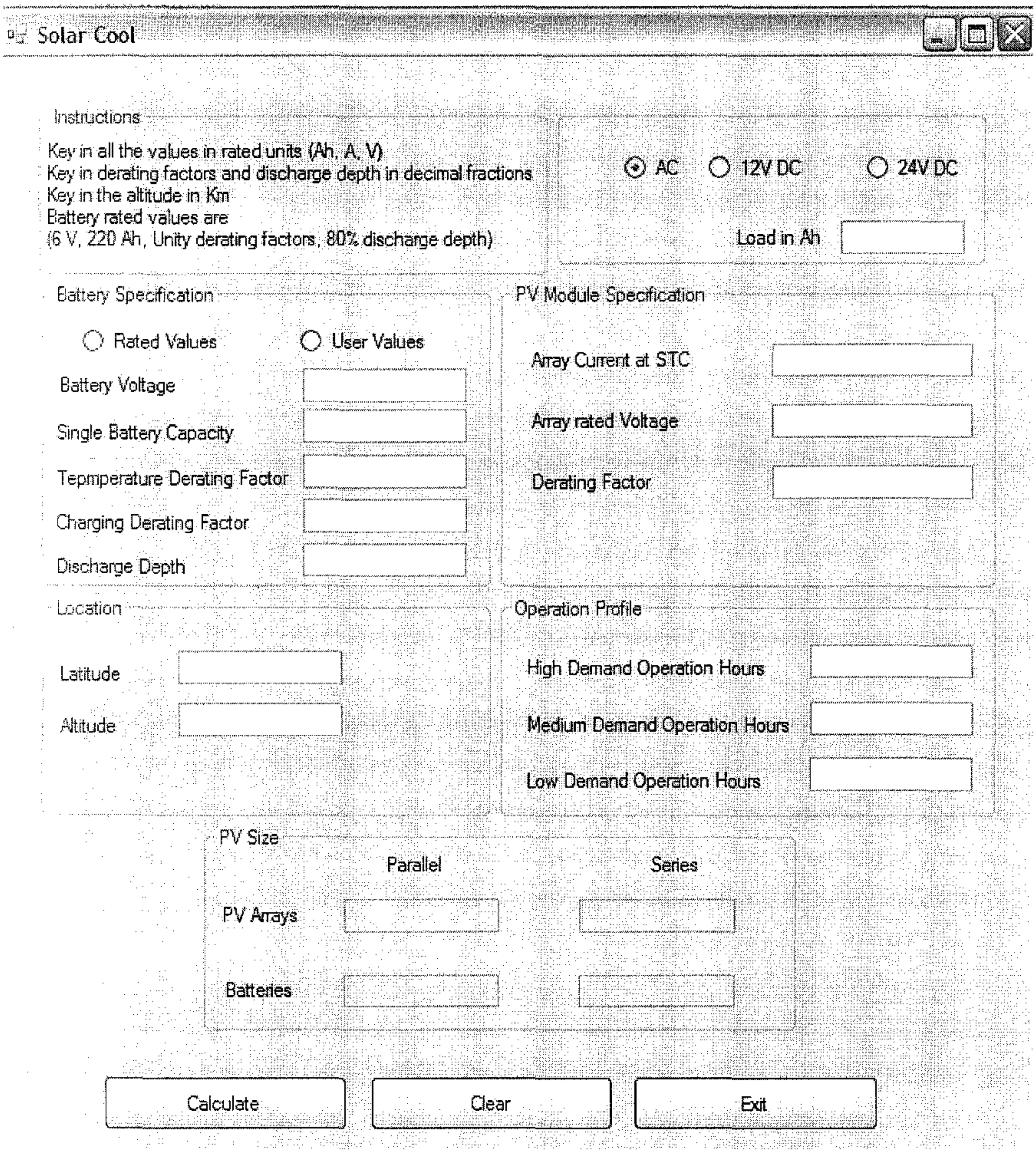
```
            highload = highload / 0.9
            mediumload = mediumload / 0.9
            lowload = lowload / 0.9
        End If

        a1 = 0.4237 - 0.00821 * ((6 - TBaltitude.Text) ^ 2)
        a2 = 0.5055 + 0.00595 * ((6.5 - TBaltitude.Text) ^ 2)
        a3 = 0.2711 + 0.01858 * ((2.5 - TBaltitude.Text) ^ 2)

        'Estimation model stare

        Dim n As Integer

        Dim aa, ba, declina, sunshineanglea, sunshinehoura,
daylighta, hourangle1a, hourangle2a, radiationa, Ta, Tda As Double
        Dim SPHa As Decimal

        Iglow1 = 500
        For n = 1 To 59
            aa = 360 * (284 + n) / 365
            declina = 23.45 * Math.Sin(aa * Math.PI / 180)
            ba = -1 * Math.Tan(TBlatitude.Text * Math.PI / 180) *
Math.Tan(declina * Math.PI / 180)
            sunshineanglea = 180 * Math.Acos(ba) / Math.PI
            sunshinehoura = 12 - (sunshineanglea / 15)
            daylighta = (48 / 360) * sunshineanglea
            hourangle1a = 15 * (12 - (daylighta + sunshinehoura))
            hourangle2a = 15 * (12 - sunshinehoura)
            radiationa = ((12 * 3600 * 1367 / 3.142) * ((1 + 0.033 *
Math.Cos((360 * n / 365) * Math.PI / 180)) *
(Math.Cos(TBlatitude.Text * Math.PI / 180) * Math.Cos(declina *
Math.PI / 180) * (Math.Sin(hourangle2a * Math.PI / 180) -
Math.Sin(hourangle1a * Math.PI / 180)) + 6.284 * ((hourangle2a -
hourangle1a) / 360) * Math.Sin(TBlatitude.Text * Math.PI / 180) *
Math.Sin(declina * Math.PI / 180))))
            Ta = a1 + a2 * Math.Exp(-1 * a3 /
Math.Cos((TBlatitude.Text - declina) * Math.PI / 180))
            Tda = 0.271 - 0.2939 * Ta
            SPHa = (Ta * radiationa + Tda * radiationa) / 3600000

            If Iglow1 > SPHa Then
                Iglow1 = SPHa
            End If

        Next

        Dim ab, bb, declinb, sunshineangleb, sunshinehourb,
daylightb, hourangle1b, hourangle2b, radiationb, Tb, Tdb As Double
        Dim SPHb As Decimal

        Iglow2 = 500


        For n = 304 To 365
            ab = 360 * (284 + n) / 365
            declinb = 23.45 * Math.Sin(ab * Math.PI / 180)
            bb = -1 * Math.Tan(TBlatitude.Text * Math.PI / 180) *
Math.Tan(declinb * Math.PI / 180)
            sunshineangleb = 180 * Math.Acos(bb) / Math.PI
            sunshinehourb = 12 - (sunshineangleb / 15)
            daylightb = (48 / 360) * sunshineangleb
            hourangle1b = 15 * (12 - (daylightb + sunshinehourb))
```

```
            hourangle2b = 15 * (12 - sunshinehourb)
            radiationb = ((12 * 3600 * 1367 / 3.142) * ((1 + 0.033 *
Math.Cos((360 * n / 365) * Math.PI / 180)) *
(Math.Cos(TBlatitude.Text * Math.PI / 180) * Math.Cos(declinb *
Math.PI / 180) * (Math.Sin(hourangle2b * Math.PI / 180) -
Math.Sin(hourangle1b * Math.PI / 180)) + 6.284 * ((hourangle2b -
hourangle1b) / 360) * Math.Sin(TBlatitude.Text * Math.PI / 180) *
Math.Sin(declinb * Math.PI / 180))))
            Tb = a1 + a2 * Math.Exp(-1 * a3 /
Math.Cos((TBlatitude.Text - declinb) * Math.PI / 180))
            Tdb = 0.271 - 0.2939 * Tb
            SPHb = (Tb * radiationb + Tdb * radiationb) / 3600000

            If Iglow2 > SPHb Then
                Iglow2 = SPHb
            End If

        Next

        'comparisons to get daylight(ow, high ,and meduim) values

        If Iglow1 > Iglow2 Then
            Iglow = Iglow2
        Else
            Iglow = Iglow1
        End If

        Dim ac, bc, declinc, sunshineanglec, sunshinehourc,
daylightc, hourangle1c, hourangle2c, radiationc, Tc, Tdc As Double
        Dim SPHc As Decimal

        Ighigh = 500


        For n = 60 To 180
            ac = 360 * (284 + n) / 365
            declinc = 23.45 * Math.Sin(ac * Math.PI / 180)
            bc = -1 * Math.Tan(TBlatitude.Text * Math.PI / 180) *
Math.Tan(declinc * Math.PI / 180)
            sunshineanglec = 180 * Math.Acos(bc) / Math.PI
            sunshinehourc = 12 - (sunshineanglec / 15)
            daylightc = (48 / 360) * sunshineanglec
            hourangle1c = 15 * (12 - (daylightc + sunshinehourc))
            hourangle2c = 15 * (12 - sunshinehourc)
            radiationc = ((12 * 3600 * 1367 / 3.142) * ((1 + 0.033 *
Math.Cos((360 * n / 365) * Math.PI / 180)) *
(Math.Cos(TBlatitude.Text * Math.PI / 180) * Math.Cos(declinc *
Math.PI / 180) * (Math.Sin(hourangle2c * Math.PI / 180) -
Math.Sin(hourangle1c * Math.PI / 180)) + 6.284 * ((hourangle2c -
hourangle1c) / 360) * Math.Sin(TBlatitude.Text * Math.PI / 180) *
Math.Sin(declinc * Math.PI / 180))))
            Tc = a1 + a2 * Math.Exp(-1 * a3 /
Math.Cos((TBlatitude.Text - declinc) * Math.PI / 180))
            Tdc = 0.271 - 0.2939 * Tc
            SPHc = (Tc * radiationc + Tdc * radiationc) / 3600000

            If Ighigh > SPHc Then
                Ighigh = SPHc
            End If

        Next
```

```
        Dim ad, bd, declind, sunshineangled, sunshinehourd,
daylightd, hourangle1d, hourangle2d, radiationd, Td, Tdd As Double
        Dim SPHd As Decimal
        Igmedium = 500

        For n = 181 To 303
            ad = 360 * (284 + n) / 365
            declind = 23.45 * Math.Sin(ad * Math.PI / 180)
            bd = -1 * Math.Tan(TBlatitude.Text * Math.PI / 180) *
Math.Tan(declind * Math.PI / 180)
            sunshineangled = 180 * Math.Acos(bd) / Math.PI
            sunshinehourd = 12 - (sunshineangled / 15)
            daylightd = (48 / 360) * sunshineangled
