Optimization of Potential and Autonomy of a Photovoltaic System for Street Lighting

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Abstract: - The global need for energy savings requires the usage of renewable sources in many applications. Solar energy can be used for street lighting usually in cases of low consumption applications because of the low efficiency of photovoltaic (PV) panels. This research aims to illuminate a low traffic road according to CIE M5 Class requirements, using solar energy as more as it is possible. The objective is to decrease the energy consumption and also to use the appropriate lamp for the lighting of low traffic roads. According to recent studies in the mesopic region, the ideal lamp for this application is a metal halide lamp. In this study, a specific methodology is developed, which calculates the annual solar energy and the annual power output that the whole system can use. The calculations can be optimized throw a specific methodology that converts the potential of the system according to the tilt angle of the system's PV panel. The PV lighting system is an integrated unit with a PV panel, lamp, battery, inverter, charger etc. As a result of low power efficiency of PV panel energy losses and unstable weather conditions the system should not be full-autonomous. For this reason an interconnection to the local network is necessary, so a control unit is also developed. The autonomy of the whole system, as it calculated, is approximately 315 days per year. The energy savings of the proposed system is finally calculated.

Key - words: photovoltaics, renewable energy sources, outdoor lighting, street lighting, energy saving.

1 Introduction

In many instances street lighting at night can be a costly and complicated matter. Issues such as, no available grid power or expensive trenching and cabling requirements can prevent adequate lighting being installed. An indicated solution is street lighting with PV systems. With very low maintenance these solar streetlights will pay for themselves. Many applications have been made especially the last decade round the world [1-5]. In countries such as USA, UK, Italy several PV street lighting projects have been carried out in order to save energy. In Greece many efforts have been made for the expansion of this technology, but still the results are not very satisfactory. The applications are limited in building projects, but the need of cheap and clean energy, especially in Greece where is observed high amount of sunlight, have lead to the realization of projects of street lighting, but in experimental level yet.

This case study develops a method to illuminate a road by using a PV system. The complete system, apart from a PV system and a luminaire, is mounted on a single pole. At the beginning is considered the solar radiance that cascades to the panel. This permits the selection of the suitable PV panel. The other important devices of the system as the charger, the battery, the control unit and the inverter are also determined. Further calculations using the efficiency factor of each device and also a specific methodology to transform the solar radiation on a horizontal surface to a tilted surface determine the output power, which is important for the selection of the appropriate luminaire.

2 Solar Radiation in Central Greece

The solar radiation is the major factor in order to develop a PV system. One way to calculate the solar radiation is the statistic maps, available in the international literature. The maps of solar radiation provide the solar energy distributions in various geographic areas of Greece. The maps show only the average of entire year so it is not sufficient for study of solar energy per month or day. However the meteorological service of National Technical University of Athens (NTUA METEO) provides more analytical data. This service records the solar radiation 24 hours/day, using pyranometer, every day, throughout the year in Central Greece. Suitable for this study are the records of year 2001. The records start at January 1st, 2001, 00:00 up to December 31st, 2001, 23:50. These data consist of about 53.000 measurements, 1 every 10 minutes. At this point it is clear that all calculations, estimations and results represent the records of the year 2001 which is a normal meteorological year.

The elaboration of measurements is focused mainly in the reduction of their number and in the determination of a daily mean of power output. For this reason an application in Visual Basic was created which processes all the measurements. The basic steps and criteria of application are analyzed below.

Initially the number of sunlight and darkness hours is calculated using the recorded data. Especially, the records higher than 0.0001 kW/m² in ten-minute intervals are considered as "sunlight parts". All other records are considered as "darkness parts". This method gives the hours of sunlight and darkness per day. The next step is the estimation of the mean power of solar radiation per day. Multiplying the mean power by the hours of sunlight results the solar radiation (kWh/m²) for each day. Fig.1 shows the diagram of solar radiation in Central Greece.

