Modelling and Analysis of Water Cooled Photovoltaics

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Abstract

The project is focused on modelling and analyzing modern photovoltaics. Two types of PV are presented and analyzed: the water cooled PV and the air cooled PV. The former uses water in order to cool the panel while the latter uses air as the coolant. Naturally ventilated panels and water cooled panels can provide higher efficiencies than conventional ones. The aim of the project is to analyze - model both systems and compare them in order to reveal the most promising. Furthermore, by altering various physical parameters of the heat exchanger in the water PV system, the maximum efficiency is aimed. This information can be used in maximizing the efficiency of any collector design. Various important characteristics that a conventional PV can provide, such as the power, are calculated and compared to those of a water cooled PV. Finally another aim of the project is to investigate whether a PV is able to provide energy to a typical house and what is the autonomy of it.

In order to model the water cooled panel an excel spreadsheet was constructed. By using this spreadsheet all the important physical parameters from the heat exchanger as well as from the panel were altered and the results were analyzed. The impact every change had on the effectiveness as well as the normal operation of the system could then be recorded. By the use of the spreadsheet, the maximum efficiency of the panel can be achieved. This information could be very important in designing-constructing collectors. Another method used in the project was the direct comparison of both air cooled and water cooled systems in order to reveal advantages and disadvantages. A real life scenario was created and all the important characteristics of a PV panel were calculated in order to see if such a panel can provide sufficient energy to a house. Finally a quantification analysis was performed in order to see what is the maximum power a PV can provide and compare it with the one from the water cooled panel.

The results of the project showed that the most efficient and promising system is the water cooled photovoltaic. Apart form higher efficiency it can provide extra heat which can be used in the house. Such a system proved to be feasible. Furthermore it was clearly shown that altering various parameters of the system has as a result different efficiencies-output. Finally the real life scenario of a PV installed in a Greek house demonstrated that the whole configuration is feasible and that the energy supplied is sufficient to meet the daily demand of a modern house.

1. Introduction

1.1 Overview

Nowadays, most of the world's energy (80%) is produced from fossil fuels. Massive exploitation is leading to the exhaustion of these resources and imposes a real threat to the environment, apparent mainly through global warming and acidification of the water cycle. The distribution of fossil fuels around the world is equally uneven. Middle East possesses more than half of the known oil reserves. This fact leads to economical instabilities around the world which affect the whole geopolitical system.

The present system as it is cannot be maintained for more than two generations. The impact it has on the environment as well to the humans cannot be disputed. Firstly there is the greenhouse effect. This effect is the capacity of the atmosphere to retain heat. Seen from space, the earth radiates energy at wavelengths characteristic of a body at -18°C. However, the average surface is some 33°C higher, due to the presence of gases that are relatively transparent to solar radiation but opaque to the infrared radiation given off by the earth. These gases effectively trap the heat between the surface and mid atmosphere. Carbon dioxide CO_2 is particularly important in this respect. The burning of fossil fuels, coal in particular inevitably produces atmospheric emissions of CO_2.

It should be said here that a doubling of CO_2 concentration (expected by 2035-2055) will cause an average temperature rise of 3 to 5°C. This equals the rise between the coldest period of the last ice age, 18000 years ago and the presence moment. Such heating is going to have disastrous consequences for humanity. Major parts of polar ice caps will melt and the sea level will increase covering big areas of the earth. Many ecosystems will be destroyed, unable to adapt to the change.

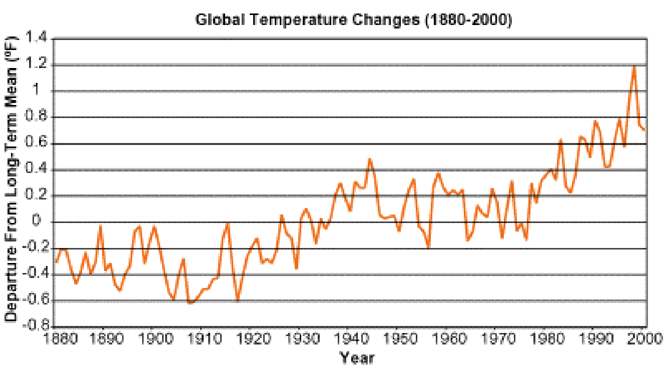

Figure 1. Global temperature changes

Furthermore, the combustion of fossil fuels is responsible of the production of nitric acid and sulfuric acid. These elements are creating the phenomenon called acid rain. It harms plant life and contributes to global pollution. Furthermore, once incorporated in the seawater is very difficult to eliminate. [20]

Moreover, there is a danger arising from the increase of the energy use from the countries of the Third World. It is expected that these countries will try to increase their standard of living which is at the minimum level for decades. This will have as a result the increase of the depletion of the limited stock, creating an even more severe ecological problem. These countries even today, cannot afford the cost of protecting the environment. Consequently they will increase the rate of combustion of oil and coal, will accelerate the deforestation or they will turn to nuclear energy.

Keeping the above in mind as well as the fact that oil is running out fast, alternatives should be adopted. Renewable energy is one of the most promising alternatives to the above problems. Photovoltaic panels in particular can provide a good source of producing *clean* electricity. The photovoltaic effect was first discovered by the physicist Edmund Becquerel in 1839. Despite that, this technology is considered to be a very recent one. The first cell which could be considered as PV was constructed in 1941 with an efficiency of 1%.

Present photovoltaic technology has been well developed since 1941. PV panels are used as the primary electricity source in space missions and satellites. The cost of producing electricity for house applications has dropped dramatically and PV panels are becoming more and more economic viable. New materials have been developed and new technology has created PV panels at efficiencies of 20% in many cases.

One relative new type of PV panel is the hybrid PV panel. This type of panel converts the sun's radiation to electricity while providing heat to the system for other purposes. This can be done by either air or a fluid coolant. The cooling medium apart from conducting heat is cooling the panel making it more efficient. The most widely used fluid is water.

1.2 General about PV

The conversion of solar energy to electrical and thermal energy has been practiced for many years. In order to convert the solar energy to electrical, photovoltaics are used. Photovoltaic modules use the photoelectric effect in order to directly perform the above conversion. This technology has been practiced for many years. The widely used heat collection systems are flat-plate collectors and solar cells for thermal and electrical applications respectively.

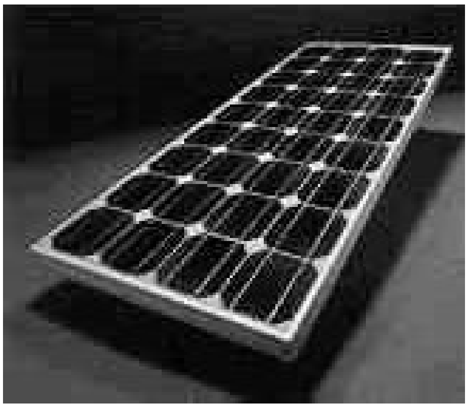

Figure 2. Picture of a PV panel

Photovoltaic panels convert solar radiation to electricity with efficiencies in the range of 5% to 20%, depending on the type of the cell. Polycrystalline silicon solar cells offer the highest range of possibilities for applications. This is a consequence of their modest price relative to the monocrystalline silicon cells, and their considerable stability and efficiency (about 15%). Furthermore, these cells are sold in the form of panels having dark blue appearance which is aesthetically pleasant.

When the temperature of a photovoltaic module is increased, the efficiency drops. This can typically result in an efficiency drop off of 0,5% per °C increase in the cell operating temperature. The operating temperature is increased because a large part of the solar radiation is not converted to electricity but is absorbed by the panel as heat. Natural circulation of air is the easiest and cheapest way to remove this heat from the panel and consequently increase the efficiency.

Another, more efficient way is to use a liquid as the coolant of the panel. This is the general philosophy of hybrid photovoltaic-thermal collectors. In these systems the natural or forced circulation of a heat removing fluid can be used not only for PV cooling, but also for heat generation. This heat can be used to preheat the hot water for applications in the building.

As said before the hybrid PV thermal systems are still under development. Nevertheless, various experiments and publications have been made producing interesting results. Hendrie [1] used both air and liquid as the coolant while Florschuetz [2] has presented an extension of the Hotter-Whiller[1] model to analyze the PV/T collectors by assuming a liner correlation between efficiency of cell and temperature. Single and double air heaters were used by Chandra et al [3] while Agarwal and Garg [4] carried out experiment on air and water-cooled photovoltaic systems.

The IT Power and Newcastle Photovoltaic Application center has recently carried out a study on the PV hybrid system, commissioned by the Joint Research Center at ISPRA. Finally, various other works have been published by Garg and Adhikari [5], Brinkworth and Marshall [11] on model of naturally ventilated PV claddings.

1.3 Aims of the project

As previously stated, naturally ventilated PV panels as well as water-cooled photovoltaics offer higher electrical efficiencies as well as useful heat. The studies above, and others, show the potential of these relative new systems as well as the general interest on the topic.

The current project, will present a model of air-cooled PV panel as well as a water-cooled panel. Then, a comparison between the two systems will reveal the most efficient. A spreadsheet will be presented in order to see how the physical properties of the heat exchanger at the water-cooled PV can change the output of the system as well as the efficiency of it. Various parameters will be tested and compared. All the above will be done in order to optimize the PV component and to provide some useful information for designers.

Furthermore, a quantification analysis will be performed. This analysis will be done in order to see what is the maximum power a PV panel can provide and compare it with the one using water as the coolant.

[1] This model will be discussed in the chapter “Technology review”.

Finally at the end of the project, an example of how a PV system is installed and how it can contribute to the energy demand of a typical Greek house is presented. This part of the thesis is done in order to see if a PV system is able to produce enough electrical energy for a house as well as to calculate various important parameters associated with a real life scenario. The number of batteries used, the area needed by the PV panels as well as collectors tilt and other parameters are investigated. Finally a discussion is performed as to see if the thermal energy produced by a hybrid model can be used inside the house.

2. Technology review

2.1 General theory of PV cells

The conversion of the energy carried by electromagnetic radiation into electrical energy is a physical phenomenon known as the photovoltaic effect. Solar cells are without doubt the most important type of device for carrying out such conversion. When sunlight falls on semiconductor materials (e.g. silicon), the photons making up the sunlight can transmit their energy to the valence electrons.

Silicon is representative of the diamond crystal structure. Each atom is covalently bonded to each of its four nearest neighbors. That is, each silicon atom shares its four valence electronic with the four neighboring atoms, forming four covalent bonds. Silicon has atomic number 14, and the configuration of its 14 electrons is 1s22s22p63s23p2 [6]. The core electrons, 1s2, 2s2 and 2p6, are very tightly bound to the nucleus and, at real-world temperatures, do not contribute to the electrical conductivity. At absolute zero, as N silicon atoms are brought together to form the solid, two distinct energy bands are formed-the lower, "valence" band and the upper, "conduction" band. The valence band has 4N availability energy states and 4N valence electrons and is therefore filled. Conversely, the conduction band is completely empty at absolute zero. Thus the semiconductor is a perfect insulator at absolute zero.

As the temperature of the solid is raised above absolute zero, energy is transferred to the valence electrons, making it statistically probable that a certain number of the electrons will be raised in energy to such an extent that they are free to conduct electrical charge in the conduction band. These electrons are called intrinsic carriers. The amount of energy necessary to bridge the valence and conduction bands is referred to as the forbidden gap or energy gap E.g., which is 1.12 eV at room temperature for silicon.

Each time a photon breaks a bond, an electron becomes free to roam through the lattice. The absent electron leaves behind a vacancy, or hole, that can also move through the lattice as electrons shuffle around it. The movement of the electron and holes in opposite directions generates an electric current in the semiconductor. The current can carry on through an external circuit, allowing the energy absorbed from the light to be dissipated in some useful way. To separate the electrons from the holes and prevent the bonds from reforming, an electrical field is used. It provides a force propelling the electrons and holes in opposite directions. The result is a current in the direction of this field.

The main characteristics that distinguish photovoltaics from other renewables are:

- Direct production of electrical energy, even in very small scale of few Watt or mWatt
- They are easy to use. In certain small applications they can be installed directly from the user
- They can be installed in city centers without offending aesthetically the environment
- They can be combined with other sources of energy (hybrid systems)
- They can be expanded in order to meet higher demands
- Their operation has minimum noise production as well as no emissions
- Their operation life can be large with minimum maintenance
- They require high investment cost

2.2The four main types of silicon photovoltaic cells

The four general types of silicon photovoltaic cells [17] are:

- Single-crystal silicon.
- Polycrystalline silicon (also known as multicrystal silicon).
- Ribbon silicon.
- Amorphous silicon (abbreviated as "aSi," also known as thin film silicon).

Single-crystal silicon

Most photovoltaic cells are single-crystal types. To make them, silicon is purified, melted, and crystallized into ingots. The ingots are sliced into thin wafers to make individual cells. The cells have a uniform color, usually blue or black

Polycrystalline silicon

Polycrystalline cells are manufactured and operate in a similar manner. The difference is that a lower cost silicon is used. This usually results in slightly lower efficiency, but polycrystalline cell manufacturers assert that the cost benefits outweigh the efficiency losses. The surface of polycrystalline cells has a random pattern of crystal borders instead of the solid color of single crystal cells.

Ribbon silicon

Ribbon-type photovoltaic cells are made by growing a ribbon from the molten silicon instead of an ingot. These cells operate the same as single and polycrystalline cells.
The anti-reflective coating used on most ribbon silicon cells gives them a prismatic rainbow appearance.

Amorphous or thin film silicon

The previous three types of silicon used for photovoltaic cells have a distinct crystal structure. Amorphous silicon has no such structure. Amorphous silicon is sometimes abbreviated "aSi" and is also called thin film silicon.

Amorphous silicon units are made by depositing very thin layers of vaporized silicon in a vacuum onto a support of glass, plastic, or metal.

Since they can be made in sizes up to several square yards, they are made up in long rectangular "strip cells." These are connected in series to make up "modules.

2.3 Structure of the solar cell

In conventional solar cells, the electrical field is created at the junction between two regions of crystalline semiconductor having contrasting types of conductivity (Figure 3). If the semiconductor is silicon, one of these regions (the n-type) [6] is doped with phosphorus, which has five valence electrons (one more than silicon). This region (the p-type) is doped with boron, having three valence electrons (one less than silicon). Here the concentration of holes is greater. The large difference in concentrations from one region to the other causes a permanent electric field directed from the n-type region towards the p-type region. This is the field responsible for separating the additional electrons and holes produced when light shines on the cell.

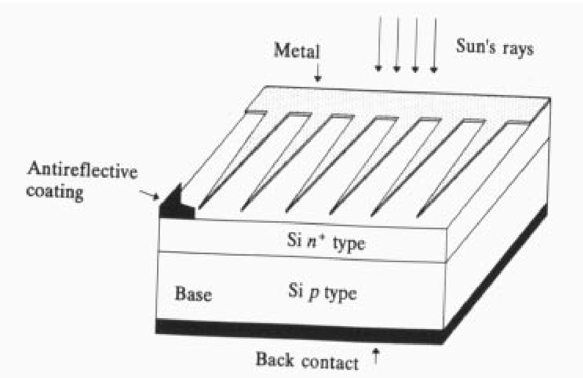

Figure 3: **The p-n junction (from Duffie [6]).**

Nearly all cells currently available have a p-n junction of this type. In silicon cells (the most common type of cell) the junction is obtained by diffusing a layer of phosphorus into a wafer of silicon previously doped with boron. The junction is very shallow, typically only about 0,2 to 0,5 μm deep. This layer is called the emitter. The electrical contact with the illuminated side of the cell (the side where the diffusion occurs) has to leave most of the surface uncovered, otherwise light cannot enter the cell. However, the electrical resistance of the contact must not be too high. Furthermore, the electrical contact on the dark side of the cell covers the whole surface of the cell.

The processes going on inside the cell can be described as follows:

- Photons that reach the interior of the cell and have energy equal to or greater than the band-gap are absorbed in the bulk of the semiconductor, generating electron-hole pairs that can function as carriers of current.

- The electric field, or potential difference, produced by the p-n junction is responsible for separating the carriers before they have a chance to recombine. The result is a potential difference and current in the external circuit including the load.

- The presence of a potential difference produces the phenomena of injection and recombination of electron-hole pairs. In the solar cells these amount to losses. The extent of the losses depends on this potential difference.

Major parts of a PV

1. ***PV panel***

The voltage and the power of PV cells are very small in order to supply a device. For this reason, many cells are combined together in a PV panel with common electrical output.

One of the main features of the panel is the peak power. The peak power is the power from the photovoltaic when the solar irradiance is 1000 W in every square meter, when the temperature is 25 ° C. it is obvious that the power from the panel depends on the area of the panel, the type and its operation temperature. The maximum power is given from the manufacturer.

The operating voltage is another important characteristic of the panel. Most photovoltaics today are constructed in a way that they produce power higher than 12 V in order to charge the 12 V batteries. Apart from the voltage, the operating current is another parameter. It is the current which is determined from the maximum power from the panel and the voltage created, when the irradiance is equal to $1000W/m^2$. For a panel with peak power equal to 40 W and operating voltage 17 V, the operating current would be equal to:

40 W/ 17 V=2,3A
For bigger PV systems, panels with operating voltages equal to 24 V or even 48 V are used.

The short circuits current (Isc) as well as the open circuit voltage (Voc) are other important parameters. The short circuit current is the current from the PV when it is connected with a cable of minimum resistance. The open circuit voltage is the voltage of the PV when it is measured by a cable with infinite resistance. Both of the above are two of the main parameters of the PV cell.