            hourangle1d = 15 * (12 - (daylightd + sunshinehourd))
            hourangle2d = 15 * (12 - sunshinehourd)
            radiationd = ((12 * 3600 * 1367 / 3.142) * ((1 + 0.033 *
Math.Cos((360 * n / 365) * Math.PI / 180)) *
(Math.Cos(TBlatitude.Text * Math.PI / 180) * Math.Cos(declind *
Math.PI / 180) * (Math.Sin(hourangle2d * Math.PI / 180) -
Math.Sin(hourangle1d * Math.PI / 180)) + 6.284 * ((hourangle2d -
hourangle1d) / 360) * Math.Sin(TBlatitude.Text * Math.PI / 180) *
Math.Sin(declind * Math.PI / 180))))
            Td = a1 + a2 * Math.Exp(-1 * a3 /
Math.Cos((TBlatitude.Text - declin) * Math.PI / 180))
            Tdd = 0.271 - 0.2939 * Td
            SPHd = (Td * radiationd + Tdd * radiationd) / 3600000

            If Igmedium > SPHd Then
                Igmedium = SPHd
            End If

        Next

        ' in case of selecting rated values calculate the battery
sizes(low,high,meduim)

        If RBrated.Checked Then
            Batterydurationlow = -0.48 * Iglow + 4.58
            Batterysizelow = (lowload * Batterydurationlow) / 0.8

            Batterydurationmedium = -0.48 * Igmedium + 4.58
            Batterysizemedium = (mediumload * Batterydurationmedium)
/ 0.8

            Batterydurationhigh = -0.48 * Ighigh + 4.58
            Batterysizehigh = (highload * Batterydurationhigh) / 0.8
        ElseIf RBuser.Checked Then
            Batterydurationlow = -0.48 * Iglow + 4.58
            Batterysizelow = (lowload * Batterydurationlow) /
(TextBox2.Text * TextBox3.Text * TextBox4.Text)

            Batterydurationmedium = -0.48 * Igmedium + 4.58
            Batterysizemedium = (mediumload * Batterydurationmedium)
/ (TextBox2.Text * TextBox3.Text * TextBox4.Text)

            Batterydurationhigh = -0.48 * Ighigh + 4.58
            Batterysizehigh = (highload * Batterydurationhigh) /
(TextBox2.Text * TextBox3.Text * TextBox4.Text)
        End If

        'compare battery sizes and get the largest value
        If Batterysizelow > Batterysizemedium Then
```

```
            Batterysize = Batterysizelow
        Else
            Batterysize = Batterysizemedium
        End If
        If Batterysize < Batterysizehigh Then
            Batterysize = Batterysizehigh
        End If
        If RBrated.Checked Then
            Batteryparallel = (Batterysize / 220) / Batteryseries
        ElseIf RBuser.Checked Then
            Batteryparallel = (Batterysize / TextBox1.Text) /
Batteryseries

        End If

        If TBlatitude.Text >= 10 Then

            PVlow = (lowload / Iglow / TextBox7.Text) /
TBcurrent.Text

            PVmedium = (mediumload / Igmedium / TextBox7.Text) /
TBcurrent.Text

            PVhigh = (highload / Ighigh / TextBox7.Text) /
TBcurrent.Text

            If PVlow > PVmedium Then
                PV = PVlow
            Else
                PV = PVmedium

            End If
            If PVhigh > PV Then
                PV = PVhigh
            End If

            PVparallel = PV / PVseries

        Else

            If Iglow < Igmedium Then
                Igs = Iglow
            Else
                Igs = Igmedium
            End If
            If Ighigh < Igs Then
                Igs = Ighigh
            End If

            PV = (highload / (Igs * 0.85) / TextBox7.Text) /
TBcurrent.Text

            PVparallel = PV / PVseries

        End If
        Me.TextBox8.Text = PVparallel.ToString(0)
        Me.TextBox10.Text = Batteryparallel.ToString(0)
        Me.TextBox9.Text = PVseries.ToString(0)
        Me.TextBox11.Text = Batteryseries.ToString(0)
    End Sub
```

```
    Private Sub Solar_Load(ByVal sender As System.Object, ByVal e As
System.EventArgs) Handles MyBase.Load
        'Dim l As Decimal
        'l = 0.5
        'Dim d As Decimal
        ' d = 180 * Math.Acos(l) / Math.PI
        'Me.TextBox8.Text = d



    End Sub

    Private Sub Button2_Click(ByVal sender As System.Object, ByVal e
As System.EventArgs) Handles Butt_clear.Click
        With Me
            .TextBox1.Clear()
            .TextBox2.Clear()
            TextBox3.Clear()
            .TextBox4.Clear()
            .TextBox5.Clear()
            TextBox6.Clear()
            .TextBox7.Clear()
            .TextBox8.Clear()
            .TextBox9.Clear()
            .TextBox10.Clear()
            .TextBox11.Clear()
            .TextBox12.Clear()
            .TBhigh.Clear()
            .TBmedium.Clear()
            .TBlatitude.Clear()
            .TBhigh.Clear()
            .TBcurrent.Clear()
            .TBlow.Clear()
            .TBaltitude.Clear()

        End With

    End Sub

    Private Sub Butt_exit_Click(ByVal sender As System.Object, ByVal
e As System.EventArgs) Handles Butt_exit.Click
        Dim whichbuttondialog As DialogResult
        whichbuttondialog = MessageBox.Show("Are you sure you want
to exit", "Exit", MessageBoxButtons.YesNo, MessageBoxIcon.Question,
MessageBoxDefaultButton.Button1)
        If whichbuttondialog = Windows.Forms.DialogResult.Yes Then
            Me.Close()

        End If
    End Sub

    Private Sub RBuser_CheckedChanged_1(ByVal sender As
System.Object, ByVal e As System.EventArgs) Handles
RBuser.CheckedChanged
        Me.Select()
        TextBox1.Enabled() = True
        TextBox2.Enabled() = True
        TextBox3.Enabled() = True
        TextBox4.Enabled() = True
        TextBox6.Enabled() = True
    End Sub
End Class
```