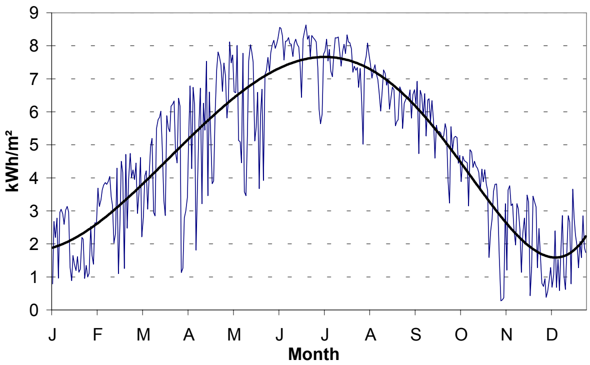

Fig. 1 – Annual distribution of solar radiation in Central Greece (horizontal surface).

3 Calculation of Solar Energy on the Tilted Photovoltaic Panel

The pyranometer measures solar radiation at the horizontal level, so the diagram on Fig. 1 shows the daily solar energy that prostrates on the horizontal surface. For different angles of the surface the solar radiation that prostrates varies. A specific method is used, in order to calculate the solar radiation on tilted surfaces. This method transforms the solar radiation values from horizontal surface to tilted surface as shown below. The daily solar radiation on a tilted surface (H_t) is:

H_t = (Solar beam component + Sky diffuse component + Surface/Sky reflectance component)

or

$$H_t = (H-H_d)R_b+H_d\,((1+\cos\beta)/2)+H*\rho_s((1-\cos\beta)/2)$$

where

H: solar radiation measurements (pyranometer)

β: angle of the PV panel relative to a horizontal surface (varies from 0^o to 90^o)

ρ_s: surface reflectance (=0.2)

$R_b=(\cos(\varphi-\beta)\cos(\delta)\sin(\omega_{ss})+(\omega_{ss})\sin(\varphi-\beta)\sin(\delta))/(\cos(\varphi)\cos(\delta)\sin(\omega_s)+\omega_s\sin(\varphi)\sin(\delta))$

φ: latitude (=38^o for Central Greece)

δ: solar declination (=$23.45\sin(2\pi((284+n)/365))$)

$\omega_s = \cos^{-1}(-\tan(\varphi)\tan(\delta))$

$\omega_{ss} = \min(\omega_s, \cos^{-1}(-\tan(\varphi-\beta)\tan(\delta))$

$H_d = H(1.391-3.569K+4.189K^2-2.137K^3)$, $\omega_s<81,4^o$

$H_d = H(1.311-3.022K+3.427\,K^2-1.82K^3)$, $\omega_s>81,4^o$

K: Ratio of solar radiation at the earth level to the radiation before entering the atmosphere

Using these equations, it is calculated the solar radiation H_t on titled surfaces for various angles (Fig.2). The orientation of the PV panel is south.

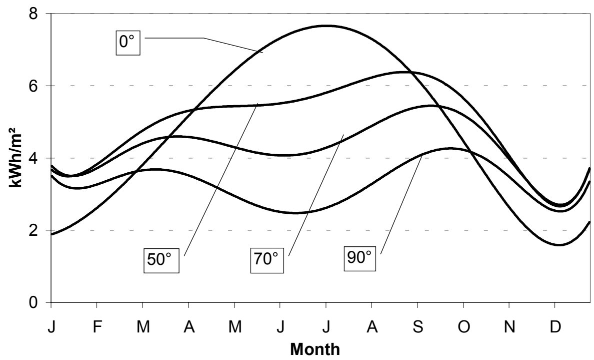

Fig. 2 – Calculated annual distribution of solar radiation on tilted surfaces.

4 Photovoltaic System

The system under consideration consists of a PV panel, a charger, a storage device, an inverter, the luminaire and the control unit (Fig. 3).

The selection of the panel can be based on the more critical criteria such as power output, semiconductor material (multi-crystalline, mono-crystalline, amorphous silicon), voltage charge of battery, dimensions and weight.

The dimensions, the weight and the shape of the panel were especially considered for the particular application. This study requires only the knowledge of dimensions of this panel and the efficiency (12%). The peak power of the PV panel is not considered for the calculations. However the weight and shape of the PV panel are two important factors for the safe mounting on the pole.