In every curve, represented in the diagram, there is a point where the voltage and the current have such values that the electrical power (P=VxI) has the maximum value. It is obvious that for that particular point, the rectangle that is created has the maximum area of all possible ones created. That point is called point of maximum power and the following formula can be written:

$P_{max}=I_{max}xV_{max}$
where: P_{max} is the maximum power
I_{max} is the maximum current
V_{max} is the maximum voltage

When R (resistance) is equal to zero or infinity, the electrical power is zero, since in the first case the voltage is zero, and in the second the current reaches zero. In intermediate cases, the electrical power is gaining values which are represented in figure below:

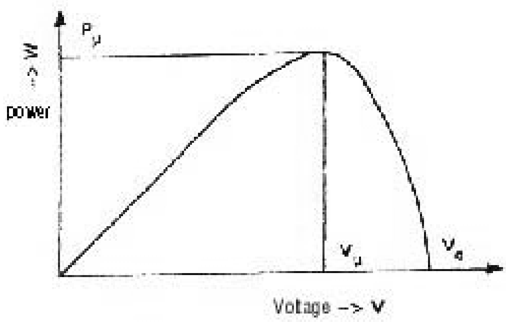

Figure 4: Power as a function of voltage (from T.E.I Han [17])

Therefore for given solar irradiances, the biggest power the PV can provide depends on the appropriate choice of the system's resistance. The above holds for constant irradiance and temperatures.

For different irradiances, a group of transposed curves is created. This represented n the figure below:

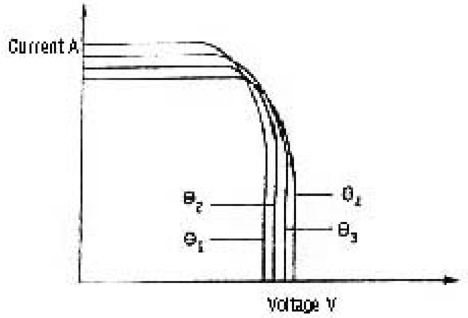

Figure 5: Current vs. voltage (from T.E.I Han [17])

2. ***Voltage regulator or controller***

This device controls the current flux from the PV to the batteries. When the battery is fully charged, the voltage regulator decreases the current not to overcharge the battery. When the battery is overcharged, the operational life is decreased.

3. ***Battery***

The electrical energy is stored to the batteries in order to be provided in intervals with minimum solar irradiance (during nights, cloudy days). Generally the batteries used for PV systems are the same as the ones used in cars. The most common type is the battery with lead electrodes (poles) in a sulphuric acid solution. This type is the most economic viable for PV systems. In cases were there is large temperature variations, alkaline Ni-Cd (nickel-cadmium) batteries are used.

Every battery has various characteristics which should be taken into consideration before connecting it to a PV system:

- Total capacity: it represents the total load, in Ah, stored in the battery
- The battery voltage: it depends on the type of the electrolyte as well as the number of the elements
- The discharge depth: it is the level of discharge that the battery can reach daily, in order to be maintained in good condition and retain the normal operational life.

- The cost per KWh: in order to calculate the total electrical energy that the battery will provide during it's life cycle, the useful capacity C_x , the voltage V and the total number of charge-discharge (N) should be used in the following formula:

$E_{tot}= C_x \, xVxN$

When the cost of the battery is divided with E_{tot}, the cost for every KWh is found. It is obvious that this cost should be kept low.

- Operating temperature: the capacity of the battery is decreasing with decreasing temperatures. Many manufactures provide, among other specifications, the correction curve of the battery. An example is given below:

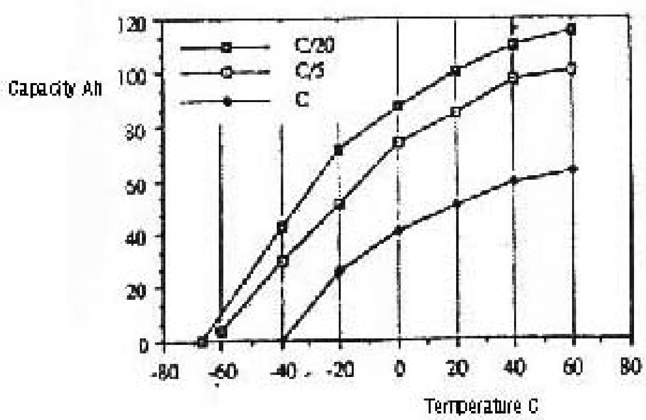

Figure 6: Capacity vs. temperature (from T.E.I Han [17])

From the figure above, it can be seen that for discharge rate of C/5, and minimum temperature 0 °C, the corrected capacity is 73 Ah. Rate of discharge of C/5 means that the battery can provide 20 A and has capacity of 100 Ah.

- Operational life of the battery: the operational life of the battery depends on many factors such as the rate of charging and discharging, the number of charges, and the extreme operating temperatures. In a PV system, a common lead battery has an operational life no more than 5-6 years. On the other hand, nickel-cadmium batteries last longer when they are operating in similar conditions.

4.Load

The term load indicates the total number of electrical appliances that they will be operated with the electrical energy provided by the PV. For a PV system to be well designed, the electrical energy that these appliances consume in a time interval of one month, should be equal or less to the energy produced by the system in the same time interval. For every electrical appliance, various parameters should be known before connecting them the PV system:

- The type of the operational current: It could be either direct or alternate. In the second case, the frequency should de known as well.
- The value of the operational voltage
- The power dissipated during its operation.

The PV systems and the battery, provide direct current. In order to minimize losses from the conversion from D.C. to A.C., appliances which operate with D.C. would be preferable. Nevertheless, due to the use of the A.C. from the power stations most of the appliances work in that type of current.

4.Inverter

This device converts D.C to A.C. in order for many devices to operate. One type of an inverter is the centrifigular one. At this type, the D.C. current rotates a motor which provide power to a A.C. generator. This type of inverter is rare today, since there are types with no moving parts. The efficiency of the later is higher and their maintenance small.

Depending on the type of the photovoltaic, there is the appropriate inverter. A stand-alone PV is connected to a converter which operates with the electrical energy from the PV and converts

D.C. to A.C. In the case where the PV is connected to the grid a converter is connected which operates with the energy from the grid and again transforms D.C. to A.C.

The table below represents the various costs associated to a complete PV system.

COST FACTOR	CONTRIBUTION TO THE TOTAL COST
PV panels	**65%**
PV panel support and cabling of the PV elements	**5%**
Batteries	**15%**
Voltage, power controllers arrangement and protection control	**12%**
Auxiliary generator	**3%**

Table 1. Example of various costs of a stand-alone PV system

As said before, the main parameters which characterize the photovoltaic cell are: the open circuit voltage (Voc), the short circuit current (Isc), the voltage at maximum power point (Vmax) and the current at maximum power point (Imax). Furthermore, another important parameter is the Fill Factor (FF) which is also a measure of the quality of the silicon cells conversion ability. All the above are described below:

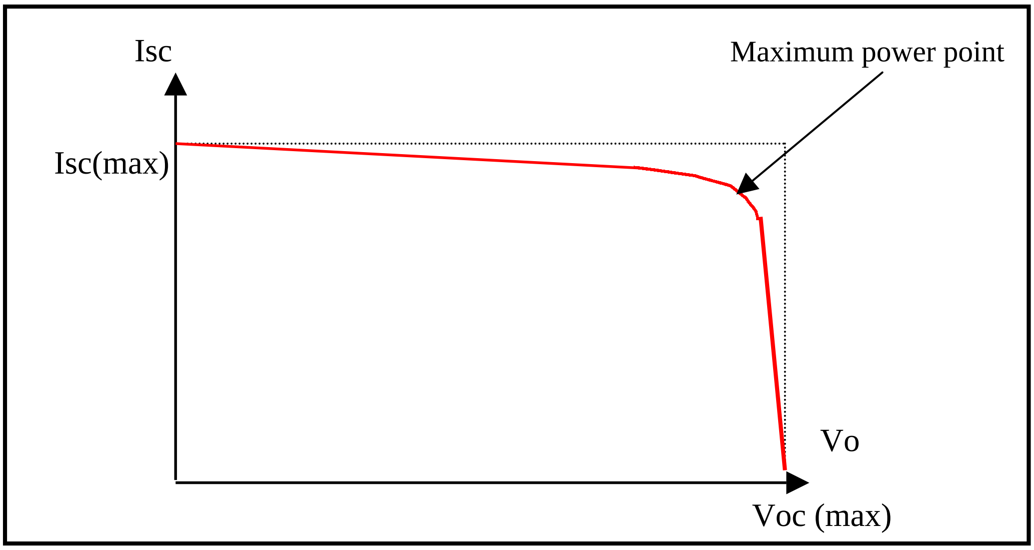

Figure 7: Characteristics of a PV module

The Fill Factor [7] is an important parameter and can be described as follows:

$$FF = \frac{V\max * \mathrm{Im}ax}{Voc * Isc}$$

The Fill Factor varies little among devices and takes values in the range of 0,7 to 0,8 for many crystalline semiconductor cells (Si, GaAs, InP).

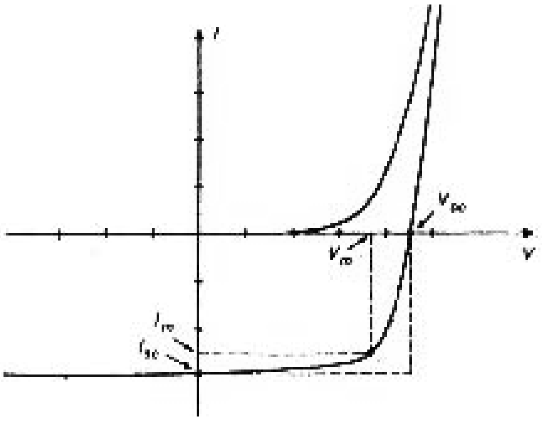

Figure 8: Fill Factor (from T.E.I Han [17])

The energy-conversion efficiency of a solar cell is defined as the ratio between the maximum electrical power that can be delivered to the load and the power input. Therefore:

$$\eta = \frac{V_M * I_M}{P_{input}} = \frac{FF * V_{OC} * I_{SC}}{P_{input}}$$

This efficiency and the maximum power output are obtained only if the resistance of the load has the right value of V_M/I_M.

The power absorbed by the collector is given by:

$$Q_p = GA\tau_c\alpha_p$$

where:

Qp= absorbed power (W)

G= total irradiance (W/m^2)

A= area of solar collector (m^2)

τ_c= transmission factor of cover

α_p= absorptance factor of collector plate

The power loss from the collector is given by:

$$Q_L = UA(T_c - T_a)$$

where:

Q_L= power loss from the collector (W)

U= collector U value (W/m^2K)

T_c= temperature of collector plate (K)

T_a= ambient air temperature (K)

The useful power supplied by a solar collector (Qs) can be derived from the above equations which forms the basis of the ***Hotter-Whiller*** equation:

$$Q_s = Q_p - Q_L$$

$$Q_s = GA\tau_c\alpha_p - [UA(T_c - T_a)]$$

In the case of the PV module the above equation becomes:

$$Q_s = GA\tau_c\alpha_p - [UA(T_c - T_a)] - GA\varepsilon_E$$

where:

ε_E: efficiency of electrical conversion

The factors affecting the performance as well as the Fill Factor are:

- Cell operating temperatures
- Atmospheric conditions
- Band gap of semiconductor

- Solar intensity
- Cell materials

The cell operating temperature and the cell conversion efficiency has an inverse linear relationship. As the cell temperature increases, the efficiency decreases. This can typically result in an efficiency drop of 0,5% per °C increase in cell operating temperature. As the cell heats up, its bandgap decreases, allowing more electrons to jump into the conduction band. This provides a small increase in Isc. However, the increased temperature also means increased kinetic energy on a molecular level. The influence of the electric field at the p-n junction is reduced for the faster-moving electrons, allowing them to recombine more easily with holes. This reduces Voc considerably.

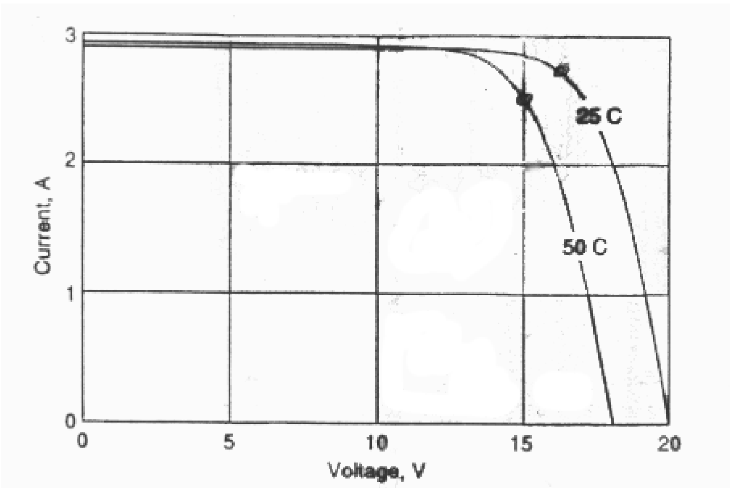

Figure 9: **Current as a function of voltage for various temperatures (from Tripanagnostopoulos [9])**

As the Voc decreases over the increase of Isc, a rise in the cell temperature decreases the power of the PV panel. This is illustrated above.

As mentioned before, the atmospheric conditions affect the FF as well as the efficiency. This refers to the condition of the environment where the PV is used. Dust on the panel as well pollution from cars affect the cell performance of the module.

The bandgap of the semiconductor affects the FF and efficiency. Band gap is the energy difference between the valence and conduction bands in a semiconductor. Each band gap responds best to a particular spectral distribution, so the cell cover is manufactured to ensure that the favored light reaches the cell.

The solar intensity is another very important parameter. The intensity varies with different locations around the earth. Normally, the PV panel will operate more efficient with higher solar intensities.

Finally another important parameter is the material used. Single-crystal silicon has been the material of choice for high-performance, highly reliable solar cells since the successful deployment of silicon photovoltaic systems for space power. Most of the terrestrial photovoltaic power systems sold today are also crystalline silicon. The need to lower the cost of terrestrial photovoltaic power has focused research efforts on alternative materials as well as on less expensive means of producing solar-grade silicon.

Crystalline silicon is made by growing large cylindrical single crystals, called boules. The boules are sliced into thin wafers, from which photovoltaic devices are made. Slicing is an expensive and material-wasteful process. Several approaches have been investigated to minimize the cost of the original silicon material and to eliminate the slicing step.

A less expensive material, polycrystalline silicon, bypasses the expensive and energy-intensive crystal growth process. The molten silicon is instead cast directly into either cylindrical or rectangular ingots. The polycrystalline material has a large number of crystallites separated by grain boundaries [19]. The material has poorer crystalline quality, and light-induced electron-hole pairs can recombine at the grain boundaries without producing current in the external circuit. Although polycrystalline materials result in less efficient solar cells than crystalline silicon, they are sufficiently cheaper that they are commercially viable. The cast material must still be sliced, however, leading to a loss of about half of the material. Improvements in sawing techniques such as multiple-wire saws continue to reduce the loss in producing thinner wafers.

The lowest-cost approach would be to minimize the required amount of semiconductor material. Thin films have been developed that are only a few micrometers thick. Such films are produced by a number of vapor-deposition approaches carried out with in-line, highly automated systems. The techniques are adaptable to a number of semiconductor materials that are optimized for solar cell operation. It has been shown that silicon, with its bandgap of 1.12 eV, I s not optimal. Materials with bandgaps nearer to 1.5 eV, such as GaAs and CdTe, have higher theoretical efficiencies. Thin films are cheaper than crystalline structures but typically have lower efficiencies. Ultimately, however, thin films will be necessary for producing low-cost electricity, because the bottom line-the cost per watt-is more important than efficiency.

2.4 Panel position

The position of the photovoltaic panel is very important to its effective function. In order for the PV to produce the maximum amount of energy, it should intercept the highest possible flux. This occurs when the panel is perpendicular to the sun's incoming rays.

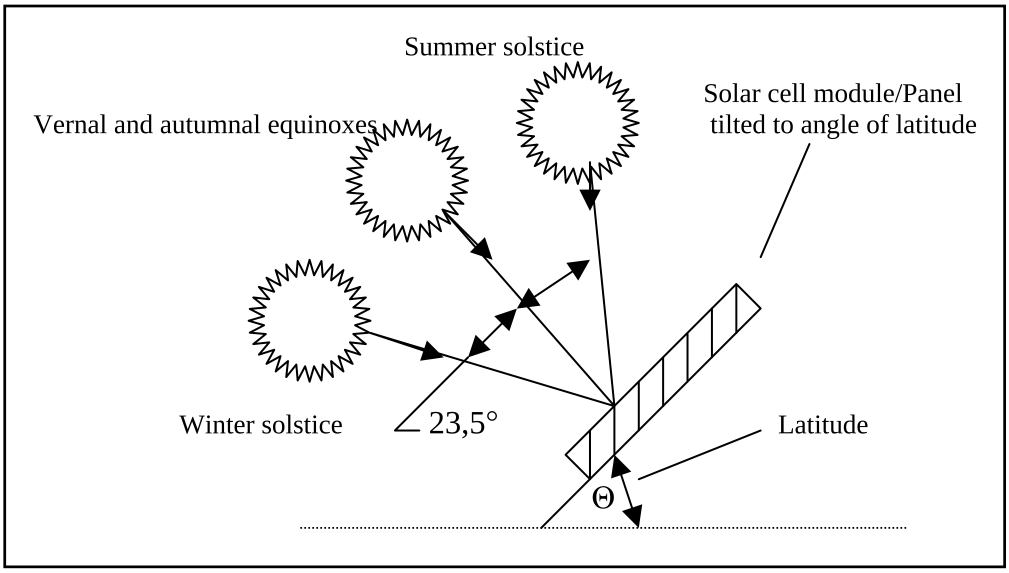

Figure 10: Sun's position at local noon on a fixed south-facing surface at various times of year

The above figure shows the position of the sun at solar noon relative to a PV panel oriented to the South and tilted at the latitude angle. The maximum variation of the sun's angle in this case is ± 23,5°. The reason many designers select the latitude angle is to get the most energy for the whole year from the fixed flat-plate arrays. As indicated by Figure 2.4, the average position of the sun angle relative to the plane of the panel occurs at the two equinoxes. The optimum tilt angle is site-dependent and calculation of this angle requires a solar irradiance prediction computer programme. There is a common agreement that for the higher latitudes the optimum tilt angle is usually 10 to 15° lower than the latitude angle. [21] Hence, a general rule of thumb for the tilt angle of PV panels is to choose an angle which is zero to 15° lower than the site latitude angle.