Solar Cool
Instructions
Key in all the values in rated units (Ah, A, V)
Key in derating factors and discharge depth in decimal fractions
Key in the altitude in Km
Battery rated values are
(6 V, 220 Ah, Unity derating factors, 80% discharge depth)
AC
12V DC
24V DC
Load in Ah
Battery Specification
Rated Values
User Values
Battery Voltage
Single Battery Capacity
Tepmperature Derating Factor
Charging Derating Factor
Discharge Depth
PV Module Specification
Array Current at STC
Array rated Voltage
Derating Factor
Location
Latitude
Altitude
Operation Profile
High Demand Operation Hours
Medium Demand Operation Hours
Low Demand Operation Hours
PV Size
Parallel
Series
PV Arrays
Batteries
Calculate
Clear
Exit

APPENDIX D

ESTIMATED SOLAR RADIATION & PEAK SUN HOURS FOR 6 CITIES

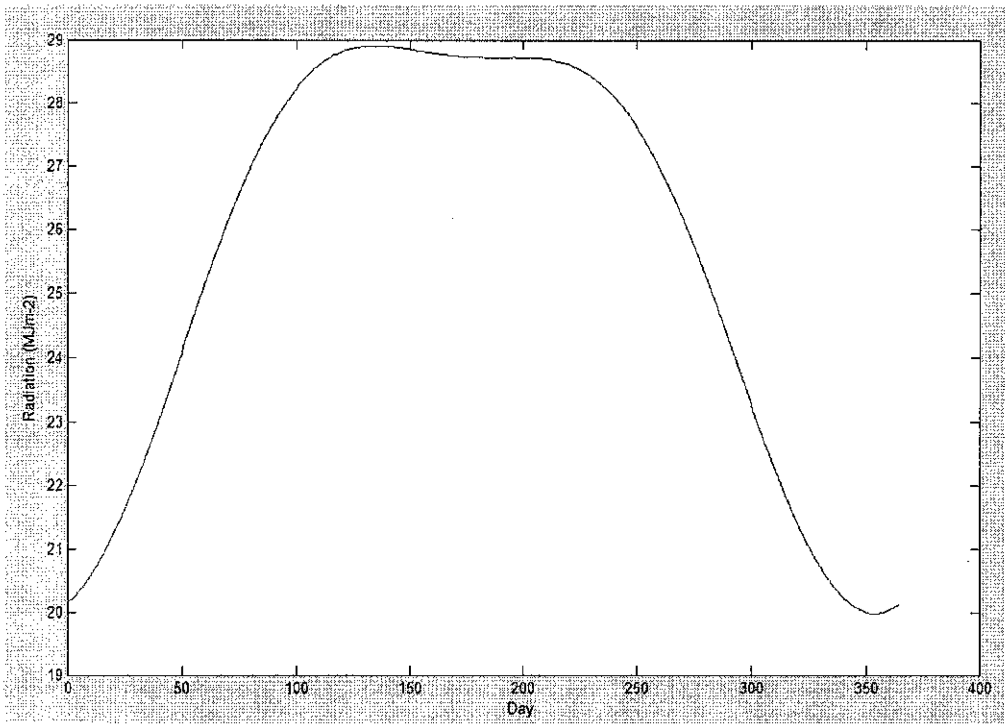
Khartoum

Latitude: **15.6**
Longitude: **32.54**
Altitude: **382**

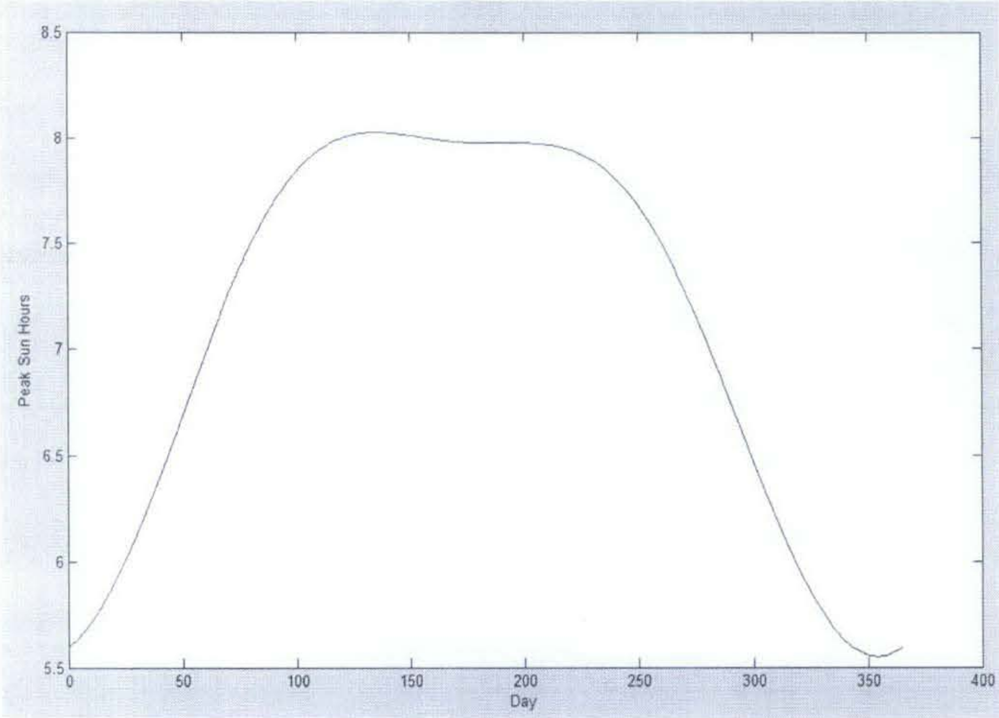
Actual average radiation: 22.82 $MJm^{-2}\ day^{-1}$

Estimated average radiation: 25.63 $MJm^{-2}\ day^{-1}$

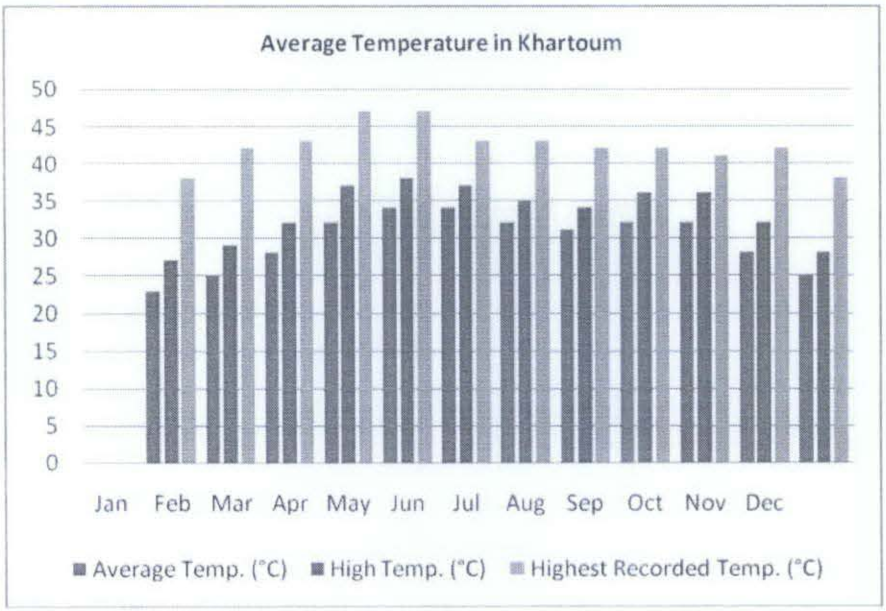
Estimated peak sun hours: 7 hours



Estimated radation for one year



Estimated peak sun hours for one year



Average temperature in Khartoum for one year

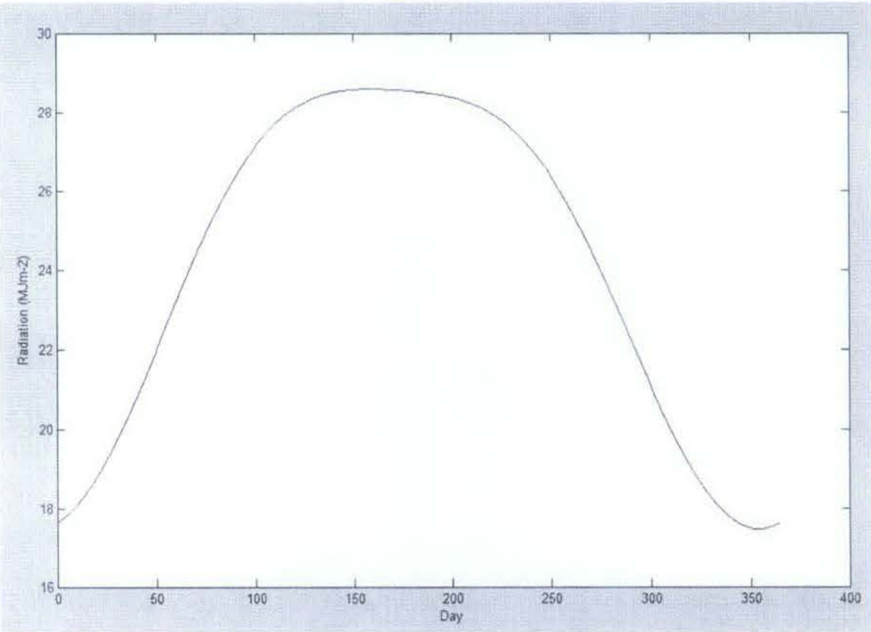
PortSudan

Latitude: **19.58**
Longitude: **37.21**
Altitude: **3**

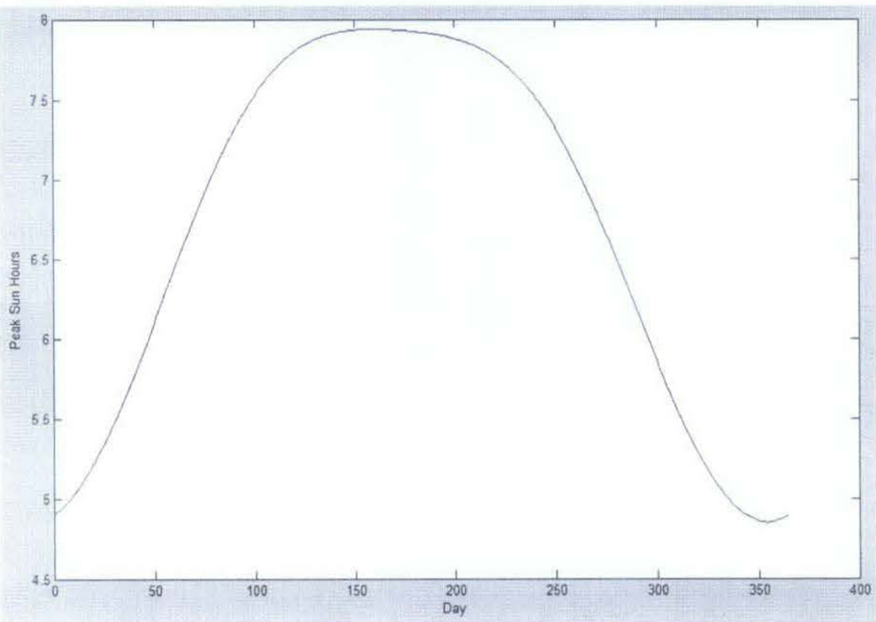
Actual average radiation: 20.87 $MJm^{-2}\ day^{-1}$

