Performance evaluation of small scale grid connected photovoltaic systems in Europe

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Abstract: - This study investigates the effect the recent reduction of government support in many EU countries has on the economic performance of small scale grid connected photovoltaic (PV) systems, with or without the use of a tracking system. The study was performed for three locations across Europe, namely Athens in Greece, Berlin in Germany and London in UK, each of which is described by different climatic and economic conditions. An economic analysis based on current economic data and local legislation has been performed for a 6.9kWp system and economic analysis diagrams are being presented to help evaluate any future changes of the feed-in tariff rates and capital cost, as well as possible feed-in tariff rate and capital cost subsidies.

Key-Words: - TRNSYS Simulation, Net Present Value (NPV), Feed In Tariff (FIT), Life Cycle Cost Analysis (LCCA), Photovoltaic (PV) Panel, Tracking System

1 Introduction

Today, the sun is one of the most important sources of renewable energy. Solar energy may be captured at almost every inhabited area of the planet and may be either transformed to thermal energy or converted directly into electric energy by using photovoltaic (PV) panels [1, 2].

PV panels were originally developed for use in space applications [3]; however, the swift technological growth of the last few decades lowered the production costs and increased their conversion efficiency, turning PV panels into an affordable investment for on-grid and off-grid electricity production applications [4-7]. In Europe, governments used to offer considerable monetary subsidies and other incentives in order to promote the adoption of clean forms of energy, especially by small companies and individual investors. PV energy generation is considered to be one of the better alternative energy sources [8, 9], therefore it received a large portion of the total government funding. Throughout the past decade, in several countries such as Portugal, Germany, UK and Greece, the favorable legislation led to significant investments taking place [10]. Nevertheless, the recent European economic crisis combined with the mixed feedback they were receiving from experts led several governments to withdrawing their support and dramatically reducing FIT rates [11, 12].

The aim of this study is to assess the annual energy production of a grid connected PV system installed at an annual optimal fixed inclination, as well as that of a system mounted on a two axis tracking system, in three different locations across Europe. For comparison purposes, we chose the installation locations under study to be situated in Greece, a country which still offers significant incentives to PV system investors, in contrast to the United Kingdom and Germany, both of which countries are major markets which dramatically reduced the FIT rates for ground based installations in 2011-12. To conclude, an economic analysis is being conducted taking into account the recent local economic data and legislation.

2 Simulation and system parameters

Hourly climatic data from the three selected European cities, such as the global solar irradiation, the global diffuse irradiation, the ambient temperature and the wind velocity, were used to calculate the performance parameters of the PV systems. Hourly values were used as they were distributed with TRNSYS [13], which were generated using Meteonorm [14].

The installation under study consists of 30 Solon Blue 230/07 polycrystalline panels, thus resulting to a total installed power of 6.9kWp. The technical specifications [15] of each panel are being displayed in table 1. The system is ground based, grid connected via a Fronius IG Plus 70-2 6.5kW inverter with a peak power input of 6.9kW [16]. The tracker considered in this paper is the Ovak T-6600 two-axis hydraulic slew drive mount. The motion
restrictions of the tracker are 223° horizontal movement (-111.5° to 111.5° with 0° being the true south) and 20° to 90° vertical movement. The system has an annual energy consumption of 40kWh which is being deducted from the annual electricity consumption.

**Table 1**

<table>
<thead>
<tr>
<th>PV Panel Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{eq}$</td>
</tr>
<tr>
<td>$V_{mp}$</td>
</tr>
<tr>
<td>$I_{mp}$</td>
</tr>
<tr>
<td>$V_{oc}$</td>
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<tr>
<td>$I_{sc}$</td>
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<tr>
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<td>$R_{s}$</td>
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<tr>
<td>$P$</td>
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<tr>
<td>NOCT</td>
</tr>
<tr>
<td>$\mu_{Voc}$</td>
</tr>
<tr>
<td>$\mu_{Isc}$</td>
</tr>
<tr>
<td>$\mu_{Prmp}$</td>
</tr>
</tbody>
</table>

Furthermore, a system performance degradation of 1% per annum, cable Ohmic losses of 105.9mOhm and module mismatch losses of 1% were taken into account. The simulation software TRNSYS was used for the study of the PV system. TRNSYS is a transient simulation program which can be used for simulation of a wide variety of solar energy applications, with proven results when simulating PV systems [17].