2.5 Heat transfer

Photovoltaic panels absorb energy and convert it to electricity. Not all this energy is converted to electricity since the panels are not 100% efficient. Most of this energy is converted to heat. This heat can be transferred away by conduction, convection and radiation.

2.5.1 Conduction

Conduction [8] is the transfer of heat from one part of a substance to another part of the same substance, or form one substance to another in physical contact with it. In the case of the PV panel, energy is absorbed by the silicon cell and heat is conducted to the back and front of the panel via the intervening layers. Fourier's law **for steady state**, one-dimensional applications states that:

$$Q = -\lambda A \frac{dt}{dx}$$

where:

Q is the heat flow

λ is the thermal conductivity of the material
A the area of the section at right angles
dt/dx the change of temperature with respect to the length of the path of the heat flow.

For a single plane slab of thickness L, the equation becomes:

$$Q = -\lambda A \frac{(T_2 - T_1)}{L}$$

and for a composite slab consisting of two materials is:

$$Q = A \frac{(T_2 - T_1)}{\frac{L_1}{K_1} + \frac{L_2}{K_2}}$$

This is the equation used in the case of the PV panels. Furthermore, after the heat has reached the surface, it is transferred to the surroundings by a mixture of convection and radiation.

2.5.2 Convection

Convection is the transfer of heat within a fluid by mixing of one portion of the fluid with another. The movement of the fluid may be caused by differences in density resulting from the temperature differences as in natural convection (or free convection), or the motion can be produced by mechanical means as in forced convection.

Convective heat transfer is described using correlations between certain dimensionless parameters. Such parameters are the Nusselt, Reynolds and Prandtl numbers. These parameters are used in order to determine the value of h for each case:

$$Q = hA(T_s - T_f)$$

Newton's Law of cooling is then used in order to calculate the convective heat transfer.

2.5.3 Radiation

Radiation is the means of heat transfer between distant surfaces. Energy is carried by electromagnetic waves.

The equation below is used in this case:

$$Q = \frac{\sigma A(T_1^4 + T_2^4)}{(\varepsilon_1)^{-1} + (\varepsilon_2)^{-1} - 1}$$

where σ is the Stefan-Boltzman constant

A the area of the surface
$T_{1,2}$ are the surface temperatures
$\varepsilon_{1,2}$ are the surface emissivities

2.6 The stack effect

An important part of the theory of the photovoltaic panels is the phenomenon called stack effect. This phenomenon causes the air to be driven up the duct by the buoyancy of the warmth of the inside air relative to that outside. It is a very important parameter in determining the efficiency of a naturally ventilated system.

The pressure difference Ps is given by:

$$P_s = \frac{gP_a}{R_a}[(T_c)^{-1} - (T_h)^{-1}](h_2 - h_1)$$

where: Pa is the atmospheric pressure

Ra is the air constant

$T_{h,c}$ are the temperatures at heights $h_{2,1}$

g the acceleration due to gravity

in a stack effect the flow rate of the air is determined by that pressure difference. By looking at the equation, if the temperature or the height is increased, the flow rate will be increased. This flow rate is determined by the general equation:

$$Q_a = c(P_s)^n \qquad \text{where c, n constants}$$

2.7 Cooling medium

The cooling fluid passing through the tubes of the heat exchanger should have the properties below:

- high thermal transmittance for a given speed of the fluid and for given tube diameters
- high heat capacity in order not to provide increased flow
- small viscosity in order to provide small amounts of energy for it's transport
- it should not be oxidised in order to avoid rustiness inside the tubes
- non toxic
- non erosive-corrosive
- it's steam pressure should be as low as possible in order to use in lower pressures
- inexpensive

Water

The thermo physical properties of water establish it as a good cooling medium. The coefficient of thermal transmittance between metal and fluid is very good and can be improved under boiling. Nevertheless, its use under liquid form in high temperatures involves higher pressures. For this reason it cannot be used in temperatures higher than 320 ° C (150 bar) [16]. Another disadvantage is that it provides oxidation. Finally, in freezing point, it can produce damages to the system.

Oils

There are various types of oils, synthetic or mineral, that can be used as cooling mediums. These products can cover a wide area of temperatures, even more than 400 ° C. Their thermal capacity is not as good as the capacity of water, but they can be used under low-pressure conditions. Their viscosity is a function of temperature and for this reason liquids which are used in high temperatures, cannot be circulated in low temperatures. Due to the fact that they are flammable, they should not come in contact with air.

Special liquids

The use of mixture of salts is done in higher temperatures (500° C-600° C) because below the melting point (140° C) for the mixture NO_3K, NO_2Na, NO_3Na (53%, 40%, 7 %) the mixture is solidifying. Mercury can also be used in the temperature range between 360 and 540 ° C but it is toxic and very expensive.

Gases

They can be used in very high temperatures between 500° C-1000° C for air under pressure. A major disadvantage is that they have small heat capacities and the energy needed for their circulation is high. Therefore it is needed a special design for the whole configuration.

As mentioned before at the introduction of the project, two ways of cooling the photovoltaic module will be presented and discussed. The first one is a steady state simulation of a PV/T air heating collector and the second one is a water cooled PV/T. Various results will be explained and the main similarities and differences discussed. Finally, by comparison of the results, the most efficient way of cooling the panels will be presented. This comparison is obtained from the literature review.

Between the two systems discussed above, the project is more concentrated on the water cooled PV which is the main topic of discussion-analysis. This system provides a wide area of analysis and simulation. It can be combined in such a way in order to provide extra heat to a house as well as electricity. It can work on higher efficiencies and can operate as a hybrid system. Furthermore, the analysis is done in order to see the feasibility of such a system and what factors affect its efficiency and operation. The above reasons justify the option selected.

Apart from the actual developed systems discussed above, the general theory behind them will be discussed for a better understanding of the systems.

2.8 Air cooled photovoltaic panel

One way of cooling the photovoltaic unit is by using air. Of course in this particular case air is used to absorb the heat from the unit and consequently to cool it. The heat absorbed by the air can be used for providing warm air inside the building.

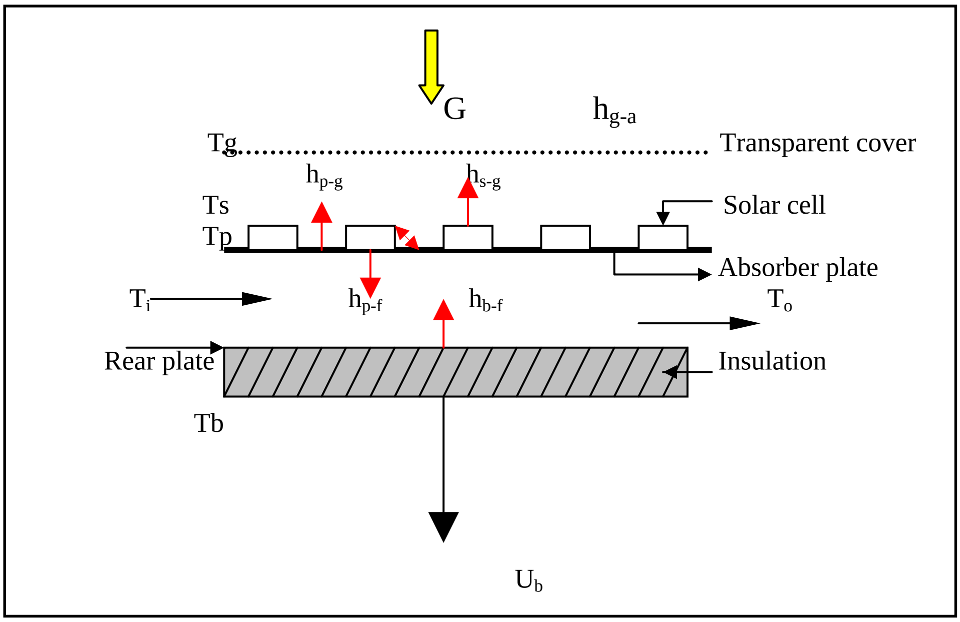

Figure 11: Schematic configuration of a conventional PV/T air heating collector along with the associated energy transfer mechanism

The above figure shows the PV configuration along with associated flows for a PV/T air heating system. This PV system includes the transparent cover, a metallic black absorbing surface and a well-insulated rear plate. The latter has a gap between the absorber so air is able to pass through. In the actual model, the solar cells are pasted 1 m wide on the absorber plate at equal distances along the surface.

There are various assumptions taken into consideration:

- Steady-state energy transfer
- Temperatures of various components vary along the direction of the flow only
- The heat capacity of the transparent is neglected (very small)
- There is no leakage of air from the system
- Side losses are negligible

Theory

(The nomenclature for the theory below can be found in Appendix 1)

In order to calculate the heat removed as well as the coefficients we must introduce the following formulae:

for the transparent cover:

$$a_1 G + h_{p-g}(T_p - T_g) + h_{s-g}(T_s - T_g) = h_{g-a}(T_g - T_a) \qquad \text{(a)}$$

for solar cell:

$$a_2 G = h_{s-p}(T_s - T_g) + h_{s-g}(T_s - T_g) + E(T_s) \qquad \text{(b)}$$

where

$$E(T_s) = (1 - a_1) a_s \eta_s A_R G$$

for the absorber plate:

$$a_3 G + h_{s-p}(T_s - T_p) = h_{p-g}(T_p - T_g) + h_{p-b}(T_p - T_b) + h_{p-f}(T_p - T_f) \qquad \text{(c)}$$

for rear plate:

$$h_{p-b}(T_p - T_b) = h_{b-f}(T_b - T_f) + U_b(T_b - T_a)$$

(d)

and for working fluid (which is air):

$$\left(\frac{\dot{m}C_f}{B}\right)\frac{dT_f}{dx} = h_{p-f}(T_p - T_f) + h_{b-f}(T_b - T_a)$$

(e)

The fraction of energy absorbed by different components of the system is defined as:

$$a_1 = (1 - R_g)a_g$$
$$a_2 = (1 - R_g)(1 - a_g)a_s$$
$$a_3 = (1 - R_g)(1 - a_g)(1 - a_s)(1 - A_R)a_p$$

where A_R is the ratio of collector area to the area covered by solar cells.

Solving equations (a)-(d) for the temperature of the transparent cover, solar cell, absorber plate and rear plate and substituting these values into equation (e), the following linear differential equation is obtained:

$$\frac{dT_f(x)}{dx} + pT_f(x) = q$$

At this point we have to solve the above for the fluid (air) temperature. In order to do that we will use the initial boundary condition:

$$T_f(x) = T_i \quad at\, x = 0$$

we can obtain:

$$T_f(x) = \frac{q}{p} + (T_i - \frac{q}{p})e^{-px}$$

The fluid temperature can be averaged over collector length and can be calculate as:

$$\bar{T}_f = 1/L \int T_f(x)dx$$

substituting we have:

$$\bar{T}_f = 1/L \int \quad T_f(x) = \frac{q}{p} + (T_i - \frac{q}{p})e^{-px}$$

Solving the above integral:

$$\bar{T} = \frac{q}{p} + \frac{1}{pL}(T_i - \frac{q}{p})(1 - e^{-pl})$$

Now, applying the boundary condition

$$T_f(x) = T_0 \quad at \quad x = L$$

we can calculate the outlet temperature as follows :

$$T_0 = \frac{q}{p} + (T_i - \frac{q}{p})e^{-pl}$$

Various performance parameters

The thermal efficiency can be calculated by:

$$n_t = \frac{\dot{m}C_f(T_o - T_i)}{G}$$

while the solar cell efficiency:

$$n_s = n_f[1 - \beta_r(T_s - T_r)]$$

where

$$\beta_r = (T_s^* - T_r)$$

The electrical efficiency:

$$n_e = n_s A_R(1 - R_{g1})(1 - R_{g2})(1 - a_{g1})(1 - a_{g2})$$

and the system efficiency:

$$n_T = n_t + n_e$$

A simulation model

The above is the general theory used in order to perform various calculations for a simulation model. The model below discussed is done by Garg and Adhikari [5].

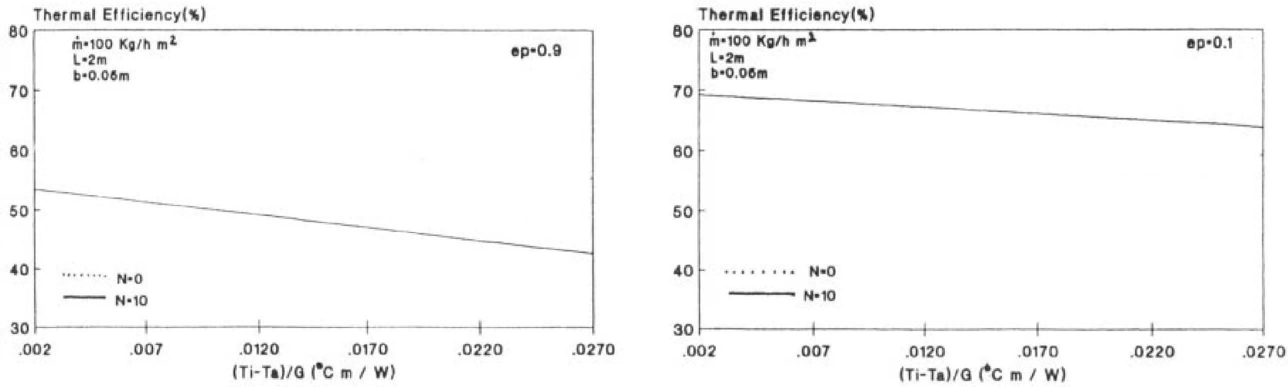

Figure 12: Testing curves of PV/T air heating collectors (from Garg [9])

Figure 12 represents the thermal efficiencies curves for fixed duct depth, collector length, mass flow rate and different solar densities 0 and 10 *10m^2, corresponding to the absorber with and without selective coating. The two different values of the solar density represent the absorber without solar cells (conventional air heater) and the absorber fully covered with solar cells respectively. As it can be seen from the figure, the thermal efficiency of the system is higher when the absorber is not fully covered with solar cells.

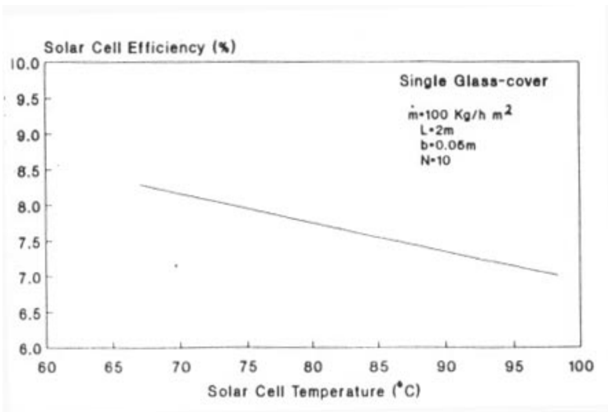

Figure 13: Solar cell efficiency (from Garg [9])

As it can be seen from the figure above, the solar cell efficiency calculated and plotted, decreases as the temperature of the panel increases. Keeping in mind the theory presented in the previous chapters, this phenomenon was expected.

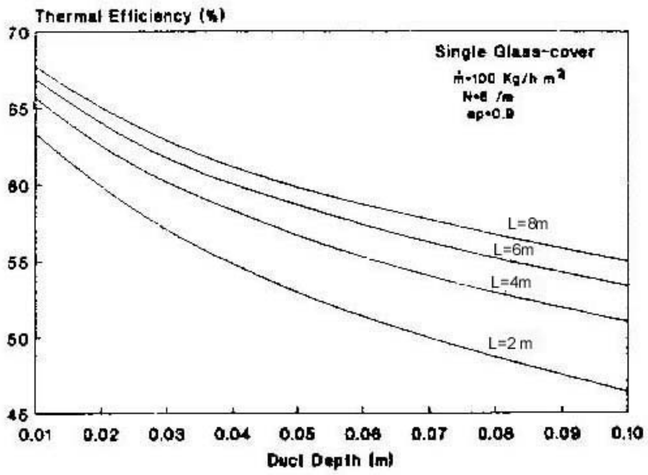

Figure 14: Thermal efficiency as a function of duct depth (from Garg [9])

The above figure represents how the thermal efficiency of the system changes with the increase in duct depth. The depth was varied from 0,01 m to 0,1 m. Apart from the duct depth, the length was also varied. The maximum efficiency was 67,5 % for duct depth equal to 0,01 m and length of 8m. The minimum efficiency was 57% for duct depth equal to 0,1 m and length 2m. Therefore the thermal efficiency of the system drops with increasing duct depth. Nevertheless when the length is decreased the efficiency is also decreased. These characteristics can be attributed to the decreasing absorber to air heat transfer coefficients. Therefore the system efficiency, which is a sum of thermal and electrical efficiencies, also decreases with increase in duct depth and decrease in collector length.