Estimated average radiation: 24.18 $MJm^{-2}\ day^{-1}$

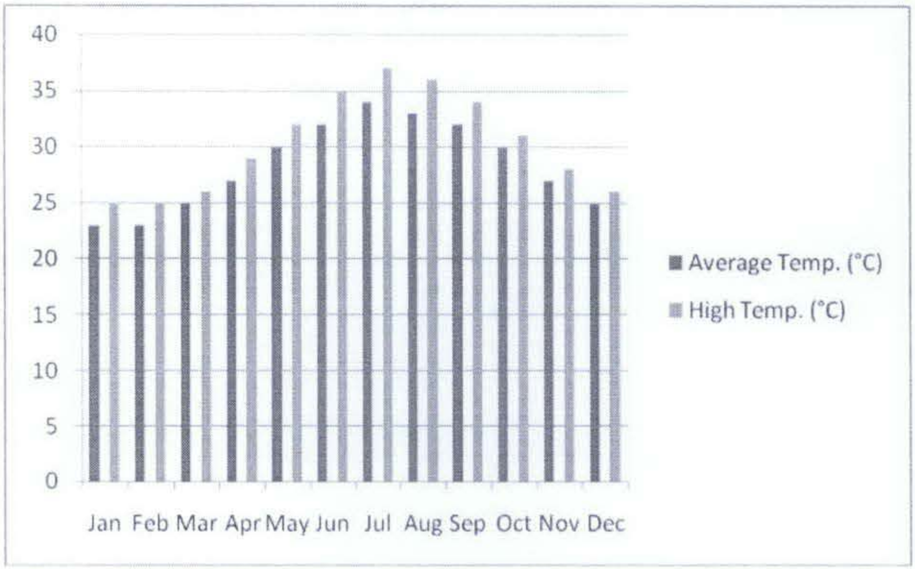
Estimated peak sun hour: 6.7 hours



Estimated radiation for one year



Estimated peak sun hour for one year



Average temperature in Port Sudan for one year

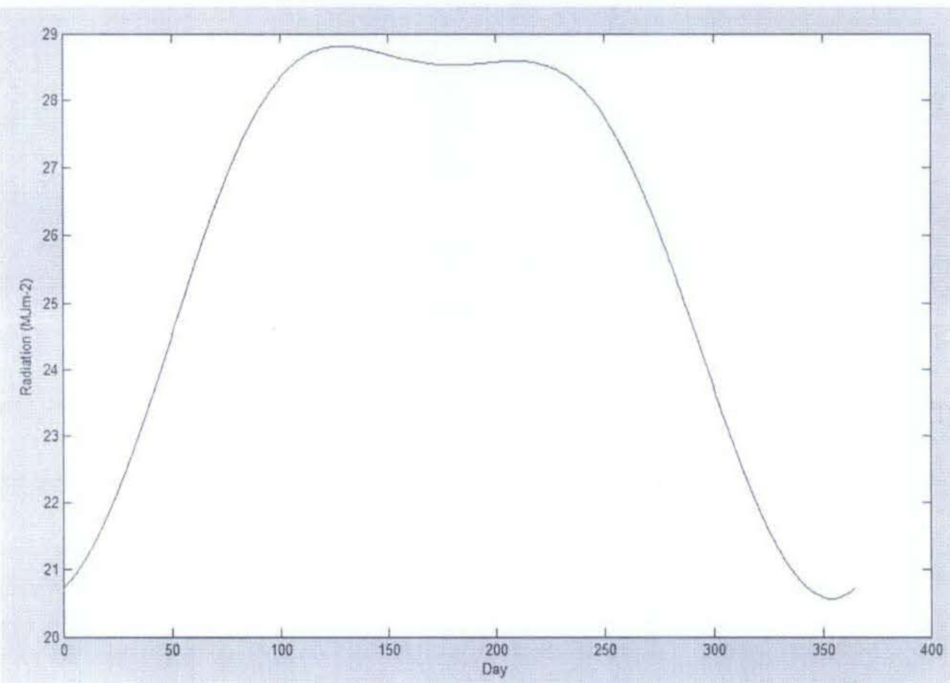
Wad Madani

Latitude: 14.4
Longitude: 33.48
Altitude: 408

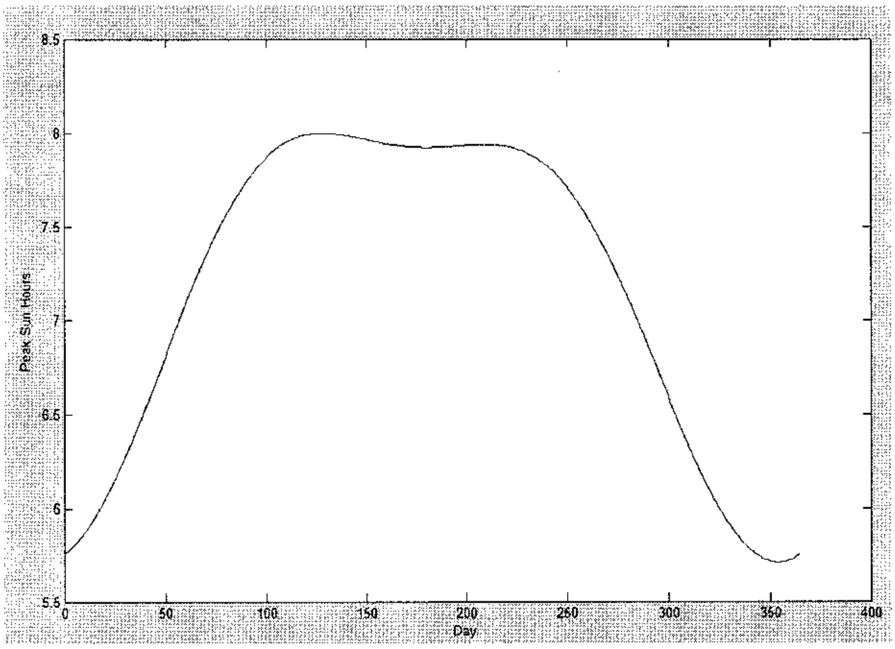
Actual average radiation: 22.86 MJm^{-2} day^{-1}