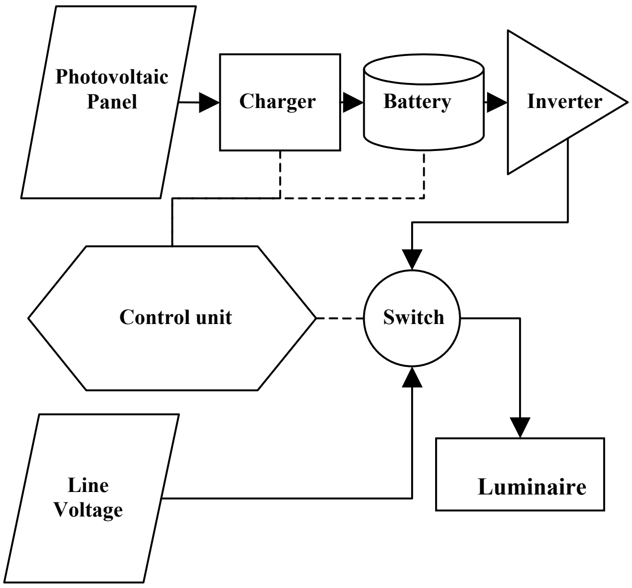

Fig. 3 – Block diagram of the system.

After extensive research and study as better choice it was found to be the BP Solar panel, BP SX 150 (Fig. 4). This has maximum power 150W and surface roughly 1.2m² according to the data sheet. These data are used for the calculation of the power output of the system. Table 1 shows the main characteristics of the PV panel.

Fig. 4 – Selected solar panel.

The system of this application consists of a poly-crystalline PV panel, a battery and an inverter. The surface of the panel is approximately 1.2 m² and its efficiency 12%. The capacity of the battery is 60 Ah and its efficiency 85%. The maximum power output of the inverter is 60 W and its efficiency 90%.

Table 1 – Characteristics of the PV panel.

Panel code	BP SX 150
Maximum power (Pmax)	150W
Voltage at Pmax	34.5V
Current at Pmax	4.35A
Warranted minimum Pmax	140W
Short-circuit current (Isc)	4.75A
Open-circuit voltage (Voc)	43.5V
Temp. coefficient of Isc	(0.065±0.015)%/°C
Temp. coefficient of voltage	-(160±29)mV/°C
Temp. coefficient of power	-(0.5±0.05)%/°C
NOCT	47±2°C
Length	1.593m
Width	0.790m
Weight	15.4Kgr

The power potential of the PV system (Fig. 5) is calculated using the annual distribution values of solar radiation (from Fig. 2) and the electrical characteristics of the system components. The power losses of battery and inverter were considered as well the tilting of the PV panel. It is obvious that the daily power potential of the system, for a full operation cycle, varies according to the tilting angle of the PV panel.

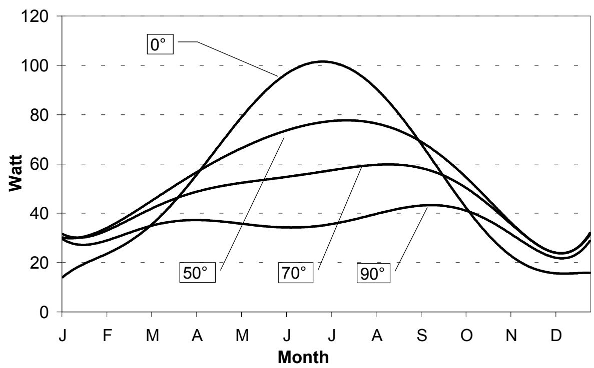

Fig. 5 – Calculated power potential of the system (tilted PV panel, battery and inverter).

It should be noted that the calculations determine the operation time of the system taking on account the hours of darkness minus 30΄ after the sunset and 30΄ before sunrise. This consideration was based on the actual operation schedule that is applied by the Public Power Corporation of Greece.

5 Lighting System

For the purposes of this investigation, a common road with two lanes is used. Due to the weak power potential of the PV system, a low consumption lamp with high efficiency is needed. The most commonly used types of lamps for street lighting are: low and high pressure sodium, mercury vapour and metal halide. From these types the metal halide was found to be the more suitable especially due to recent researches showing that their spectrum approaches better the mesopic vision [6].

The optimum combination of luminaire/lamp was found after several lighting calculations on the same type of road. It is a Philips SGS luminaire with a CDM-T 35 W metal halide lamp (Figs. 6, 7).

Fig. 6 –Selected luminaire (Philips, Iridium SGS 252 GB CR CT-POT) [8].

Fig. 7 – Selected lamp (Philips, CDM-T35W) [8].

The calculation of the lighting installation has been performed using Philips Calculux Road 5.0. The calculated lighting parameters (illuminance and luminance) as well as the technical characteristics of installation are presented in Table 2.

The low power potential of the system requires an efficient installation. Therefore a rather high maintenance factor is essential. The value of 0.85 for the maintenance factor is acceptable, given that the selected luminaire is of IP 65 type. However such an installation requires regular maintenance. This assumption is in accordance with recently proposed energy policy.

Table 2 – Characteristics of lighting installation.

Luminaire type		Philips Iridium SGS 252 GB CR CT-POT P.5
Lamp		Philips CDM-T35W/830
Lamp output		3300 lumens
Ballast		Electronic
DLOR		0.84
ULOR		0.00
TLOR		0.84
Total Power		44 W
Carriageway		Single carriageway
Road width		6 m
Reflection table		Asphalt CIE R3
Installation		Staggered
Height		7.00 m
Spacing		22.00 m
Overhang		0.50 m
Tilt 90^{o}		5.00 ^{o}
Overall Maintenance Factor		0.85
Luminance	Average	0.56 cd/m²
	Maximum	0.75 cd/m²
	Min/average	0.54 cd/m²
Illuminance	Average	8.60 lux
	Maximum	14.60 lux
	Min/average	0.57 lux
Surround ratio	Left	0.51
	Right	0.51
Threshold increment (TI)		12.70 %

The calculated illuminance and luminance distributions of the road under consideration are shown in Figs. 8 and 9. It should be noted that the all calculated values meet the requirements of CIE No.132 international standard for a typical low traffic road of M5 class [7].

One of the important parts of the system is the control unit. This unit controls the type of power source that will supply the luminaire. This procedure is performed every day before the lamp starting.

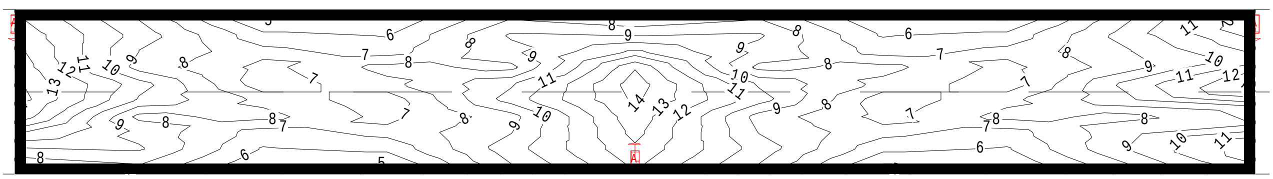

Fig. 8 – Illuminance calculation (Philips Calculux Road 5.0)

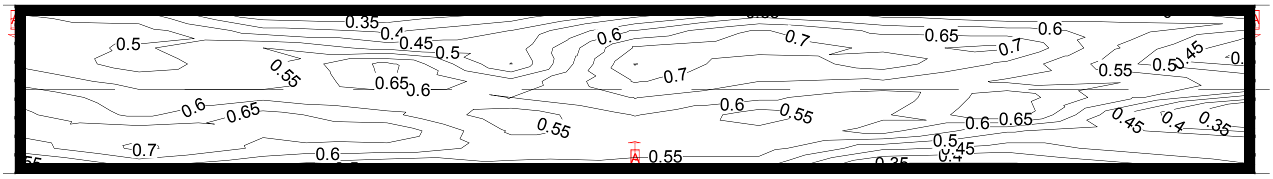

Fig. 9 – Luminance calculation (Philips Calculux Road 5.0)

The control unit monitors the stored energy and decides whether the energy is enough to supply the lamp for full operation cycle. The check level is always high enough in order to avoid undesirable interruption. If the energy is enough to supply the luminaire for the full operation cycle then the system allow battery to supply the system. On the other hand if the battery charge level is low the control unit connects the luminaire to the line voltage. Using this method the battery can be charged enough the next day, or days, in order to supply the system.