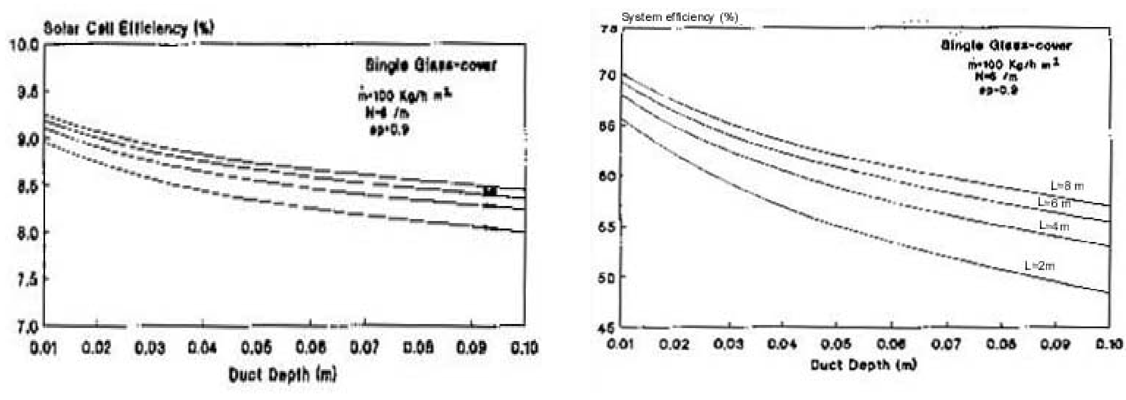

Figure 15: Solar cell efficiency and system efficiency as a function of duct depth (from Garg [9])

The above statement is graphically represented by Figure 15. The left one represents the solar cell efficiency and the right one the system efficiency.

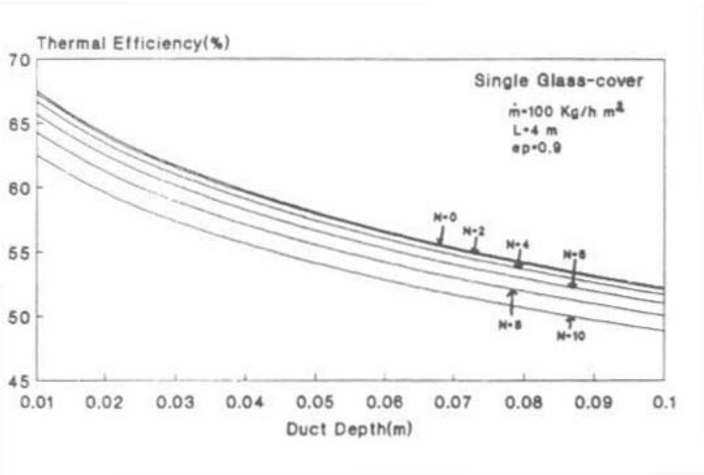

Figure 16: Thermal efficiency (from Garg [9])**

Figure 16 represents the variation of performance parameter as a function of duct depth and cell density. The thermal efficiency is observed to be decreasing with increase in duct depth and cell density.

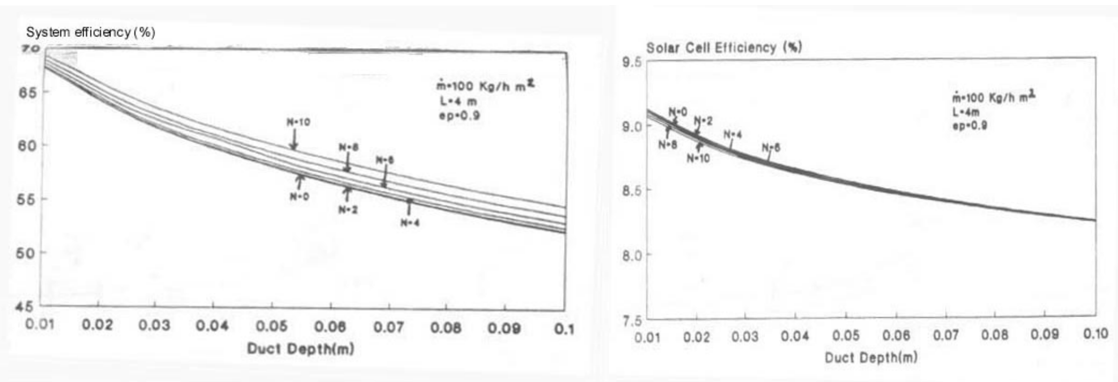

Figure 17: System efficiency and solar cell efficiency as a function of duct depth and number of solar cells (from Garg [9])

However solar cell efficiencies are observed to be almost equal. This is due to the fact that the conversion of transmitted solar irradiance into electrical energy is more and more as cell density increases by reducing the thermal energy fraction. Increasing cell density results in very large values of electrical efficiency and therefore the system efficiency observed to increase with cell density, although thermal efficiency is lower for a larger value of cell density.

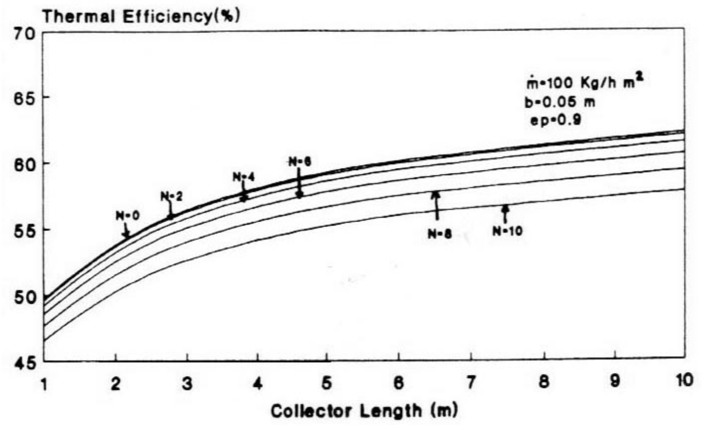

Figure 18: Thermal efficiency as a function of number of solar cells and collector length (from Garg [9])

The above figure represents graphically how the thermal efficiency of the system is altered with changes in collector length as well as the number of cells. The thermal efficiency is increasing with the increase of the length, and decrease with the increase of number of cells.

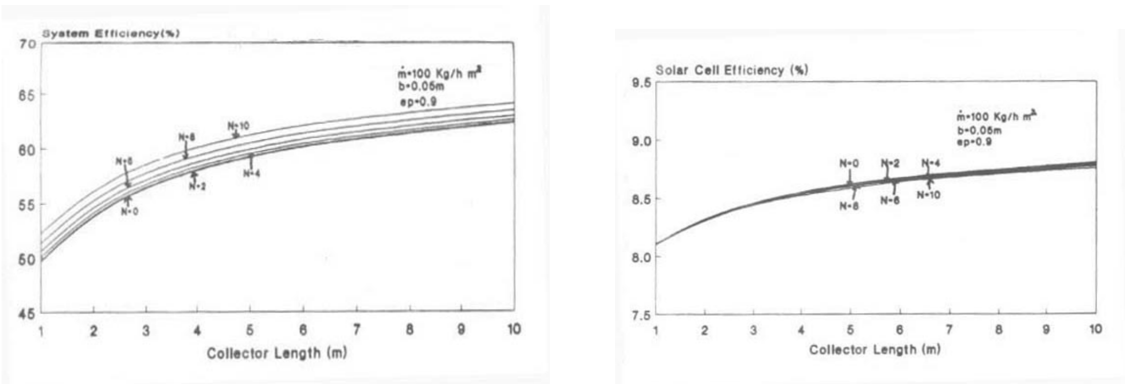

Figure 19: System efficiency and solar cell efficiency as a function of number of solar cells and collector length (from Garg [9])

The system efficiency is increased with collector length increases, as well as with increases in the number of solar cells. The solar cell efficiency however has not been changed greatly. The collector length seems to be a more important parameter in this case.

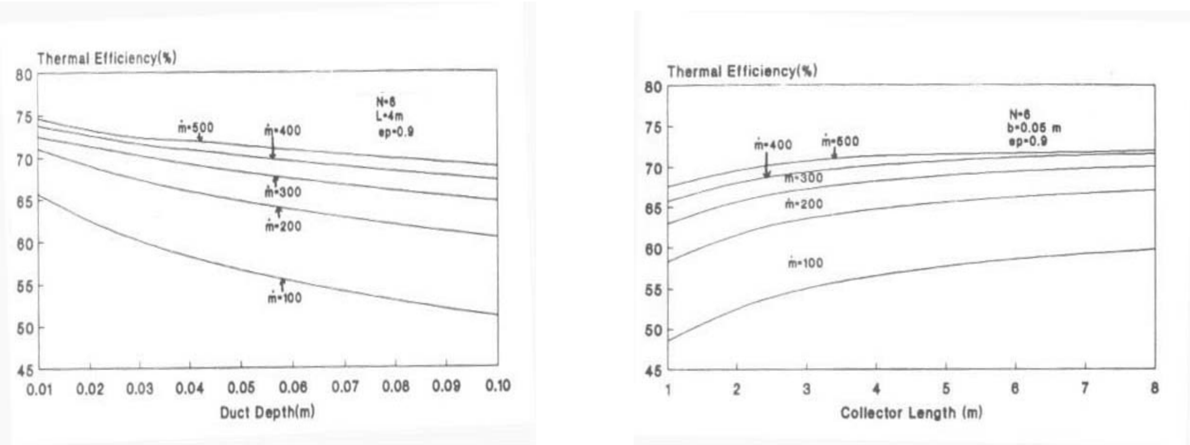

Figure 20: Thermal efficiency as a function of mass flow rate and duct depth, collector length respectively (from Garg [9])

As it can be seen from the above figures, the thermal efficiency drops with increased duct depth but is increased with increased flow rates. On the other hand, the efficiency is increased with increased length and increased flow rates. The impact the thermal efficiency has on the system efficiency for both cases, is represented in the figure below.

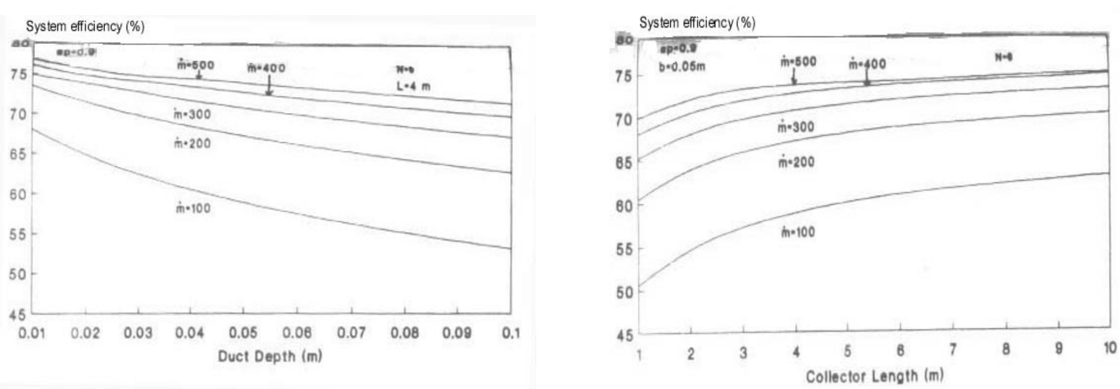

Figure 21: System efficiency as a function of mass flow rate and duct depth, collector length respectively (from Garg [9])

The system efficiency in both cases follows the behaviour of the thermal efficiency presented above. It decreases on the left diagram and increases on the right.

2.9 Water cooled photovoltaic panel

As said before, instead of air as the coolant of the panel, water can be used in order to absorb more heat and to cool the panel more effectively. This system which is using a fluid as the coolant, is called hybrid. It transforms the sun's radiation to electrical energy and simultaneously absorbs the heat from the panel. By this way, the panel is working in lower temperatures (higher efficiency), and the heat produced can be used for covering a part of thermal requirements of a building, for example preheating the water used for hot water applications.

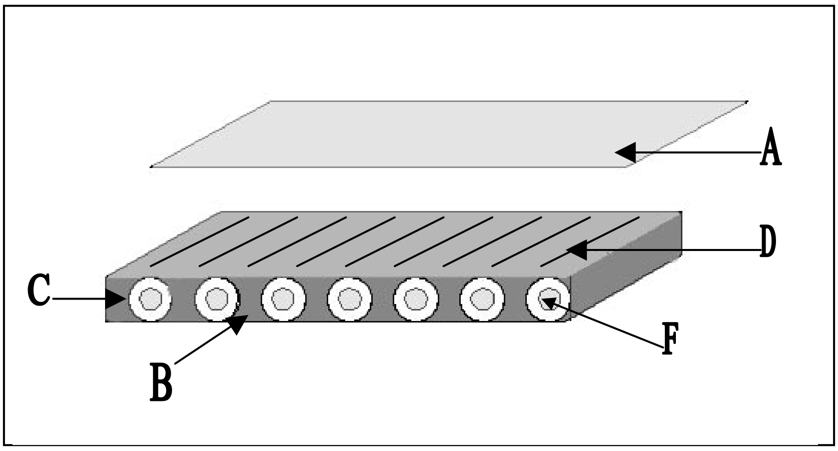

Figure 22: Hybrid system

As it can be seen from the figure, the hybrid system is constructed by a PV panel "A", a heat exchanger "B" consisting of pipes "C" with fins "D" in contact with the backside of the module, ant thermal insulation around and back of the heat exchanger. The fluid "F" passes inside the pipes of the heat exchanger. The whole configuration can include a system which can monitor and control the inlet temperature of the water.

The cold water can be stored in a tank which is connected to a pump in order to circulate the water around the panel. Another tank is used in order to store the warm water leaving the heat exchanger. Cold water is entering the first tank by the supply network. Considering the fact that the water is continuously entering from the supply network, the temperature of the first tank is kept at low levels for better PV cooling.

Various performance parameters-theory

Again the theory of calculating various parameters is the same as in the case of the air-cooled panel.

A simulation model

As an example of such a hybrid system, the experiment done by Trypanagnostopoulos [9] was used. The PV model used was a pc-Si panel with an absorber surface area of 0,4 m^2. The maximum PV temperature values without water circulation were measured in the range of 40°C to 70°C, depending on the incident solar radiation, ambient temperature and wind velocity.

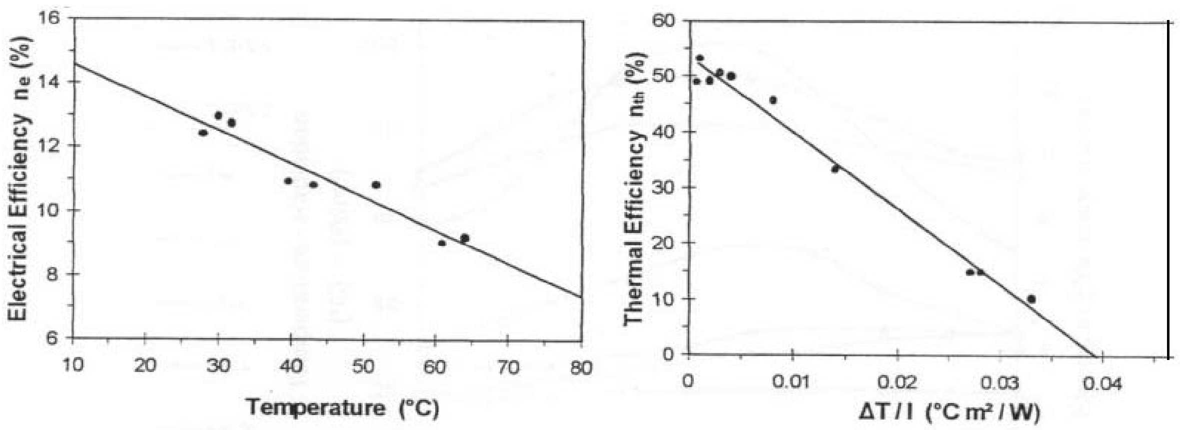

Figure 23: Experimental results of electrical and thermal efficiency

The above graph presents the electrical efficiency of the module for solar radiation intensity I of about 900 W/m^2 as well as the thermal efficiency of the system. As it can be seen from the graph on the left, for once more the electrical efficiency drops rapidly when the temperature is increased. At the temperature range of 30°C the electrical efficiency n_e equals to 13% while at 60 n_e drops to 9,5%.

Furthermore, the right graph presents the thermal efficiency of the heat exchanger. In this case, the water circulation through the PV heat exchanger can extract heat with thermal efficiency of 55%. $\Delta T/I$ represents (Ti-Ta)/I where Ti, Ta are the input water temperature and the ambient temperature respectively.