Estimated average radiation: 25.84 MJm^{-2} day^{-1}

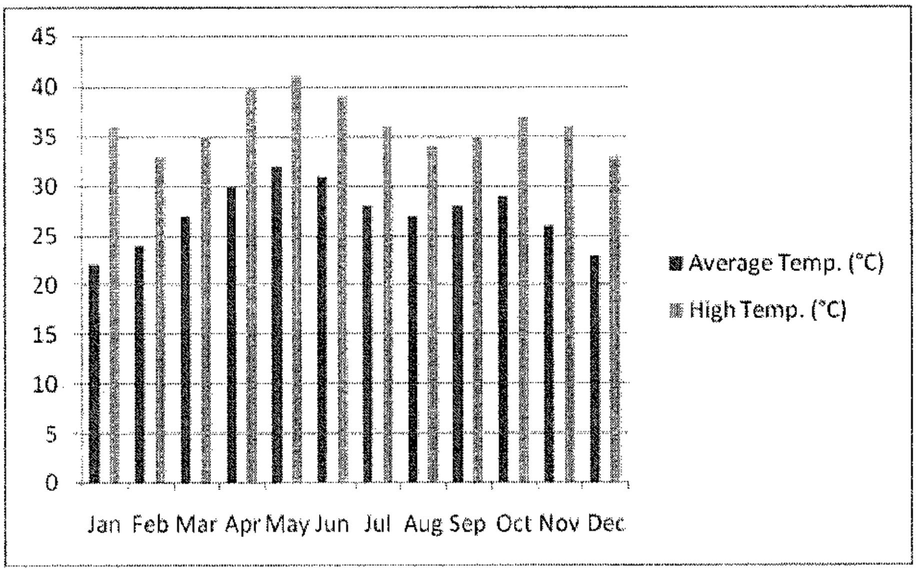
Estimated average peak sun hour: 7.1 hours



Estimated radiation for one year



Estimated peak sun hours for one year



Average Temperature in Wad Madani for one year

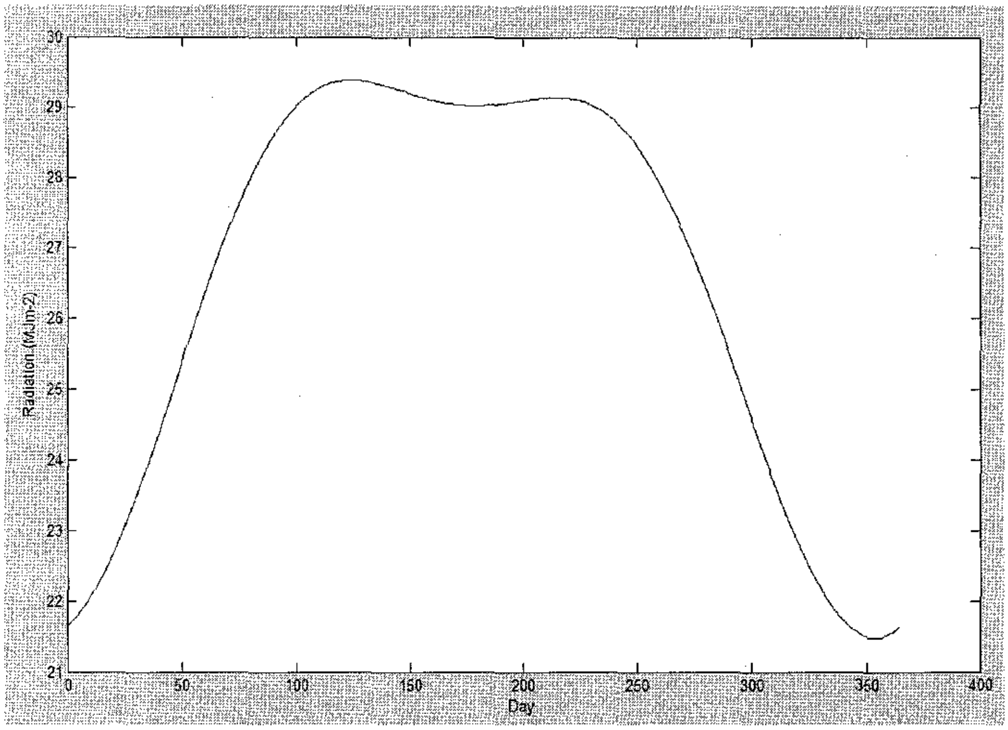
El Fasher

Latitude: **13.61**
Longitude: **25.33**
Altitude: **733**

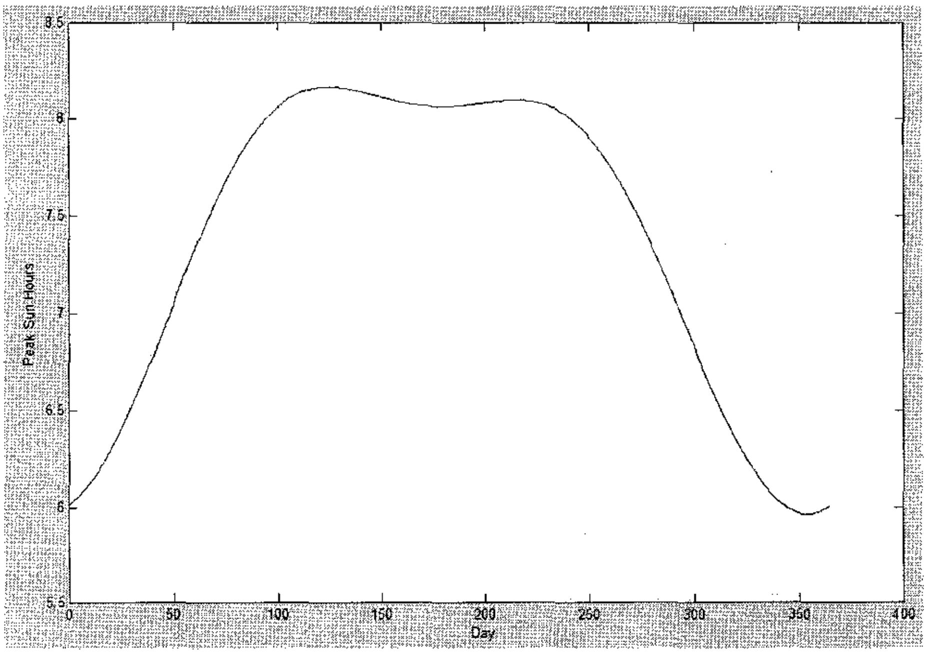
Actual average radiation: 22.8 $MJm^{-2}\ day^{-1}$