6 System Autonomy - Energy Savings

The total power consumption of the system with all losses calculated is about 44 W. At this point the issue is how many days the solar energy is able to operate the system, for a full operation cycle.

According to the system output diagram (Fig. 5) the system can operate in nominal wattage (44W) in most of the summer period and less in winter period. So it is obvious that the PV panel must be fixed in a suitable angle so as to collect the most energy at winter period and also enough energy at summer period. In this thought the threshold power is 44W. After calculation and examination, for all possible photovoltaic panel’s tilt angle, the appropriate angle appear to be 55° (south orientation). Fig. 10 shows the optimized annual system potential.

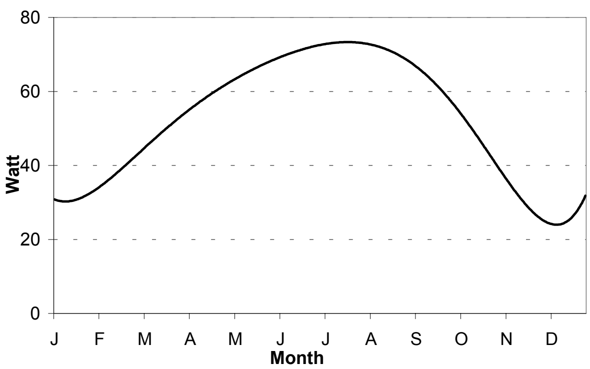

Fig. 10 – Power potential of the system (PV panel fixed at 55°)

The next step is to calculate the annual autonomy of the system. According to the values of diagram of Fig. 10 the PV system is able to charge the battery in the level that can supply the luminaire for a full operation cycle, about 250 days a year. As for the remaining 115 days, according to calculations, the battery can be fully charged in 2 or 3 days. This means that the battery can supply the luminaire for 65 cycles of operation. Therefore other 65 days are added. So the total autonomous days of operation are 315 per year.

The energy savings can be calculated for a year by comparing the energy consumption of the luminaire with and without the PV system. The operation cycle of the lighting system varies for 8.5 to 13.5 hours per day. At the calculations will be used the mean time of 11hour per day. So a stand alone lighting system (without PV system) needs energy equals to 44W*365days*11h/day= 176.7KWh per year from electric grid. Using the PV system the lighting system needs 44W*50days*11h/day= 24.2KWh per year from electric grid. The energy savings are about 86% as shown in Fig. 11.

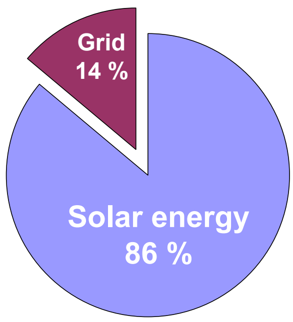

Fig. 11 – Autonomy of the PV lighting system

7 Conclusions - Remarks

The autonomy of the proposed system has been found to be about 315 days per year. This conclusion has been derived using the meteorological data of year 2001. According to weather conditions, sunlight and clouds, the days of autonomy may change slightly. For example a long period of bad conditions and low sunlight will force the system to operate using the line voltage for many days. On the other hand, the system will be fully autonomous during the sunny periods. As 2001 is a normal meteorological year the calculated days of autonomy represent the estimated operation for a typical year.

The lighting system of this application is most appropriate for lighting of low traffic roads. According to recent research works the metal halide lamp is suitable for mesopic vision lighting. There are many other combinations of luminaries that can be used in any cases of lighting.

One of the most important factors for the system efficiency is the location of the pole. In case that a pole is surrounded by high buildings or trees, which prevent the sunlight to reach the PV panel, the output of the system will be lower. The panel should be free of dust, pollution and other pollutants by regular maintenance. All these factors may change the total power output day by day.

The main objective of the system is the energy saving. This paper examined such a system that illuminate a low traffic road with clean energy for more than 85% of the annual operation time. If the proposed method is widely implemented, the savings are considerable, compared to the total energy consumption of street lighting.

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