Once again, the effect of temperature on the efficiency was the declining of the latter. It is clearly obvious the necessity of operating the whole system at lower temperatures. This, in combination with the fact that the thermal efficiency reaches the value of 55%, shows that the presence of the heat exchanger is beneficial to the system. In order to prove that experimentally, the following graph is presented:

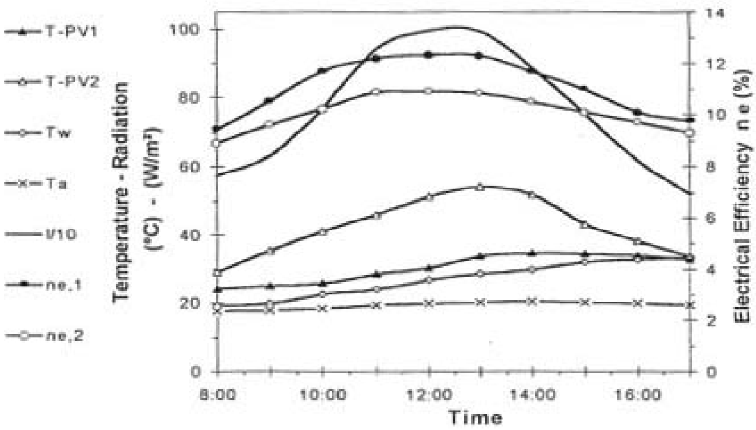

Figure 24: Variation of temperatures, solar radiation and electrical efficiencies

The results presented in the above graph were taken during the experiment done in the time 8:00 to 17:00 for a typical daily operation of a simple PV module and the module with the heat exchanger. Where

I : the incoming solar radiation intensity

T_{PV1} : the operating temperature of the PV1 (with heat exchanger)

T_{PV2} : the operating temperature of the PV1

T_a : the ambient temperature

T_w : the water temperature of the tank T1

$n_{e,1}$: the electrical efficiency of PV1

$n_{e,2}$: the electrical efficiency of PV2

As it can bee seen from the graph, the operating temperature of the system including the cooling system (PV1) is lower than the temperature of PV2. At the region with the highest incoming solar radiation intensity, that is between 11:00 and 14:00, the difference between these temperatures is approximately 20°C. Considering the effect of high temperatures to the system this is a very big value. Consequently the electrical efficiency of the PV1 is higher than PV2. The efficiency of PV1 is 15% higher.

In order to determine the time interval on the limited effective operation of the system without water circulations, various experiments were carried out [9]. These tests without continuous water circulation were performed in several time intervals. Temperature data from photovoltaics PV1 and PV2 were recorded in order to remark and estimate this cooling procedure. These tests showed that a cold water circulation for 5 minutes through the heat exchanger of PV1 with flow rate of 60 lt/h, can be considered sufficient to operate the nest 5 minutes without water circulation keeping the PV1 mean temperature under 35°C (for I=900W/m^2. Ta=20°C and Tw=20°C). For lower water flow rate or longer time than 5 minutes without water circulation, PV1 mean operating temperature increases and the electrical efficiency gain decreases. The above can be used in order to optimise the best effective operation of the hybrid system, reducing the working time of the pump circulating the water.

As said before the water leaving the heat exchanger has gained heat from the PV module. This water can be stored in well-insulated tanks for use in hot water applications. The water produced cannot cover the needs for hot water for the whole building but it can be used for preheating applications.

Applications of hybrid systems

As said before the hybrid systems can produce electrical energy as well as thermal energy for application in a building. It is very important during the installation of such systems to keep certain distances in-between the modules in order to avoid shading of the PV. The latter can decrease the efficiency of the modules.

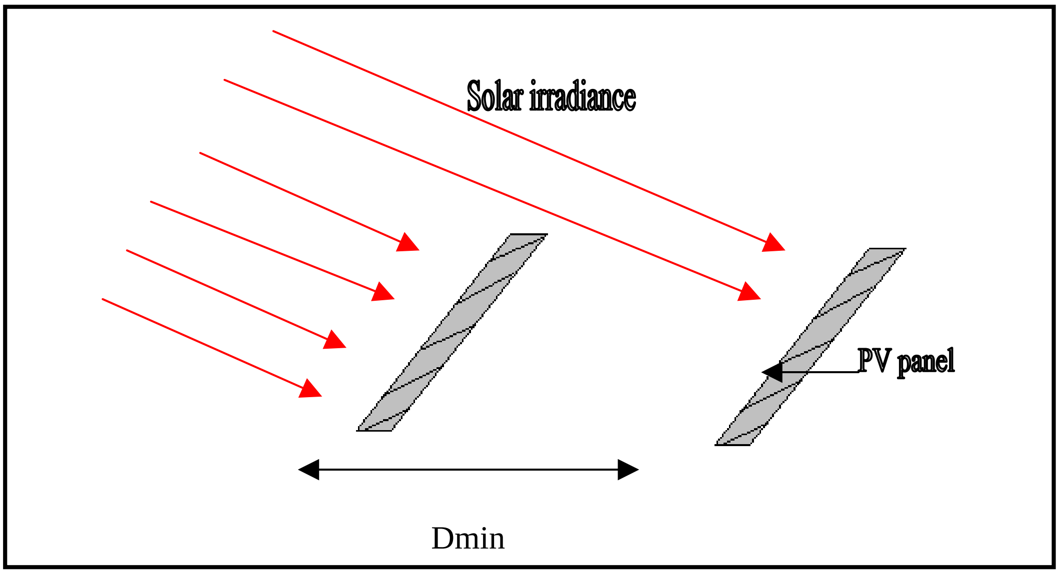

Figure 25: PV panel position

Figure 25 shows an example of the minimum distance between the modules in order to avoid shading. The distance in-between can be used if the hybrid systems are combined with diffuse reflectors installed at the bottom of the panels in order to increase the electrical as well as the thermal efficiency.

2.10 Comparison of the two systems

In the last two paragraphs two PV systems were described. The first one was the air cooled PV module and the second the water-cooled PV module. During this part, the two systems will be compared in order to see which one is the most promising.

As said before the air-cooled panel uses the air in order to cool the panel. Natural ventilation of air passing through the gaps of the system absorbs the heat from the panel. It has been recorded tat the overall efficiency of the system is higher than the efficiency of a PV module with no ventilation at all. As it can bee seen from Figure 13 for a mass flow rate of air 100Kg/h m^2 and irradiance of 900W/m^2 the efficiency of the panel has a maximum value of 8,4 % when the temperature was 67°C which was the minimum temperature value. The temperature range was from 67°C to 98°C where the efficiency was 7%.

On the other hand the water-cooled PV uses water as the coolant medium. It was operating in the range of 25°C to 30°C. Comparing these temperatures it is obvious that the PV/W is operating in lower temperatures. Consequently the overall efficiency of the system was higher. The maximum value of the efficiency was 12,5 % at 27°C. Therefore the difference between these systems is about 4,1 % in solar cell efficiency.

Furthermore, the main advantage of the water-cooled system is that the heat absorbed can be used for various applications. This system can produce electricity at higher efficiencies than the PV/T (air cooled) but simultaneously can use the absorbed heat to warm the water for preheating applications.

It should be said here that the air-cooled PV system is less efficient than the water one, but the cost of the former is lower. The heat exchanger used by the PV/W, the water tanks used as well as the whole tube configuration can result in an expensive system. Furthermore, proper insulation must be used which can be proved costly. If a choice between these two systems should be done, an economic analysis should be performed in order to calculate the payback period for both systems. This analysis is beyond the scope of the project and it is suggested as future work.

Concluding, the water-cooled photovoltaic proved to be more efficient than the air-cooled PV. Nevertheless, the latter proved to be more efficient than a normal operating photovoltaic module.

3. Developing a Model of a Water Cooled PV panel

As said before in previous chapters, a spreadsheet was developed in order to investigate how various parameters affect the overall efficiency of the system. The whole spreadsheet was based on the water-cooled PV panel which is the most promising one. At this part of the project various graphs of the spreadsheet are presented and discussed. Nevertheless, the whole theory behind the calculations should first be presented.

The general configuration of the water-cooled system follows the one presented in Figure 22 in previous chapters.

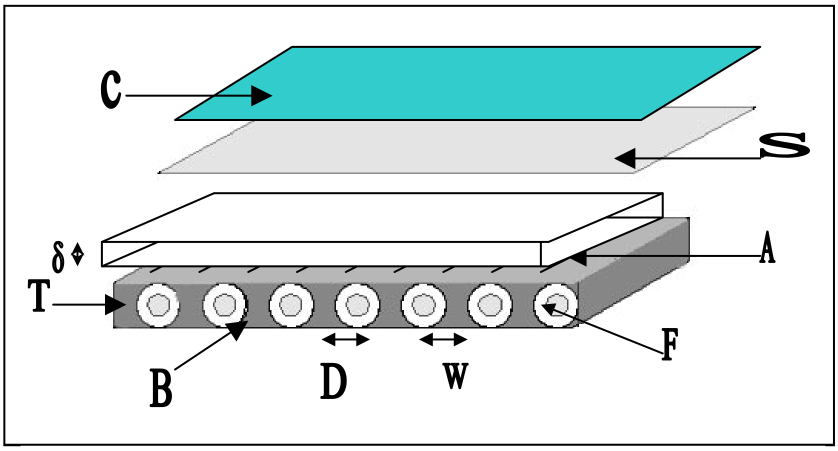

Figure 26: The PV/W model

For the figure above:

C is the cover of the system

S is the solar panel

A is the absorber

δ is the thickness of the absorber

D diameter of tube

W distance of two tubes

F fluid passing through tubes

B is the heat exchanger

T represents each tube

Between the heat exchanger's tubes there is the absorber with thickness δ. Furthermore this water cooled PV has a cover on top of the solar cell in order to be more realistic. Each of the above components is characterized by various importance parameters. These are the absorbance α(λ), emissivity ε(λ), reflectivity ρ(λ) and transmittance τ(λ). These generally obey ρ(λ)+α(λ)+τ(λ)=1 and α(λ)= ε(λ). As described in the general theory of PV, energy can be exchanged by conduction, convection and radiation. The conductive and convective terms are linear in the temperature difference. They are characterized by the generalized conductances U_{xy} between the components x and y. For example, U_{SA} is the conductance between the solar cell and the absorber while U_{Aa} is the sum of edge and bottom losses due to conductance and convection.

Energy conservation in steady state for the area above the tubes gives [8]:
for the fluid:

$$qD^{-1} + U_{Fa}(T - T_a) = U_{AF}(T_A - T) \quad (1)$$

for the absorber:

$$U_{AF}(T_A - T) + U_{Aa}(T_A - T_a) + \{\varepsilon_A \bar{\alpha}_A\}\sigma T_A^4 = U_{SA}(T_S - T_A) + \{\varepsilon_s \alpha_A\} R_S + \{\varepsilon_c \tau_s \alpha_A\}\sigma T_c^4 + \{\tau_c \tau_s \alpha_A\} E + q_f D^{-1} \quad (2)$$

and for the solar cell:

$$P(T_S) + U_{SA}(T_s - T_A) + U_{SC}(T_S - T_C) + \{\varepsilon_S \bar{\alpha}_S\} R_S = \{\tau_C \alpha_S\} E + \{\varepsilon_C \alpha_S\}\sigma T_C^4 + \{\varepsilon_A \alpha_S\}\sigma T_A^4 \quad (3)$$

where

- q is the heat per length in the fluid direction y
- D is the diameter of one tube
- σ is the Stefan's Boltzmann's constant
- $P(T_s)$ is the electric power per area that can be drawn from the solar cell, under the total irradiance E.
- q_f is the heat per length that it is bought to the tube from the fin
- R_s is the radiation from the solar cell

The above formulae contain terms in curly braces. These terms represent geometric series due to multiple reflections and transmissions [5]. The table below lists the most important ones.

$$\{\varepsilon_A \bar{\alpha}_A\} = \varepsilon_A \left(1 - \frac{\alpha_A(\rho_s(1-\rho_s\rho_c) + \tau_s^2\rho_c}{(1-\rho_s\rho_c)(1-\rho_s\rho_A) - \tau_s^2\rho_A\rho_c}\right)$$

$$\{\varepsilon_A a_s\} = \varepsilon_A a_s \left(\frac{1-\rho_s\rho_c + \tau_s\ \rho_c}{(1-\rho_s\rho_c)(1-\rho_s\rho_A) - \tau_s^2\rho_A\rho_c}\right)$$

$$\{\tau_c\tau_s a_A\} = \tau_c\tau_s a_A \left(\frac{1}{(1-\rho_s\rho_c)(1-\rho_s\rho_A) - \tau_s^2\rho_A\rho_c}\right)$$

$$\{\tau_c a_s\} = \tau_c a_s \left(\frac{1-\rho_s\rho_A + \tau_s\ \rho_A}{(1-\rho_s\rho_c)(1-\rho_s\rho_A) - \tau_s^2\rho_A\rho_c}\right)$$

For reasons of simplicity some approximations have been made in the balance equations:

1. the heat transport normal to the collector plane is independent of the heat transport in the plane
2. all material properties are presumed to be independent of temperature and equal on both sides
3. the components are further through to be thin enough to allow for neglecting temperature gradients through them
4. the ambient temperature is taken to be equal on all sides of the collector
5. all radiation in and out of the fluid is neglected

Furthermore, the calculations followed in the spreadsheet are complicated and in order to simplify them the term $U_{Fa}(T-T_a)$ is neglected supposing that the fluid is properly isolated from the ambiance. The R_s terms can also be neglected because the solar cell radiation is small. An effective heat conductivity U_{Sa} is further introduced instead of U_{SC} and the radiative cover effects are included in this term.

In order to find the transport of heat q_f from the fin to the tube, an infinitesimal segment with width Δx is considered. The energy balance equation for this segment is:

$$U_{Aa}(T_{Af}-T_A)\Delta x+\{\varepsilon_A\bar{\alpha}_A\}\sigma T_{Af}{}^4\Delta x=U_{SA}(T_s-T_{Af})\Delta x+\{\tau_c\tau_s\alpha_A\}E\Delta x-\kappa\delta\frac{dT_{Af}}{dx}\bigg|_x+\kappa\delta\frac{dT_{Af}}{dx}\bigg|_{x+dx}$$

where T_{Af} is the x-dependent temperature of the absorber on the fin , k is the thermal conductivity and δ is the thickness of the absorbing fin. The solar cell temperature may be found from the balance equation (3). This yields the differential equation:

$$k\delta\frac{d^2T_{Af}}{dx^2}=U'_{Aa}(T_{Af}-T_a)+F_R\sigma T_{Af}{}^4-S$$

where the following notation has been used:

$$U'_{Aa}=U_{Aa}+\frac{U_{SA}(U_{Sa}-cE)}{U_{SA}+U_{Sa}-cE}$$

$$F_R=(\{\varepsilon_A\bar{\alpha}_A\}-\frac{\bar{U}_{SA}\{\varepsilon_A\alpha_S\}}{U_{SA}+U_{Sa}-cE}$$

$$S=(\{\varepsilon_A\alpha_A\}-\frac{U_{SA}(\{\tau_c\alpha_S\}-\eta_0)}{U_{SA}+U_{Sa}-cE})E$$

where

U'_{Aa} is the loss factor from the absorber when the loss through the solar cells is accounted for

F_R is the radiation loss factor

S is the part of the insolation that is useful for the absorber

Due to the radiation term the differential equation has no analytical solution and an approximation should be done. Around $T_{Af}=T_a$ the right hand side is almost linear in (T_{Af} -T_a), and a Taylor expansion is quite accurate:

$$\kappa\delta\frac{d^2T_{Af}}{dx^2}\approx F_R\sigma T_a^2-S+U''_{Aa}(T_a)(T_{Af}-Ta)$$

the modified loss factor is :

$$U''_{Aa}(T_a) = U'_{Aa} + 4F_R\sigma T^3{}_a$$

which also accounts for radiation losses. In combination with the boundary conditions:

$$\left.\frac{dT_{Af}}{dx}\right|_{x=0} = 0$$

$$T_{Af}((W-D)/2 = T_A$$

where W is the width of one unit ,this gives:

$$T_{Af}(x) = T_a + \frac{S - F_R\sigma T_a^{\,4}}{U''_{Aa}(T_a)} - (T_A + \frac{S - F_R\sigma T_a^{\,4}}{U''_{Aa}(T_a)} - T_A)\frac{\cosh(\omega x)}{\cosh(\omega(W-D)2)}$$

where :

$$\omega^2 = U''_{Aa}(T_a)(\kappa\delta)^{-1}$$

The heat brought to the tube from the two half fins is thus

$$q_F = -2\kappa\delta\left.\frac{dT_{Af}}{dx}\right|_{x=(W-D)/2} = \quad (W-D)F_f(S - F_R\sigma T_a^4 - U''_{Aa}(T_a)(T_A - T_a))$$

where the fin factor F_f is defined as:

$$F_f = \frac{\tanh(\omega(W-D)/2)}{\omega(W-D)/2}$$

The fin factor is a measure on how effectively the heat is transported from the fin to the tube via the absorber.

Having found the heat from the two half fins, it is straightforward to solve the balance equations (1)-(4) to find the following expression for the generalised heat:

$$q(T) = WF(T)[s - F_R(T)\sigma T^4 - U_L(T - T_a)]$$

the collector efficiency factor F(T) is given by:

$$F(T) = \frac{\frac{D}{W}(1+\frac{W-D}{D}F_f)}{1+(U_L(1+\frac{W-D}{D}F_f)+4F_R\sigma T^3)\ /U_{AF}}$$

the effective radiation loss factor as

$$F_R(T) = \frac{(1+\frac{W-D}{D}F_f\frac{T_a^4}{T^4}}{(1+\frac{W-D}{D}F_f)}F_R$$

and the total conductive loss factor as :

$$U_L = \frac{U'_{Aa}+\frac{W-D}{D}F_f U''_{Aa}(T_a)}{(1+\frac{W-D}{D}F_f)}$$

In order for the performance of the absorbed to be maximized, the efficiency factor should be as close to unity as possible, whereas the total conductive loss factor and the effective radiation loss factor should be as low as possible.