Estimated average radiation: 26.56 $MJm^{-2}\ day^{-1}$

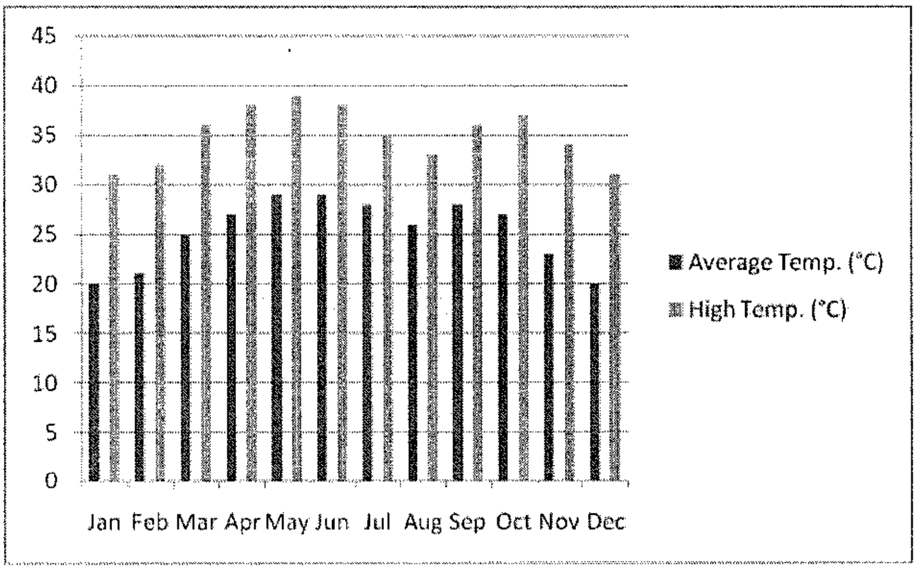
Estimated average peak sun hours: 7.3 hours



Estimated radiation for one year



Estimated peak sun hour for one year



Average temperature in Elfashie for one year

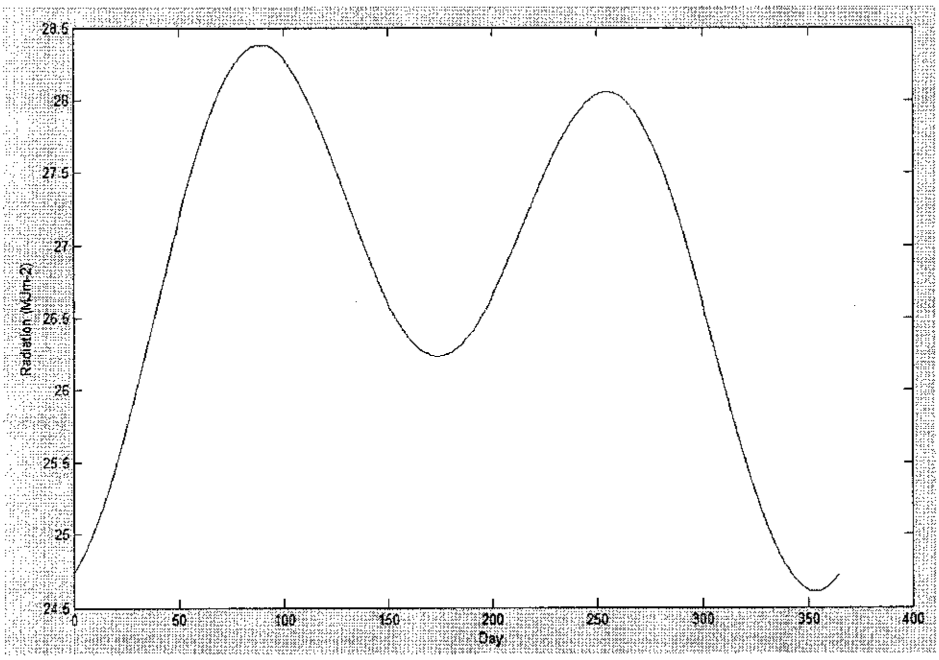
Juba

Latitude: **4.86**
Longitude: **31.6**
Altitude: **460**

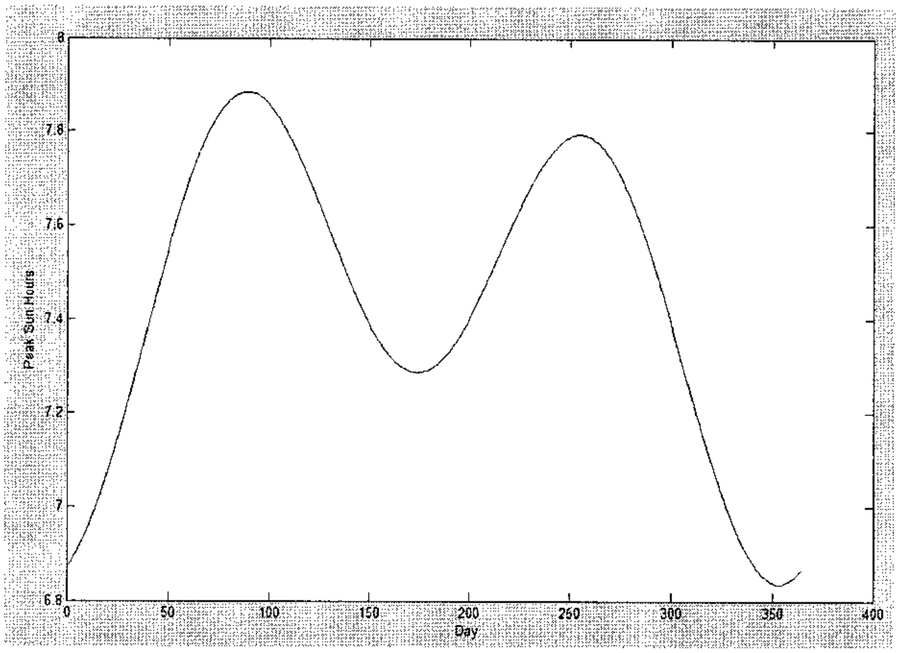
Actual average radiation: 19.59 MJm^{-2} day^{-1}

Estimated average radiation: 26.79 MJm^{-2} day^{-1}

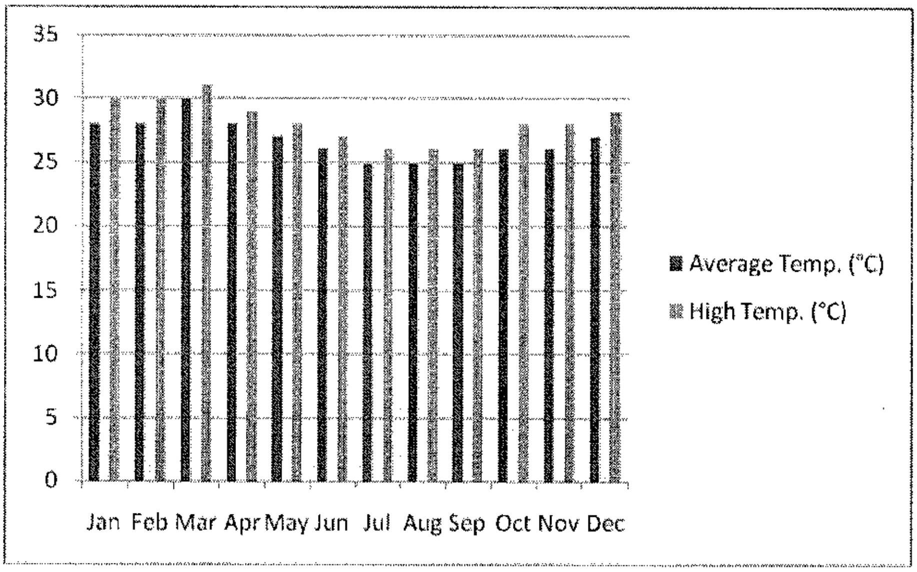
Estimated average peak sun hour: 7.4 hours