The single diode model of the PV module, displayed in equation 1, was initially developed by Townsend [18]. The model was incorporated into TRNSYS by Eckstein [19] and is also analyzed by Duffie and Beckman [20].

\[ I = I_L - I_o \left[ \exp \left( \frac{q \cdot V + I_m \cdot R_s}{N_c \cdot V_T} \right) - 1 \right] - \frac{V + I \cdot R_s}{R_{sh}} \]  

(1)

where $I$ is the module current, $I_o$ is the light current, $V$ is the module voltage, $I_m$ is the diode reverse saturation current, $R_s$ is the shunt resistance, $R_{sh}$ is the series resistance, $q$ is the electron charge, $k$ is the Boltzmann’s constant, $N_c$ is the number of cells in series and $T_c$ is the cell temperature (Kelvin). Rearranging the above equation (1) at short and open circuit conditions and at maximum power point, the equations obtained are nonlinear and are solved by numerical iterations using the short circuit current $I_{sc}$, open circuit voltage $V_{oc}$, temperature coefficient of short circuit current $\mu_{Isc}$, temperature coefficient of open circuit voltage $\mu_{Voc}$, current at maximum power point $I_{mp}$, voltage at maximum power point $V_{mp}$, series resistance and shunt resistance, which are specified by the manufacturer at Standard Test Conditions (STC). The STC are defined as: solar irradiance of 1kW/m², cell temperature of 25°C, and spectral distribution corresponding to an air mass of 1.5. These parameters concerning the chosen module are displayed in Table 1.

The model assumes that the PV array always operates at its maximum power point, meaning that the power output of the module is equal to its maximum power. The maximum power is derived by differentiating the power ($V \cdot I$), with respect to voltage and setting the results equal to zero, as displayed in equation 2.

\[ \frac{d(V \cdot I)}{dV} = 0 \]  

(2)

In order to calculate the model parameters for any cell temperature and solar irradiance, the light current $I_L$ and the diode reverse saturation current $I_o$ need to be defined. As displayed in equation 3, the light current $I_L$ depends on the solar irradiance on the inclined module surface ($G_T$), the cell temperature ($T_c$) the cell temperature at STC ($T_c,STC$), the light current at standard test conditions ($I_{L,STC}$) and the temperature coefficient of the short circuit current ($\mu_{ISC}$).

\[ I_L = \frac{G_T}{G_{STC}} \left[ I_{L,STC} + \mu_{ISC} (T_c - T_c,STC) \right] \]  

(3)

The diode reverse saturation current $I_o$ varies with the cell temperature and is given by equation 4:

\[ I_o = I_{o,STC} \left( \frac{T_c}{T_{c,STC}} \right)^{3} \exp \left[ \frac{E_g \cdot q}{k \cdot T_{c,STC}} \left( 1 - \frac{T_{c,STC}}{T_c} \right) \right] \]  

(4)

where $E_g$ is the band-gap energy of the semiconductor used in the cell (for silicon $E_g$ = 1.12eV) and $I_{o,STC}$ is the reverse saturation current at STC.

The model also calculates the cell temperature, due to its effect on the efficiency $\eta$ of the module. The most common manner to determine the cell temperature $T_c$ is using the NOCT correlated to the ambient air temperature $T_a$ as displayed in equation 5 [21]:

\[ T_c = T_a + (NOCT - 20^\circ C) \frac{G_T}{800} \left[ 1 - \frac{\eta_c}{(T_a + \alpha)} \right] \]  

(5)

Where $(t-\alpha)$ is the effective transmittance-absorbance product of the PV panel. NOCT is the Nominal Operating Cell Temperature which is defined as the cell temperature that results at an incident solar irradiance of 800W/m², an ambient temperature of 20°C, a wind speed of 1m/s and no load operation.

Furthermore, the simulation of the inverter is based on its efficiency versus power curve. One of the performance indicators that can be used to define
the overall PV system performance is the performance ratio (PR) [22, 23]. This ratio, which describes the percentage of energy produced (E) by the PV system with respect to the ideal performance, was used in the present study and is displayed in equation 6:

\[
PR = \frac{E}{H_T + n_{STC}}
\]  

(6)

where \(H_T\) is the incident solar irradiation on the inclined PV module surface and \(n_{STC}\) is the efficiency of the module under Standard Test Conditions.