The rate of heat that it is drawn from the system is

$$Q_T\ \dot{m}C_p(T_L - T_i)$$

where the outlet temperature T_L is the fluid temperature at y=L. the thermal efficiency, most conveniently defined as the ratio of the generated heat to the incoming insolation, is given by:

$$n_A = \frac{Q_T}{ELW} = \frac{\dot{m}C_p}{ELW}(T_a - T_i - \frac{q(T_a)}{q'(T_a)})(1-\exp(\frac{q'(T_a)L}{\dot{m}C_p})) \qquad (4)$$

where

$$q'(T_a) = \left.\frac{dq}{dT}\right|_{T=T_a}$$

which is the differentiated heat. After calculations the differentiated heat was found to be:

$$q'(T_a) = WF'(T_a)S - W\sigma[F'(T_a)F_R(T_a)T_a^4 + F(T_a)F'_R(T_a)T_a^4 + 4F(T_a)F_R(T_a)T_a^3] - WU_L(T_a - T_a)F'(T_a)$$

In order to find the above, we have to find the differentiated collector efficiency factor F´(T_a) as well as the differentiated effective radiation loss factor. After some relatively complex calculations:

$$F'(T_a) = -\frac{\frac{D}{W}(1+\frac{W-D}{D}F_f)(\frac{12F_R\sigma T_a^{\ 2}}{U_{AF}})}{1+[\frac{U_L(1+\frac{W-D}{D})F_f+4F_R\sigma T_a^{\ 3}}{U_{AF}}]^2}$$

$$F_R'(T_a) = \frac{(-4F_R\frac{W-D}{D}F_f T_a^{\ -1})}{(1+\frac{W-D}{D})F_f}$$

Now the equation (4) can be solved. All the above were used in order to construct the spreadsheet in the Excel package and it is presented in the Appendix [2].

4. Parametric analysis of the Water Cooled Panel

The parametric analysis of the water cooled photovoltaic is performed in order to determine the most important parameters which affect the operation of the PV panel. These parameters can either be the physical properties of the heat exchanger connected to the panel as well as the flow of water inside the tubes. After determining these factors and their importance on the efficiency of the system, the latter can be maximized. The information gained by the analysis can be used in order to maximize the efficiency of any collector design which is the main aim of the project. All the graphs presented below are related to the model presented to the previous chapter.

A said before the basic spreadsheet is presented in Appendix [2]. The upper part of the sheet contains the numbers which are constants. These values were found by a review of relevant literature (Sizmann 1991, Lampert 1987,Bogaerts 1983). The lower one contains the functions used to find the thermal efficiency.

The first graph was constructed by using the following data: W held constant and equal to 0,01m, D= 0,01, T_i=280 K, m=0,0003 kg/s. The other parameters were taken as follows: $\{\tau_c\alpha_s\}$=0,7 $\{\varepsilon_A\alpha_A\}$=0,1 $\{\tau_c\tau_s\alpha_A\}$=0,15 $\{\varepsilon_A\alpha_s\}$=0,05 , E= 800W/$m^2$, n_0=0,125 , c=5*10^{-4}, T_a=293K, U_{Aa}=1W/m^2 K^{-1}, U_{AF}=200 W/m^2K^{-1}, U_{SA}=100W/m^2K^{-1}, U_{Sa}= 6 W/m^2K^{-1}, k=385 W/mk (for copper),C_p=4200J/KgK (water), δ=5*10^{-4} m ,L=1 m.

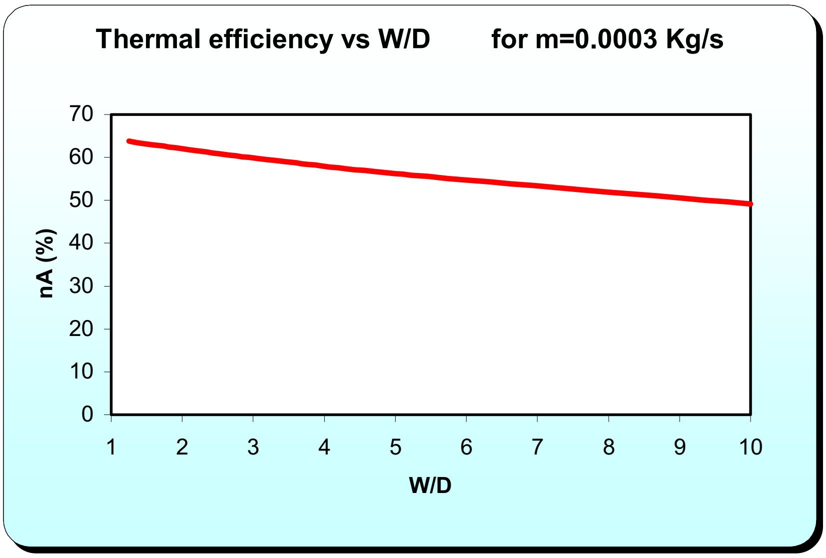

Figure 27: The thermal efficiency as a function of WD^{-1}

The thermal efficiency of the system is plotted in the above figure. The dependence W/D (with W constant) is plotted in order to show how the relative size of the fin influences the performance. D was changed from 0,01 m to 0,1 m. As it can be seen, the thermal efficiency of the system drops from 63,77% at W/D 1,25 to 56,19 % at W/D equal to 10. This efficiency reduction is due to the conduction and radiation losses from the fin, because the latter is at higher temperatures. The mass flow rate of water in this case was equal to 0,0003Kg/s. This value is slightly increased when the tube diameter is decreased, but this effect is small enough not to alter the efficiency greatly.

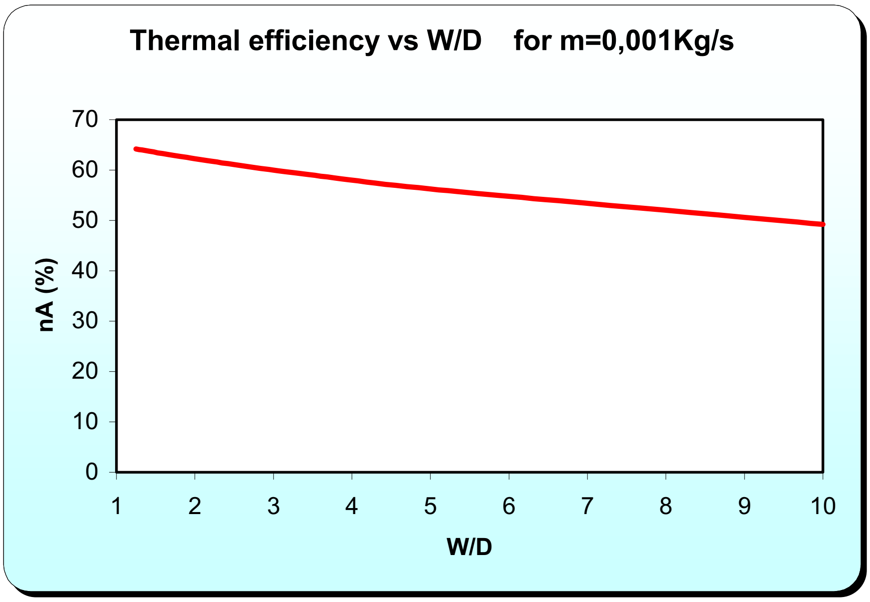

Figure 28: The thermal efficiency as a function of WD^{-1} (m=0,001kg/s)

The above graph represents the thermal efficiency with respect to W/D when the flow rate of water is increased from 0,0003 kg/s to 0,001 kg/s. The effect of such a big increase in m on the efficiency, is a small increase of the latter. In this case the highest value of n_A was 64,19% while the smallest value was 49,23%. It obvious that the **flow rate** of water doesn't play a very important role on the system's thermal efficiency. To illustrate this better, the following figure is presented.

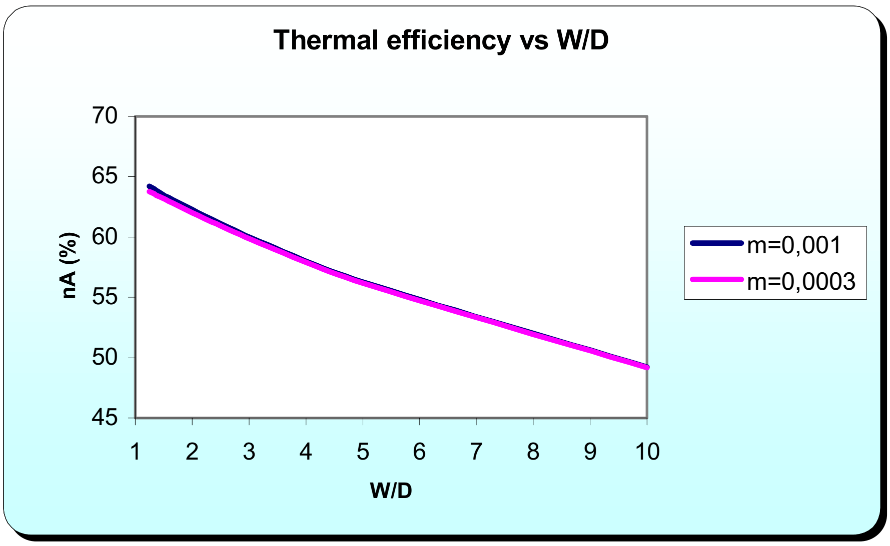

Figure 29: Thermal efficiency as a function of W/D

The figure above represents the thermal efficiency of the system when W/D is varied for m=0,0003 kg/s and m=0,001 kg/s. as it can clearly be seen, the two graphs are almost identical. A small increase of the efficiency can be shown when m is larger and W/D reaches 1. As mentioned earlier, despite that the flow rate has been increased greatly, the efficiency didn't.

Another very important parameter of the system apart from the tube diameter and the flow rate is the inlet temperature of the water entering the heat exchanger.

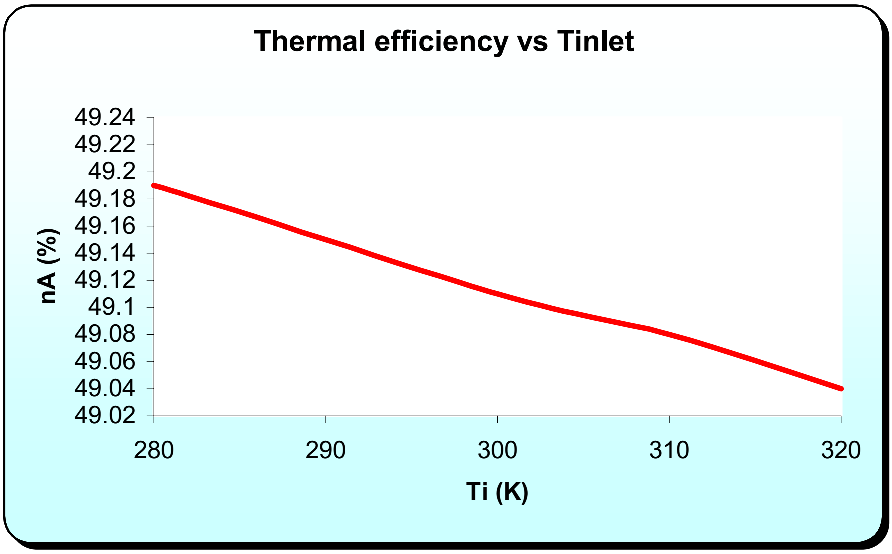

Figure 30: Thermal efficiency as a function of the inlet temperature

The inlet temperature of the water to the heat exchanger varied from 280 K to 320 K in order to see how the thermal efficiency is altered. As it was expected the efficiency dropped with increasing temperature. The interesting point is that the variations in temperature change were large, nevertheless the efficiency decreased slightly.

Keeping in mind that PV panels transform the sun's energy to electricity it can be said that one fundamental parameter is the solar irradiance E. This parameter plays a very important role on the whole system's efficiency. In order to investigate on the above, the solar irradiance E was varied, and various values of the thermal efficiency were recorded. The results of this spreadsheet are presented in the graph which follows. It should be said here that the designer has not control over this parameter. Nevertheless, for a better understanding of PV systems the thermal efficiency of the system as a function of the irradiance is presented.

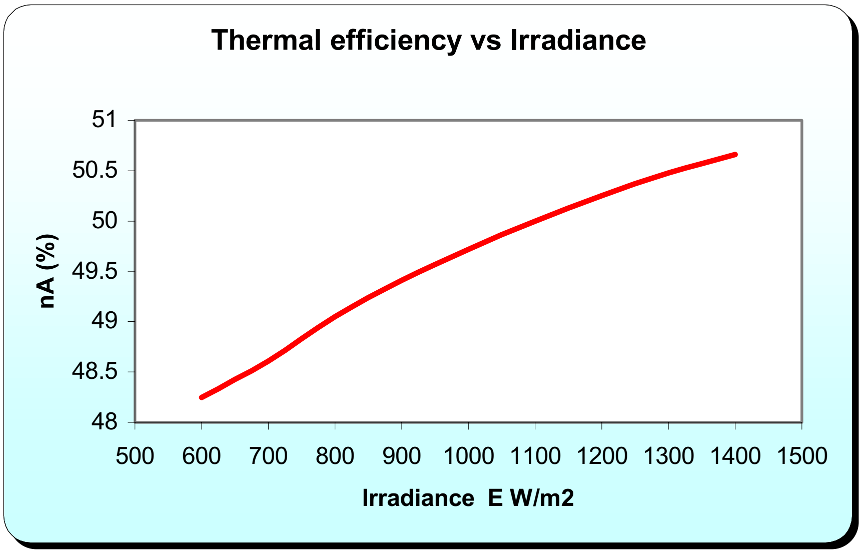

Figure 31: Thermal efficiency as a function of the irradiance

The irradiance was changed from 600 W/m^2 up to 1400W/m^2 which is considered to be two extreme values. Nevertheless the importance of E on the PV panel is well illustrated above. At 600 W/m^2 the efficiency was 48,25% while on 1400 it was 50,66%. The difference between these values is 2,41% which is considered to be high. The above graph represents a phenomenon which was totally expected from the start of the project. Nevertheless it makes clear how the efficiency is dependent on the solar irradiance.

Once again another parameter of the system was changed in order to gain some results on the efficiency. This time the length was changed. The length of the absorber was changed and various values of the efficiency were recorded. The minimum length was 1 m while the maximum value was 2.1 m. consequently the efficiency dropped from 49,19% to 49,12%. It is clear therefore the fact that the thermal efficiency of the system is not highly dependent on the fin size. If the fin size is doubled, the **thermal** efficiency of the PV only increases by 0,06 %.

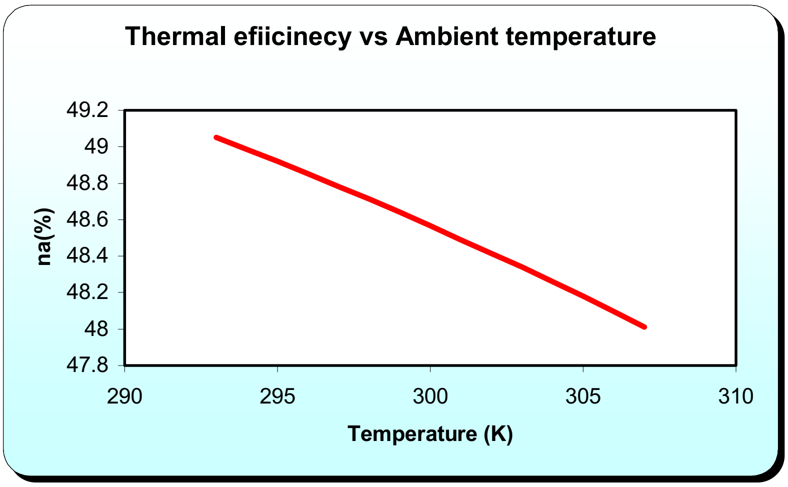

Figure 32: Thermal efficiency as a function of ambient temperature

The above graph represents the thermal efficiency of the cell with respect to the ambient temperature. The efficiency drops when the ambient temperature increases. The maximum value of the efficiency was 49 % at 293 K and the minimum was 48% at 307 K. Therefore, for a change of 14ºC the efficiency drops about 1%.

It should be made clear at this point that the above spreadsheet was developed in order to investigate how various parameters of the PV/W affect the thermal efficiency of the system. This efficiency is completely different with the electrical efficiency of the panel as well as the overall one. The relationship between them has been investigated in previous chapters. Furthermore, the graphs presented in the technology review show how the electrical and cell efficiency are varied when the thermal efficiency is altered.

5. Quantification

In this part of the project, the quantification of the photovoltaic module is presented in order to see how much energy the module can produce. The characteristics of the photovoltaic are presented below. The data set used was chosen for a typical PV system at STC.

The module's characteristics at Standard Test Conditions are:

T_{module}= 25°C

G=1000W/m^2

V_{oc}=14,6V V_{max}=12,6A

I_{sc}=4,9A I_{max}=4,1 A

Using the above data, firstly the fill factor can be calculated. The formula used is presented in the theory of the project and is:

$$
\begin{aligned}
FF &= \frac{V_{\max} I_{\max}}{V_{oc} I_{sc}} \\
&= \frac{12{,}6 * 4{,}1}{14{,}6 * 4{,}9} \\
&= 0{,}722114
\end{aligned}
$$

As said before, the Fill Factor is an indication of the quality of the silicon (0,72 is considered to be good).