Estimated radiation for one year



Estimated peak sun hour for one year



Average temperature in Juba for one year

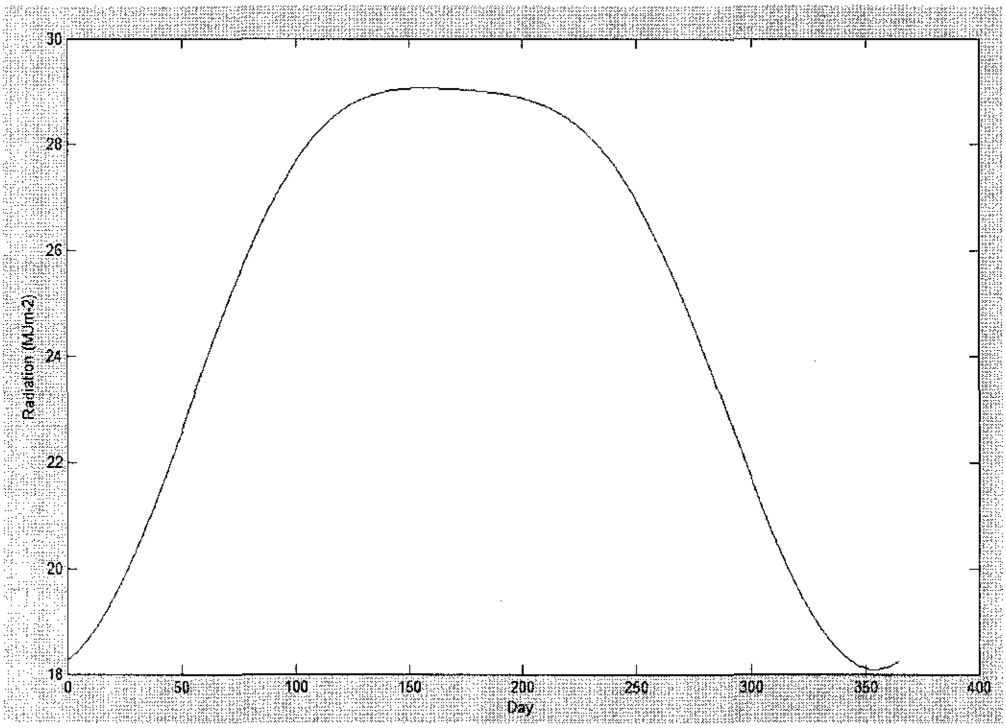
Dongola

Latitude: 19.16
Longitude: 30.48
Altitude: 226

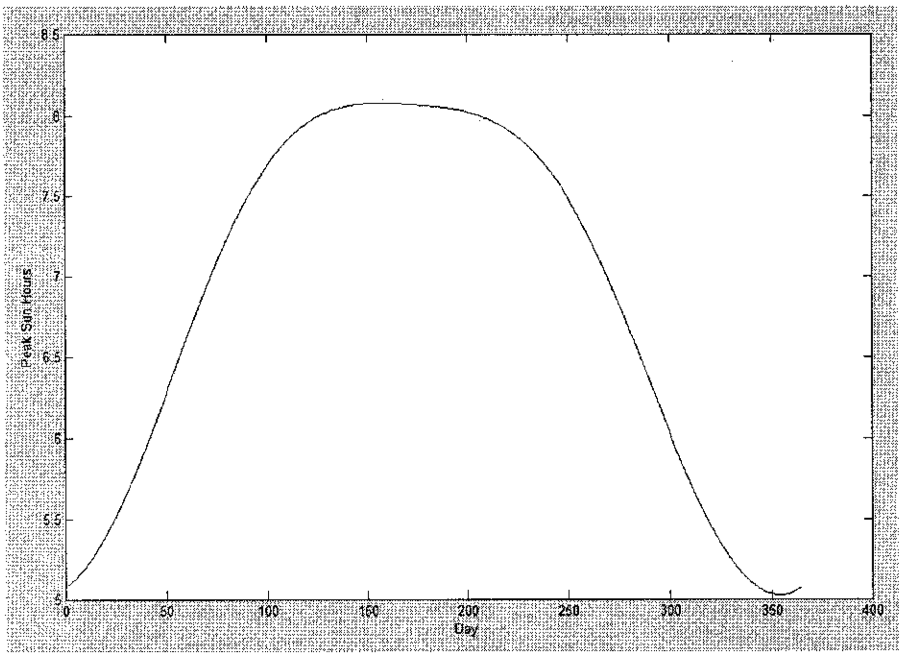
Actual average radiation: 24.06 $MJm^{-2}\ day^{-1}$

Estimated average radiation: 24.75 $MJm^{-2}\ day^{-1}$

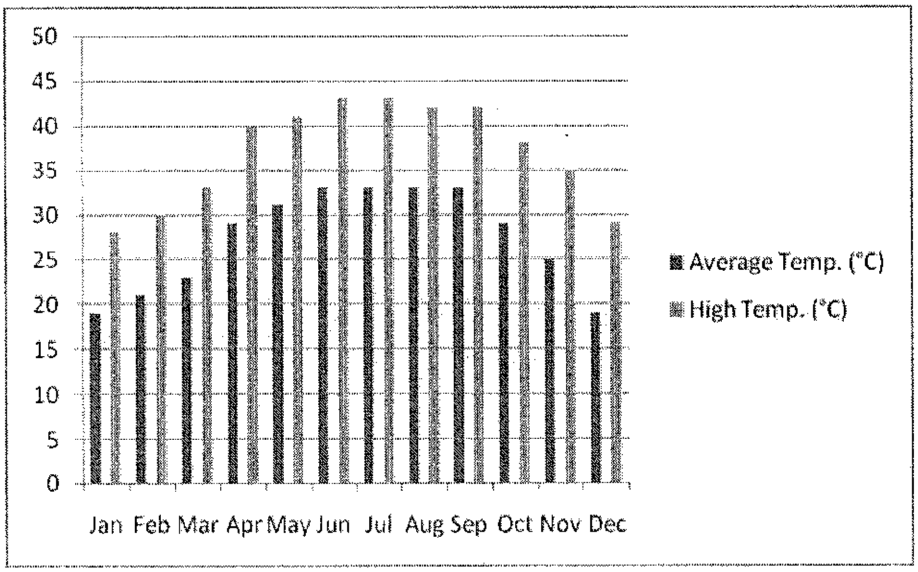
Estimated average peak hour: 6.8 hours



Estimated radiation for one year



Estimated peak sun hour for one year



Average tempearture in Dongola for one year