For the above model the incident total solar irradiance \(G_t\) on the inclined module surface is required, due to its linear dependency on light current (equation 3), and is being calculated by using equation 7, assuming that both diffuse and ground reflected irradiance are isotropic:

\[
G_r = (G - G_d\cos\theta_a + G_d(1 + \cos\beta)) - \frac{G \cdot \rho \cdot (1 - \cos\beta)}{2}
\]  

(7)

Where \(G\) is the total irradiance on horizontal surface, \(G_d\) is the diffuse solar irradiance on horizontal surface, \(\theta\) is the solar incidence angle, \(\theta_a\) is the solar zenith angle, \(\beta\) is the slope of the surface and \(\rho\) is the ground reflectance coefficient (Albedo). The Albedo is always considered equal to 0.2 throughout this study for comparison purposes.

Obviously, a two-axis tracker will reduce the incidence angle \(\theta\) to zero. However, the use of the tracker also has an effect on the diffuse and reflected radiation by affecting the slope angle \(\beta\). The calculation of the solar incidence angle \(\theta\) is important because the total solar irradiance on the inclined surface is proportional to \(\cos\theta\), as can be seen from equation 7. This angle is calculated through equation 8, from solar position coordinates (solar altitude angle \(h\), solar azimuth angle \(a\)), as well as the surface orientation \(\gamma\) and slope \(\beta\) [24].

\[
\cos \theta = \cos \beta \sinh a + \sin \beta \cos \theta \cos \omega \]  

(8)

The solar altitude angle \(h\) is given by equation 9.

\[
h = \sin^{-1}(\sin \omega \sin \delta + \cos \omega \cos \delta \cos \phi) \]  

(9)

The declination \(\delta\) of the sun is given by equation 10.

\[
\delta = 23.45 \sin \left(360 \frac{284 + n}{365}\right) \]  

(10)

Where \(\phi\) is the latitude of the location, \(n\) the day of the year and \(\omega\) the solar hour angle.

Thus, the program calculates at each time step of the simulation the incident solar irradiation on the PV modules and the electricity produced by the PV system by using the appropriate system parameters and the meteorological data from the three European locations. This process is applied for both PV systems, fixed and tracking.

For fixed mount PV systems, the annual optimal tilt angle for each location has been determined by previous researchers and can be described by the simple mathematical model displayed in equation 11 [25].

\[
\beta_{opt} = 0.764\phi + 2.14^\circ \]  

(11)

A simple economic analysis appraisal is undertaken for the electrical energy produced, based on Life Cycle Cost method. This method is widely applied for determining energy systems economics [26]. The set of presumed economic parameters are shown in Table 2.

The net cash flow of each year is displayed in equation 12:

\[
CF_T = [ES \times (FIT \times (1 + i_{FIT})^{-1})] - PP_T - MC \times (1 + i_{MC})^{-1} \]  

(12)

where \(ES\) is the energy sold to the grid during year \(T\), \(FIT\) is the feed-in-tariff price, \(i_{FIT}\) is the feed-in-tariff annual inflation rate, \(MC\) is the annual maintenance cost and \(i_{MC}\) is the inflation rate of the maintenance and operating costs.

The Bank Loan periodic payments \(PP\) are being calculated using equation 13:

\[
PP = CS \times \left(\frac{i_{BL} + \left(\frac{i_{BL}}{1 + i_{BL}}\right)^Y - 1}{1 + d}\right) \]  

(13)

Where \(CS\) is the capital cost of the system, funded entirely from a bank loan, \(i_{BL}\) is the annual bank loan interest rate and \(Y\) is the loan repayment period (years).