The **electrical power** generated from the module is to be calculated next. The module is considered to have a drop off due to temperature =0,22 W/°C and it is consisted of 2500 modules. In order to calculate the power generated, the data below will be used.

time	Gb	Gd	G(Sum)	Tmod(k)
9:00-10:00	50	180	230	295
10:00-11:00	300	150	450	311
11:00-12:00	710	130	840	341
12:00-13:00	880	110	990	359
13:00-14:00	720	130	850	343
14:00-15:00	410	150	560	327
15:00-16:00	250	170	420	311
16:00-17:00	30	190	220	303

Table.2

G_b and G_d are the beam solar irradiance and the diffuse solar irradiance respectively. The total irradiance incidental on a surface is

$$G_{sum} = G_b + G_d$$

T_{mod} is the temperature of the module at that particular time interval.

The power drop off due to temperature was described in previous chapters. In this case this value is 0,22 W/°C. This has to be converted to %/°C. So:

$$\begin{aligned} So:\ P_{max} &= V_{max} I_{max} \\ &= 12{,}6 * 4{,}1 \\ &= 51{,}66 \end{aligned}$$

$$and\ \frac{0{,}22}{P_{max}} = \frac{0{,}22}{51{,}66} = 0{,}00425\%\ /C$$

This is the power drop off expressed in %/°C. Now using

$$P_{o/p} = P_{max} \frac{G}{1000}$$

and table 2, the table below can be constructed:

time	Po/p
9:00-10:00	11,88
10:00-11:00	23,25
11:00-12:00	43,39
12:00-13:00	51,14
13:00-14:00	43,91
14:00-15:00	28,93
15:00-16:00	21,70

Table.3

It can be seen from the table that the highest power output occurs between 12:00 and 13:00 where there is the highest irradiance. Now using Table 3 and

$$P_{temp} = P_{o/p}[1 - P_{dropoff}(T_{cell} - 25)]$$

the nest table is constructed:

time	Ptemp
9:00-10:00	12,03
10:00-11:00	21,96
11:00-12:00	35,46
12:00-13:00	37,88
13:00-14:00	35,51
14:00-15:00	25,36
15:00-16:00	20,50
16:00-17:00	11,12

Table.4

Table 4 represents the power from the system for every hour, including the power drop of due to temperature effects. Now in order to calculate the total power delivered form the system the following formulae will be used: Pdel=Ptemp*No where N o is the number of modules. The power delivered is then:

time	Pdel
9:00-10:00	30083,23
10:00-11:00	54906,51
11:00-12:00	88660,18
12:00-13:00	94711,18
13:00-14:00	88782,55
14:00-15:00	63410,07
15:00-16:00	51246,07
16:00-17:00	27809,22

Table 5.

It can be seen from table 5 that the maximum power delivered by the module occurs during 12:00 to 13:00. In order to calculate the effectiveness of the module the formula below is used

$$effectiveness = \frac{P_{temp}}{P_{\max}}$$

in combination with Table 4 :

time	effectiveness
9:00-10:00	0,233
10:00-11:00	0,425
11:00-12:00	0,686
12:00-13:00	0,733
13:00-14:00	0,687
14:00-15:00	0,491
15:00-16:00	0,397
16:00-17:00	0,215

Table 6

Again the maximum effectiveness is during the same time interval. The above table is graphically presented by figure 34 below.

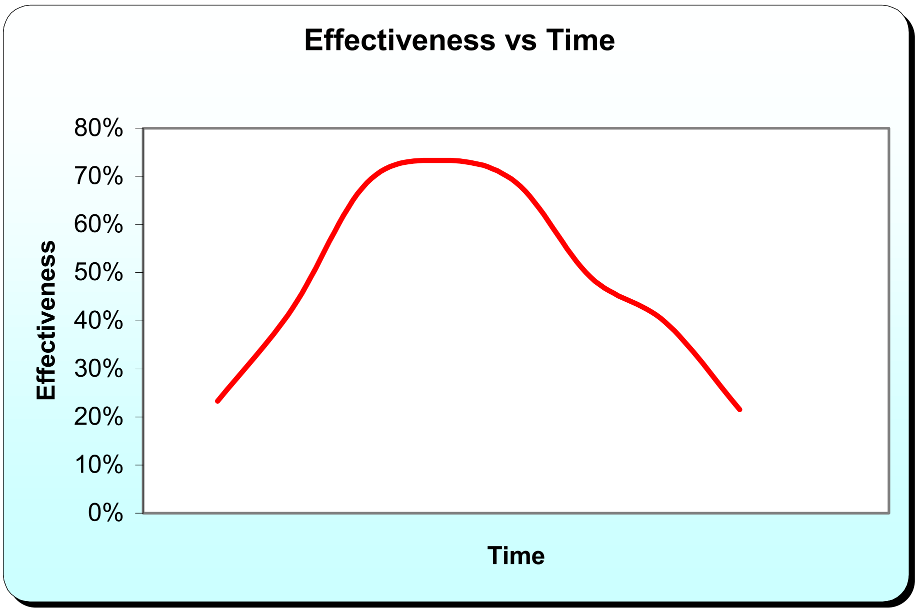

Figure 33: Effectiveness as a function of time

The effectiveness of the panel is gaining it's maximum value at the time 12:00 to 13:00. After that it starts declining again until it reaches almost the initial minimum value.

As said in the start of the quantification analysis, the PV module had a power drop off due to temperature equal to 0,22W/°C. The power associated with these losses is Ptemp and it is represented at the figure 35 below. Po/p is the power of the system if the temperature of the module did not affect the performance. It can bee seen that the bigger difference is during periods with high solar irradiance and consequently high operating temperatures. At the start of the operation of the PV the two power outputs are almost the same, and it is the same case at the end of the operation. During these time intervals the operating temperature of the module is not high.

The case where the operating temperature does not affect the performance is achieved when a water PV panel is used. It should be said that again in this case, high temperatures affect the performance of the system but the water is cooling the panel providing minimized temperatures.

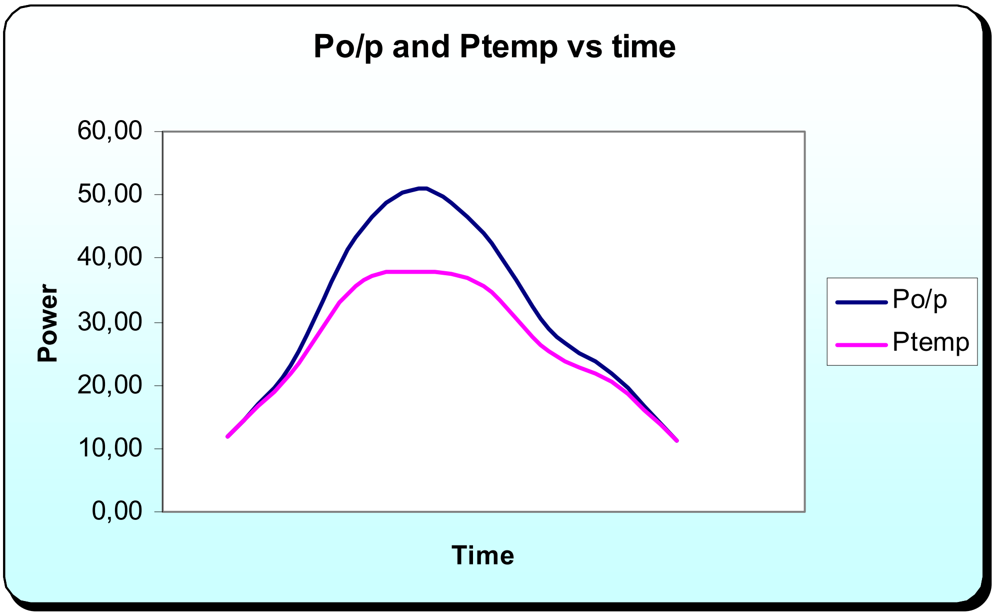

Figure 34: Po/p and Ptemp as a function of time

6. Example of a PV system in a Greek house

This system can either be a simple or a more complex one. As said before in previous chapters of the project, there are various configurations of photovoltaic systems. Before analyzing the one for the house, a general description is performed.

The simplest type of the PV is the one that it is consisted from the panels which provide energy directly to the house without storing energy or regulating the voltage. This system can provide energy only when there is illumination to the panels.

A more complex system is the one that comprises a battery for the storage of the energy from the PV. In this case the energy is provided to the various devices and the remaining is stored in the battery. This system is described below:

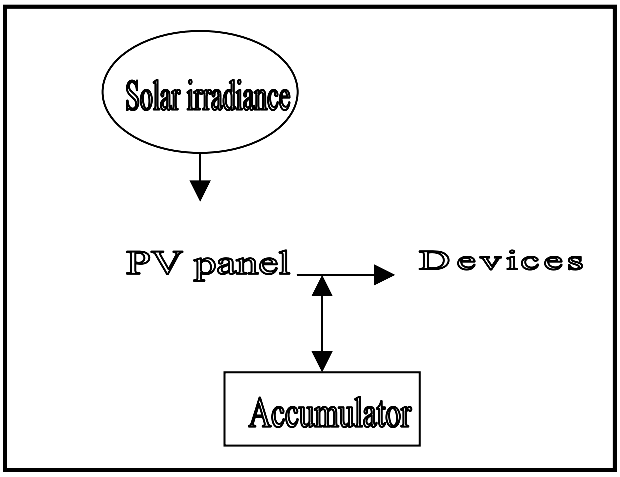

Figure 35: A stand alone PV comprising an accumulator, [17]

The size of the panels should be the appropriate not to overcharge the batteries. A regular examination of the battery should be performed otherwise the service life can be minimized. For better operation of the whole system, a voltage regulator is used. This device regulates the voltage between the panels and the batteries. The regulator is needed in a PV system which is not regularly monitored. Such systems are being used in remote areas but also in houses where the monitoring of the operation of the battery is difficult.

As said before in the theory chapter, in the case where alternate current is used, the D.C to A.C. converter is being used. This device is putted between the battery and the devices of the house. If there is a device working in D.C. the battery is supplying energy directly.

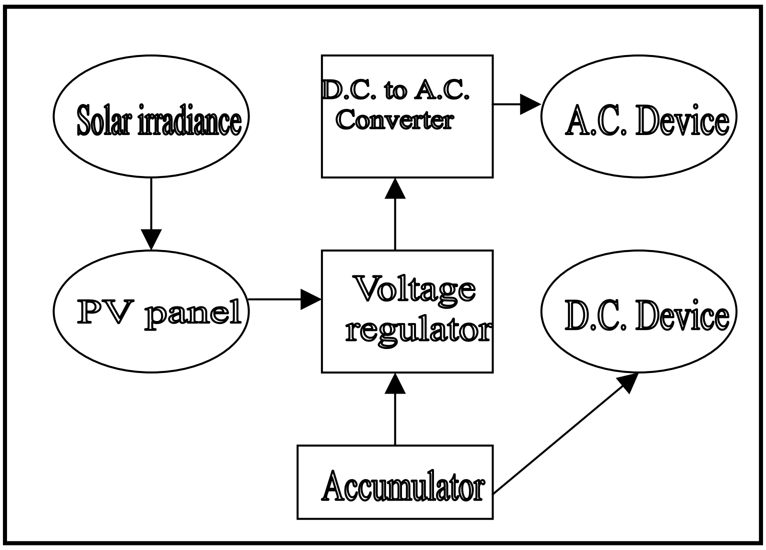

Figure 36: Figure of a stand alone PV comprising an accumulator and converter. The battery is supplying energy directly to the D.C. devices, [17]

If the power needed to supply the house is very large, the PV and the stored energy could be insufficient to meet the demand in the house. In these cases, like a cloudy period with no sunshine or an unexpected fault in the system, an auxiliary diesel generator and a battery power supply is used. This system is described below:

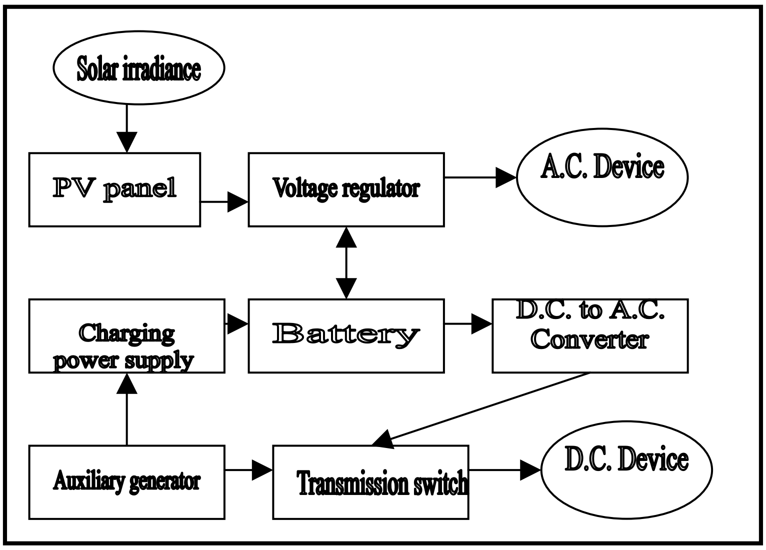

Figure 37: Stand alone PV with auxiliary generator and charging power supply,

The auxiliary generator is a way of coping with large unexpected demands. By this way there is no need of using other PV panels which would be useful only in extreme cases of low solar irradiance. It should be said here that the generator is an auxiliary device of the PV system and it is used rarely to charge the batteries. Most, or usually all the energy needed is provided form the PV panels. Only in the case where the needed power exceeds 1 KW the auxiliary generator is used.

When a stand alone PV is to be installed, the use of electrical appliances that produce heat should be minimized because such devices produce high demand for electrical energy. The electrical devices connected to the PV should be of high efficiency. If there are old appliances should be replaced by new, more technologically advanced, which offer the same or better results.

In general the dissipation of the electrical energy should be minimized in order not to use the auxiliary generator which uses gas and needs maintenance. Furthermore, such a device produces noise and cannot store the energy produced by the PV. Therefore, before installing a PV to a house, careful and precise calculations should be performed, which is not the case for a PV connected to the grid. The latter can be manufactured to provide higher amounts of energy than the amount needed for the house, since the rest of the energy can be provided to the grid.

Concluding, the stand alone PV should produce energy such as firstly to meet the demand in the house while the rest to be provided to the batteries for use during nights.

Design for usual consumption

A usual consumption for a residential installation can be taken as 7 KW per day during winter and summer and lower during autumn and fall.

Device	Power	Operation time	Electrical consumption
Lights	1,0 KW	3,0 h	3,0 KWh
Refrigerator	0,3 KW	9,0 h	2,7 KWh
Television	0,2 KW	4,0 h	0,8 KWh
Hoover	0,6 KW	0,5 h	0,3 KWh
Hair drier	0,4 KW	0,5 h	0,2 KWh
Toaster	1,25KW	0,2 h	0,3 KWh
Washing machine	3,25KW	0,2 h	0,7 KWh
Total	7 KW		8,0 KWh

Table 7.Daily electrical consumption of various devices in a house

It is obvious that if the PV system is installed to meet the demand for winter where the sunshine could be limited, it will certainly meet the demand for other seasons. It is supposed at this point that a converter with efficiency of 90% will be installed with losses to the cables of around 5%. The energy that should reach the entrance of the converter is:

E=7000Wh / 0,85 per day

E= 8235 Wh per day

Therefore the energy at the converter's exit will be 7000Wh. If the panels are orientated due φ+15° (for Greece φ=38°) [17],where φ is the latitude, then the maximum power from the panels will be :

8235Wh/day / 3,5 H/day = 2353 W

PANEL ORIENTATION: Φ+15° HOURLY CONSUMPTION / DAY			
WINTER	AUTUMN	SUMMER	FALL
3,5	5,0	5,5	4,5

PANEL ORIENTATION: Φ-15 HOURLY CONSUMPTION / DAY			
WINTER	AUTUMN	SUMMER	FALL
3,0	6,0	7,5	4,5

Table 8.

HOURLY CONSUMPTION / DAY			
WINTER	AUTUMN	SUMMER	FALL
3,0	6,0	7,5	4,5

Table 9.

If the converter used is operating with entrance voltage of 48 V (D.C.) the current from the panels will be:

Current=Voltage /Power

Current= 2353W / 48V= 49 A

If the panels used have the following characteristics:

Voltage equal to 12 V and current 2,3 A, under solar irradiance of 1000W/m^2 then it is obvious that every row of panels should be consisted of 4 panels in order to provide 4 x 12 V =48V in total.

The number of rows that will be connected in parallel is defined by the current provided by each row and the total current which should be produced by the panels in order to meet the demand.

No of rows = 49A/2,3 A / row = 21,3 rows
Therefore:
4 x 22= 88 panels
these panels will produce electrical energy per day:
22 x 48V x 2,3A x 3,5h= **8500,8 Wh**

The energy produced exceeds the value of 8235 Wh which is needed for the house per day.

The ampere hours produced by the system under 48 V are:
22 x 2,3A x 3,5h= 177,1 Ah
which are more than

7000Wh / 145 Ah = 48 V
that the house is needed per day. For the prediction of the number of batteries which will be needed in order to store the energy, the number of days with no sunshine should be taken into consideration. For these days, electrical energy should be stored in order to be provided to the system. With the storage of energy for 3 cloudy days the use of the generator can be totally avoided.

In order to have sufficient energy for the house, the batteries used should have enough energy stored for 7 days without sunshine [17] . As said before the daily energy production from the PV is 8500,8 Wh. Therefore :
8500,8Wh / 48 = 177,1 Ah
in order to meet the demand ,the amount of stored energy in the batteries should be:
177,1Ah x 3 = 531,3 Ah
and for 7 days:
177,1 Ah x 7 =1239,7 Ah

It is supposed at this point that the battery used has the following characteristics: voltage equal to 12 V, capacity equal to 140 Ah with safe level of discharge of 80% .That means that the useful capacity is 140 Ah x 0,8=112 Ah and that is the load of the battery every time is discharged.

Since the system's voltage is 48V, the batteries should be connected in rows, parallel to each other and every row to be consisted of 4 batteries. Therefore:
4 x 12 V= 48 V

For 7 days of storage the number of rows needed is
1239,7 Ah / 112 Ah/row = 11,1 rows.

11 rows of batteries consist 11 x 4 =44 batteries can store energy for 7 days with no sunshine. It is left to see if such a system can meet the demand for 7 days in the production of kilowatts-hours.
As seen before, the electrical energy needed by the system is
8235Wh x 7= 57645 Wh
Every row of batteries with level of discharge of 80%can give
48V x 112Ah = 537 Wh
For 11 rows:
537Wh x 11 = 59136 Wh which can meet the 57645Wh demand for the week

At the system described above, the generator wasn't used at all. In the case where the cloudy days were much more than 7, the stored energy in the batteries wouldn't be sufficient to meet the demand. Under these conditions the use of the generator would be essential in order to provide energy to the house.
In order to find the area of the panels that would be used for the example described above, the following procedure should be done. The electrical energy produced by a PV system is:
$E=G * \eta * A$
where G is the solar irradiance, η is the efficiency , G is the solar irradiance and A the total area needed. [17]
therefore for the example above : $A=E/(G*\eta)$ m^2

Keeping in mind the values from table 7 and in the case where the efficiency of the panels about 12% placed at an angle of 45° for January, it holds:
$A=8(KWh/d) / \{3{,}32(KWh/m^2d)*0{,}12\}=20{,}08\ m^2$

In order to have a more realistic model in the analysis, it is assumed that the electrical losses of the system (accumulators, converters), is about 30 % of the energy produced. Therefore, the coefficient of performance of the system from the exit of the PV panel, to the end of the system (inside the house) is 0,7
So the area is 20,08/0,7=**28,68 m^2**
That is the total area of the PV needed to supply electrical energy to the house.

The hybrid PV model

The above analysis was for a conventional PV system. In the case where a hybrid system was installed, apart from the electrical energy produced, the thermal energy produced could be used as well.

As seen form previous chapters, the hybrid PV system can produce electrical energy as well as thermal energy which is used to warm the cooling medium. The example above shows how a PV system can meet the daily demand for electrical energy for a house. So the hybrid model can be considered as two different mechanisms. One that provide electrical energy described and analyzed above, and another that produce heat, therefore thermal energy.

As said before, there are various cooling mediums which can be used. In the case where water is used, the thermal energy can be used as follows. Water is passing through the tubes of the heat exchanger connected to the PV panel (described in chapter 4). The heat from the panel is absorbed by the tubes and the water is warmed up. In order to have warm water inside the house, usually a boiler is used. This device uses electrical energy or gas in order to warm up the water for hot water applications.

The tubes from the heat exchanger can be connected to that boiler providing the tank with preheated water. For example, instead of warming the water from 15° C, which is the normal temperature for water, the boiler will start warming the water from 30 ° C to its final temperature. By this way, energy will be saved. The heat recovered from water is not sufficient to warm completely the water for direct use in the house. Nevertheless it can be used as preheated water inside the boiler’s tank.

If other cooling mediums are used, such as oils, their use inside the house is becoming more complex. They cannot be used for the hot water applications and they cannot be used inside the boiler. The heat gained by the panel is not sufficient for other uses. For example the hot fluid could be circulated inside the radiators providing heat to small rooms in the house. In the hybrid system, the thermal energy is small for this kind of application.

7. Discussion

7.1 General about the project

Once the project begun it was rapidly realized that the topic area was interesting but the work done on it was scarce. The main theory of photovoltaics as well as the general history about them could be easily found in books but modern air-cooled and especially water-cooled PV panel theory was very difficult to find. Various publications and periodicals were found which provided precious help.

7.2 Technology review

During this part of the project two photovoltaic panels were described and compared. The theory presented was identical for both cases and various graphs were given. The two models were constructed by different authors each one trying to achieve different goals. That was the main problem in directly comparing them. Nevertheless, a decent comparison between them was made, with valuable conclusions.

The air cooled model proved to be simpler in operation than the PV/W. The air passing through the panel does provide cooling of the system improving the efficiency. The hot air from the panel could be used as a warm air inside the building providing heat. This phenomenon was not described fully because it was beyond the scope of the analysis. The overall performance proved to be less efficient than the water-cooled PV, but it should be kept in mind that the whole cost of the system is smaller than the cost of the latter.

On the other hand, PV/W proved to be more efficient in operation than the PV/T. Furthermore, the useful heat produced could be used for preheating the water inside the building. The cost however of such a system is higher than PV/T and should be analyzed as well.

The cost analysis and payback period methods were not performed in this work since they are beyond the scope of the project. Nevertheless if a conclusion is to be made on which system is the most favorable, the above should be done. By this way, not the most efficient but the most economic system, which will provide cheaper electricity, will be revealed.

7.3 The model of the water cooled PV

This model was done in order to see how various physical parameters could change the performance of the system. Since the water PV was the main interest, it was chosen for the simulation. It should be said here that the theory behind the spreadsheet was difficult and various complex calculations were made. Furthermore, various parameters were very difficult to find in bibliography and precious time was spent on it. All the above made the spreadsheet, a time consuming task. On a more positive note, the above simulation proved that various physical parameters have an impact on the performance of the system.

7.4 Quantification analysis

This analysis was done in order to see what is the maximum power that a PV can provide and compare it with the PV/W. The general theory of photovoltaic was used in combination with an Excel spreadsheet. The analysis provided some values on power output and showed for once more that the water PV could provide higher power.

7.5 Example of a PV system in a Greek house

At this part of the thesis an example of a stand alone photovoltaic system installed in a Greek house was presented. This analysis was done in order to see various parameters of such a system in a real life scenario. The total energy produced was calculated and an analysis was performed to see if it can meet the total energy demand.

The number of PV panels as well as the area needed in order to operate was also calculated. For the days with no sunshine, the use of an auxiliary generator and various batteries were also discussed. Finally, it was discussed whether the thermal energy produced by the photovoltaic can be used for application inside the house. Depending on the cooling medium used, the heat gained can become useful or not.

8. Conclusions

From the work done and presented the main conclusions drawn are:

- An increase in the operating temperature of the panel affects the solar cell efficiency of the system. This conclusion was expected from the literature research of the project. Nevertheless the detailed effect of the temperature was presented and discussed.

- The water cooled photovoltaic panel is more efficiently cooled than a thermal photovoltaic panel, and the thermal efficiency of the former is higher

- An increase in the duct depth of the system has as a result the minimization of the thermal efficiency.

- The physical properties of the heat exchanger in the water cooled photovoltaic can alter greatly the efficiency of the system. Using the spreadsheet developed, various physical parameters of the system were tested in order to see the effect on the efficiency of the PV. In more detail, the width and the length of the tubes are very important parameters. Altering them has as a result a different value of thermal efficiency. The water flow rate is also another parameter which was analyzed. The results showed that increasing the flow rate, the efficiency is also increased. All the above, which are fully described in the results section, can be used from a designer for optimal use of a PV.

- Apart from the properties of the heat exchanger, the inlet water temperature as well as the ambient temperature plays an important role on the system's operation. As it was diagrammatically shown in the parametric analysis chapter, when the water inlet temperature is small the thermal efficiency is high. Consequently, when the inlet temperature of the coolant gets higher, the efficiency drops. A similar result stands for the ambient temperature case.

- The power gained from a conventional system is less than the one from a cooled panel (either thermal or water cooled).

- The section “Example of a PV in a Greek house” provided important theoretical and design information about a stand alone photovoltaic system. The analysis showed that a conventional PV system can provide electrical energy to a usual house and meet the daily demand. Various other parameters such as the area needed by the panels and the number of batteries used for energy storage were calculated and proved that such a system can be installed. The results of this section showed that, for the proposed PV system, the autonomy of it in terms of sunshine is 7 days. After that time interval, the auxiliary generator could be used. The use of such a generator as well as its electrical consumption was not calculated since it was beyond the scope of the analysis. Finally, the hybrid model could provide apart from electrical energy, thermal energy to the house.

In summary:

In summary it could be said that the water-cooled photovoltaic has a good potential in providing electricity as well as warm water for preheating applications. Water as a coolant medium is extracting heat more efficiently than air. Nevertheless, the whole configuration is more complex and the cost of such a system can be very large. The comparison between the two systems showed an advantage of the PV/W over the PV/T in areas such as thermal, electrical and cell efficiency. Despite that, the quality of the products has not been investigated and a comparison between these systems in that area would be very interesting.

Furthermore, the hybrid PV/W system is greatly dependent on the properties of the heat exchanger. It was proved that every change in the latter has an influence on the system’s efficiency. Apart from the physical properties such as the tube diameter and length, the water flow rate and the temperature are also very important. The designer of such a system should take into consideration all the above in order to develop the optimal system.

9. Recommendations for future work

- Cost analysis and payback period method for both systems in order to see which one is more preferable

- Investigation in the quality of the electricity and heat produced by both systems

- Implementation of both systems in real life conditions and monitoring of their performance

- Large scale experiments, as well as experiments in a more controlled environment to determine which of the many physical processes involved has the greatest influence on the optimization of the systems

- In the PV/W case, is alternative coolant than water can be used and what are the results of such a change?

- Determination of the impact of the stack effect on the system

- Demand-side studies on the buildings for which water cooled photovoltaics are proposed.

10. Appendices

Appendix 1: Nomenclature for simulation model 1

A	area m^2
D	duct dept, m
B	duct width, m
C	specific heat, J/kg°C
E	electrical energy produced by solar cell,W
G	solar iradiance,W/m^2
h	heat transfer coefficient,W/m^2°C
L	collector length,m
m	mass flow rate kg/h m^2
N	cell density, per m
p,q	coefficients of linear differential equations for fluid temperature
R	reflectivity
T	temperature
U	heat loss coefficient W/m^2°C

Appendix 2: Nomenclature for spreadsheet

C_p	heat capacity for the fluid (J $kg^{-1}K^{-1}$)
D	diameter of one tube (m)
E	irradiance (Wm^{-2})
F	collector efficiency factor
F_f	fin factor
F_R	radiation loss factor
k	thermal conductivity ($Wm^{-1}K^{-1}$)
L	length of the absorber (m)
m	mass transport (kg s^{-1})
q	heat per length in the fluid direction (Wm^{-1})
q_f	heat per length brought to the tube from the fin (Wm^{-1})
Rs	radiation from the solar cell (W m^{-2})
S	the part of the insolation that is useful for the absorber
T	temperature of the fluid (K)
Ta	temperature of the ambience (K)
T_A	temperature of the absorber (K)
T_{Af}	temperature of the absorber on the fin (K)
Tc	temperature of the cover (K)
Ti	inlet fluid temperature (K)
T_L	outlet fluid temperature (K)
Ts	temperature of the solar cell (K)

U_{MN}	generalized conductance between components M and N ($Wm^{-2}K^{-1}$)
U'_{Aa}	modified loss factor ($Wm^{-2}K^{-1}$)
U_L	total conductive loss factor ($Wm^{-2}K^{-1}$)
W	width of one unit (m)
δ	thickness of the absorbing fin (m)
ε_M	emmisivity of component M
n_A	thermal conversion efficiency
ρ_M	reflectance of component M
σ	Stefan-Boltzmann's constant (5,67 x $10^{-8}Wm^{-2}K^{-4}$)
τ_M	transmittance of component M

Greek letters

α	absorptivity, fraction of energy absorbed
ε	emissivity
η	efficiency

Subscripts

a	ambient
b	rear plate
f	working fluid (air)
g	transparent cover
g1	upper transparent cover
g2	lower transparent cover
i	inlet
o	outlet
p	absorber plate
r	reference
s	solar cell

Appendix 2: The excel spreadsheet

w/d	10	5	3	3	2	2	1
(W-D)/D	9,00E+00	4,00E+00	2,33E+00	1,50E+00	1,00E+00	6,67E-01	4,29E-01
W	1,00E-01	1,00E-01	1,00E-01	1,00E-01	1,00E-01	1,00E-01	1,00E-01
D	1,00E-02	2,00E-02	3,00E-02	4,00E-02	5,00E-02	6,00E-02	7,00E-02
Ti	2,80E+02	2,80E+02	2,80E+02	2,80E+02	2,80E+02	2,80E+02	2,80E+02
m	3,00E-04	3,00E-04	3,00E-04	3,00E-04	3,00E-04	3,00E-04	3,00E-04
Tcas	7,00E-01	7,00E-01	7,00E-01	7,00E-01	7,00E-01	7,00E-01	7,00E-01
EAaA	1,00E-01	1,00E-01	1,00E-01	1,00E-01	1,00E-01	1,00E-01	1,00E-01
TcTsaA	1,50E-01	1,50E-01	1,50E-01	1,50E-01	1,50E-01	1,50E-01	1,50E-01
Eaas	5,00E-02	5,00E-02	5,00E-02	5,00E-02	5,00E-02	5,00E-02	5,00E-02
E	8,00E+02	8,00E+02	8,00E+02	8,00E+02	8,00E+02	8,00E+02	8,00E+02
n0	1,25E-01	1,25E-01	1,25E-01	1,25E-01	1,25E-01	1,25E-01	1,25E-01
c	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04
Ta	2,93E+02	2,93E+02	2,93E+02	2,93E+02	2,93E+02	2,93E+02	2,93E+02
UAa	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
UAF	2,00E+02	2,00E+02	2,00E+02	2,00E+02	2,00E+02	2,00E+02	2,00E+02
USA	1,00E+02	1,00E+02	1,00E+02	1,00E+02	1,00E+02	1,00E+02	1,00E+02
USa	6,00E+00	6,00E+00	6,00E+00	6,00E+00	6,00E+00	6,00E+00	6,00E+00
k	3,85E+02	3,85E+02	3,85E+02	3,85E+02	3,85E+02	3,85E+02	3,85E+02
Cp	4,20E+03	4,20E+03	4,20E+03	4,20E+03	4,20E+03	4,20E+03	4,20E+03
δ	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04	5,00E-04
L	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00	1,00E+00
T	2,85E+02	2,80E+02	2,80E+02	2,80E+02	2,80E+02	2,80E+02	2,80E+02
Ta	2,93E+02	2,93E+02	2,93E+02	2,93E+02	2,93E+02	2,93E+02	2,93E+02

F(T)	7,40E-01	8,48E-01	8,93E-01	9,19E-01	9,35E-01	9,46E-01	9,54E-01
FR	5,27E-02	5,27E-02	5,27E-02	5,27E-02	5,27E-02	5,27E-02	5,27E-02
S	5,56E+02	5,56E+02	5,56E+02	5,56E+02	5,56E+02	5,56E+02	5,56E+02
q(T)	4,34E+01	5,25E+01	5,53E+01	5,69E+01	5,79E+01	5,86E+01	5,91E+01
Ff	9,77E-01	9,82E-01	9,86E-01	9,90E-01	9,93E-01	9,95E-01	9,97E-01
F(Ta)	7,40E-01	8,48E-01	8,93E-01	9,19E-01	9,35E-01	9,46E-01	9,54E-01
FR(T)	5,82E-02	6,10E-02	6,00E-02	5,89E-02	5,79E-02	5,68E-02	5,58E-02
UL	6,57E+00	6,54E+00	6,51E+00	6,48E+00	6,45E+00	6,42E+00	6,39E+00
σ	5,60E-08	5,60E-08	5,60E-08	5,60E-08	5,60E-08	5,60E-08	5,60E-08
U"Aa	6,30E+00	6,30E+00	6,30E+00	6,30E+00	6,30E+00	6,30E+00	6,30E+00
U""(Ta)	6,60E+00	6,60E+00	6,60E+00	6,60E+00	6,60E+00	6,60E+00	6,60E+00
ω	5,86E+00	5,86E+00	5,86E+00	5,86E+00	5,86E+00	5,86E+00	5,86E+00
q(Ta)	3,94E+01	4,50E+01	4,74E+01	4,88E+01	4,97E+01	5,04E+01	5,08E+01
F"(T)	-1,28E-05	-1,33E-05	-1,36E-05	-1,37E-05	-1,38E-05	-1,38E-05	-1,38E-05
FR"(T)	-6,64E-04	-6,00E-04	-5,24E-04	-4,49E-04	-3,75E-04	-3,00E-04	-2,25E-04
F"(Ta)	-1,35E-05	-1,46E-05	-1,49E-05	-1,50E-05	-1,51E-05	-1,51E-05	-1,51E-05
FR"(Ta)	-6,45E-04	-5,73E-04	-5,01E-04	-4,30E-04	-3,58E-04	-2,87E-04	-2,15E-04
FR(Ta)	5,27E-02	5,27E-02	5,27E-02	5,27E-02	5,27E-02	5,27E-02	5,27E-02
q"(Ta)	-2,96E-03	-5,88E-03	-8,82E-03	-1,18E-02	-1,47E-02	-1,77E-02	-2,06E-02
nA	4,92E-01	5,62E-01	5,92E-01	6,09E-01	6,20E-01	6,28E-01	6,34E-01
nA%	**49,19%**	**56,19%**	**59,21%**	**60,92%**	**62,03%**	**62,80%**	**63,36%**

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