The Net Present Value \((NPV)\) is being used to perform a comparative economic analysis for a 20 year period. The \(NPV\) is the sum of the present worth discounted at a rate of \(d\) and is given by equation 14.

\[
NPV = \sum_{T=1}^{T=20} \frac{CF_T}{(1 + d)^T} \]  

(14)

Table 2

<table>
<thead>
<tr>
<th>Economic Parameters</th>
<th>Athens Fixed Tracker</th>
<th>Berlin Fixed Tracker</th>
<th>London Fixed Tracker</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS (€)</td>
<td>16380</td>
<td>22560</td>
<td>16380</td>
</tr>
<tr>
<td>MC (€)</td>
<td>327.6</td>
<td>451.2</td>
<td>327.6</td>
</tr>
<tr>
<td>i_{MC}</td>
<td>5%</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td>i_{BS}</td>
<td>3%</td>
<td>3%</td>
<td>3%</td>
</tr>
<tr>
<td>i_{BL}</td>
<td>4%</td>
<td>4%</td>
<td>3.9%</td>
</tr>
<tr>
<td>d</td>
<td>5%</td>
<td>5%</td>
<td>5%</td>
</tr>
<tr>
<td>FIT (€/kWh)</td>
<td>0.395</td>
<td>0.395</td>
<td>0.1795</td>
</tr>
<tr>
<td>i_{FIT}</td>
<td>0.9%</td>
<td>0.9%</td>
<td>1.2%</td>
</tr>
</tbody>
</table>
Under all calculations, the end of life (EOL) salvage value of the systems is considered to be 0, the period of loan repayment is considered to be 10 years and the period of the financial analysis is 20 years.

3 Results and discussion
In the following paragraphs, the annual energy and economic results of the PV systems are being presented divided into three subsections, one for each country. The energy production percentage increase and the performance ratio increase are also being calculated. A spider diagram displays how FIT price and capital cost changes would affect the NPV of the economic investments, the NPV, that a bank savings account deposit of equal value as the initial capital cost of the systems would yield for investment comparison purposes, as well as the effect parallel legislation subsidies would have on these two major economic figures.

Table 3 displays the annual energy production, the performance ratio (PR) and the global to diffused irradiation ratio (H/Hd). Production in Athens is significantly higher due to the climatic profile of the area. It is interesting to note however that the PR increase a two-axis tracker induces improves at higher latitudes due to the lower temperatures (Fig. 1). As latitude increases, the tracker improves energy production during summer further but at the same time the performance gains are reduced during winter, due to the high diffuse irradiation and sunshine hours distribution [27]. Table 4 displays the NPV of the PV system over a period of 20 years, as well as the equivalent value a bank deposit of the capital cost would yield (NPVb) over the same period.

As Fig. 2 displays, investing on small scale PV energy production near Athens is an advantageous economic investment and should remain as such until the end of 2015. In Athens, the use of a two-axis tracking system imposes a significantly higher capital cost but the NPV value of the investment at the end of the 20-year economic analysis increases considerably.

Figures 2, 3 and 4 display how the major FIT price drops which took place at the beginning of this year in Germany and the United Kingdom, combined with the considerably lower annual energy production in contrast to that of Athens, Greece, forbid investments on ground based small PV energy production systems these locations.
It can also be derived that under the current economic parameters the utilization of a two-axis tracker at northern latitudes not only will not improve the parameters of the investment but degrades it even further.

These outcomes are worrisome as intense R&D on PV technologies took place during the past decade primarily thanks to government subsidies [9, 28], with forecasts which date only 3 years old expecting considerable economic support 10 to 20 years into the future [29,30].

4 Conclusion
This study investigated the energy and economic performance of small scale grid connected PV systems in Europe considering the new economic parameters effective after the second quarter of 2012. The results of this comparative study lead to the following main conclusions:

- The annual performance ratio increase of systems implementing two-axis trackers over fixed inclination systems is affected positively by latitude. Because of the lower environmental temperatures, lower energy losses due to conversion from D.C. to A.C. and operation cell temperature increase the annual performance ratio of the systems.
- The line exhibiting the NPV of the investment on a two-axis tracker constantly has a greater slope than that of the fixed inclination system. The slope is primarily governed by the annual energy production increase the two-axis tracker imposes.
- With the feed in tariff rates effective until December 31, 2015, small scale energy production PV stations will remain a viable economic investment in continental and island Greece. The utilization of a two-axis tracker improves the NPV of the investment over a 20 year analysis period.
- After the recent reductions on FIT rates and favorable legislation, ground-based PV systems are no longer a viable economic investment in Germany or UK. Considerable subsidies need to be offered in order for ground based systems to be a viable economic investment again, as in most other EU countries.
- Strong R&D on PV energy generation took place in the recent years as a result of the favorable government subsidies and legislations. Forecasters were expecting this support to last much longer; however, as major governments are dropping their support the future of PV technologies now seems uncertain.

References:


