ENERGY AND ECONOMIC COMPARATIVE STUDY OF A TRACKING VS. A FIXED PHOTOVOLTAIC SYSTEM

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Abstract

In this study the performance of a two-axis tracking system is compared to that of an identical fixed inclination system facing south at optimal annual inclination angle. The study was performed in three locations across Europe; Athens in Greece, Stuttgart in Germany and Aberdeen in UK, characterized by different climatic conditions. The monthly and annual energy output of a real world small scale electricity generation photovoltaic installation with a rated power of 6.4kWp has been calculated, taking into account all electrical and temperature losses, as well as the power consumption of the two axis tracker which has been deducted from the annual generation of the system. For each geographic location the optimal annual inclination angles were calculated correlated to the latitude of the location. Finally, an economic analysis based on current economic data and local legislation has been performed 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. This study determines that investing on grid connected photovoltaic systems critically depends not only on the area’s climatic conditions but also on the national legislation and regional energy prices.

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

Introduction

Perhaps the most important renewable energy resource is the sun. Solar energy can be captured almost anywhere on the planet and converted directly into electric power by using photovoltaic panels (Meral and Dinçer 2011). Photovoltaic panels were initially developed for use in space applications (Oliver and Jackson 2001). The rapid technological advancements of the last few decades however lowered the manufacturing costs and increased their efficiency, making the photovoltaic panels an affordable investment for on-grid and off-grid electricity generation applications (Denholm and Margolis 2007, Luque and Hegedus 2003, Lenzen 2010). With photovoltaic panels and systems becoming more popular with each passing day, significant effort is being made to increase their efficiency, performance and lower their cost. One such method is the use of motorized mounts instead of fixed mounts which allow the installation to follow the apparent path of the sun's motion, minimizing the incidence angle and increasing the performance of the system. The angle of incidence is one of the most critical factors affecting the performance of a photovoltaic panel, which angle of incidence θ is the angle between the sun's rays and the normal to the surface of the photovoltaic panel. When photovoltaic panels are installed on fixed mounts, the angle θ is almost never optimal and performance degrades considerably, especially during early morning or late noon hours. Thus motorized mounts with tracking mechanisms were developed, following the apparent path of the sun's motion by using either lighting sensors or a PLC programmed with a stellar database.

There have been a few studies regarding the performance increase the installation of a two-axis tracking mount can offer, although most were performed in locations of low latitude. Ali Al-Mohamad in Damascus, Syria, carried out an experimental test in 2004 in order to assess the impact the use of a tracker would have on the performance of a Siemens SM50_18A2 50Wp PV panel and found the increase exceeding 20%; however the experiment was only performed in a single particular day of August, thus the results lack the long-term statistical value of practical use (Al-Mohamad 2004). Likewise, Maatallah et al. investigated the theoretical daily performance of fixed, single and dual-axis tracking photovoltaic panel in Monastir city, Tunisia. The study concluded that the gains made by a dual-axis tracking panel relative to a traditional fixed panel reach 30% and 44% respectively in the winter and summer solstice days (Maatallah, et al. 2011). In early 2011, Fernando Cruz-Peragón et al performed a theoretical approach with the purpose of quantifying the solar gain which comes from the use of a two-axis tracker in Spain, as well as the economic viability of such a system, estimating an annual energy generation global gain of 21-25% (Cruz-Peragón, et al. 2011). Not long afterwards, Ángel A. Bayod-Rújula, Ana M. Lorente-Lafuente and Fernando Cirez-Oto, estimated that a two-axis tracker offered an energy output gain of 31% over a fixed optimal tilt layout while studying a 26.46kWp installation in Zaragoza, Spain(Bayod-Rújula, et al. 2011). Francisco Javier Gomez-Gil et al. compared the energy generation of real photovoltaic systems installed in southern Spain under four different configurations. Their study concluded that the annual gain of two-axis tracking system compared to a fixed is 25.2%(Gómez-Gil, et al. 2012).

It becomes clear that two-axis tracking motorized mounts can significantly improve a system's annual energy generation; however they are a significant monetary investment and the overall system performance improvement is moderate at best, therefore their usability and efficiency needs to be examined before their implementation. Furthermore, nearly all studies are being performed at relatively low latitudes; therefore it is unsafe to assume that a two-axis tracker would offer an equal performance gain as the latitude increases. The aim of this study is to compare the annual energy generation of a grid connected photovoltaic (PV) system installed at an annual optimal fixed inclination with a two axis tracking system, for three different locations across Europe, namely Athens in Greece, Stuttgart in Germany and Aberdeen in UK. Finally, an economic analysis of both systems was conducted taking into account the local economic data and legislation, in order to realize whether stand-alone photovoltaic electricity generation systems are a viable economic investment after the recent massive cuts on the feed in tariff rates.

Methodology

Climatic data from the three selected European cities were used to calculate the solar irradiation received by a surface with a fixed and variable tilt angle during a year. The technical characteristics of a commercially available photovoltaic panel and inverter, in combination with the processed climatic data, were used to calculate the energy generated by the fixed and tracking system. The PV system described in paragraph 2.2 remains identical for all of the three sites. Analytical equations for the aforementioned calculations are presented in the following sections. Finally, a sensitivity analysis concerning the economic viability of the systems is undertaken.

Climatic Data

Hourly climatic data such as the global solar irradiation, the global diffuse irradiation, the ambient temperature and the wind velocity were used. In the table 1, the monthly average daily irradiation on horizontal surface ($\overline{\mathrm{H}}$), the monthly average daily diffuse irradiation on horizontal surface ($\overline{\mathrm{H}_d}$), the ambient temperature (T_{av}) and the wind velocity (U_w) are shown for the three chosen cities. For Athens real hourly climatic data as these were recorded in the Renewable Energy Laboratory of the Department of Energy Technology at the Technological Educational Institution of Athens (38.0N, 23.675E) were processed. For Stuttgart (48.83N, 9.2E) and Aberdeen (57.17N, 2.08W), hourly values were used as they were distributed with

TRNSYS ("Trnsys 16 - a Transient System Simulation Program" 2006), which were generated using Meteonorm ("Meteonorm Version 5.1" 2004).

Table 1: Climatic Data

Month	Athens				Stuttgart				Aberdeen			
	$\overline{H}$ $\left(\frac{kWh}{m^2 day}\right)$	$\overline{H_d}$ $\left(\frac{kWh}{m^2 day}\right)$	T_{av} (°C)	U_w (m/s)	$\overline{H}$ $\left(\frac{kWh}{m^2 day}\right)$	$\overline{H_d}$ $\left(\frac{kWh}{m^2 day}\right)$	T_{av} (°C)	U_w (m/s)	$\overline{H}$ $\left(\frac{kWh}{m^2 day}\right)$	$\overline{H_d}$ $\left(\frac{kWh}{m^2 day}\right)$	T_{av} (°C)	U_w (m/s)
January	2.10	1.07	8.36	2.26	0.91	0.60	0.00	4.60	0.44	0.33	3	5.29
February	3.01	1.57	10.63	2.47	1.71	1.00	1.10	3.10	1	0.69	2.34	5.10
March	4.85	2.33	13.99	2.35	2.57	1.50	5.00	4.60	2.27	1.24	4.53	5.59
April	5.39	2.27	16.57	2.71	3.77	2.00	7.80	3.60	3.5	2.06	6.42	4.80
May	6.13	2.45	20.46	2.89	4.73	2.60	12.80	3.10	4.74	2.58	8.6	4.60
June	7.29	2.55	24.67	3.33	5.14	2.80	15.60	3.10	4.84	2.81	11.24	4.18
July	6.92	2.42	28.15	3.21	5.30	2.70	17.80	3.10	4.44	2.79	13.3	4.11
August	6.22	2.18	26.35	2.78	4.49	2.30	17.80	3.10	3.5	2.31	13.02	4.09
September	4.25	1.44	23.01	2.62	3.26	1.70	14.40	3.10	2.45	1.45	11.02	4.51
October	3.67	1.58	18.88	2.94	1.95	1.20	9.40	3.60	1.28	0.87	8.73	4.80
November	2.33	1.21	16.05	2.73	1.18	0.80	3.90	4.10	0.55	0.41	3.94	5.09
December	1.53	0.82	11.15	2.65	0.72	0.50	1.70	4.60	0.28	0.21	3.83	5.19
Annual	4.47	1.82	18.19	2.75	2.98	1.64	8.90	3.64	2.44	1.48	7.53	4.78

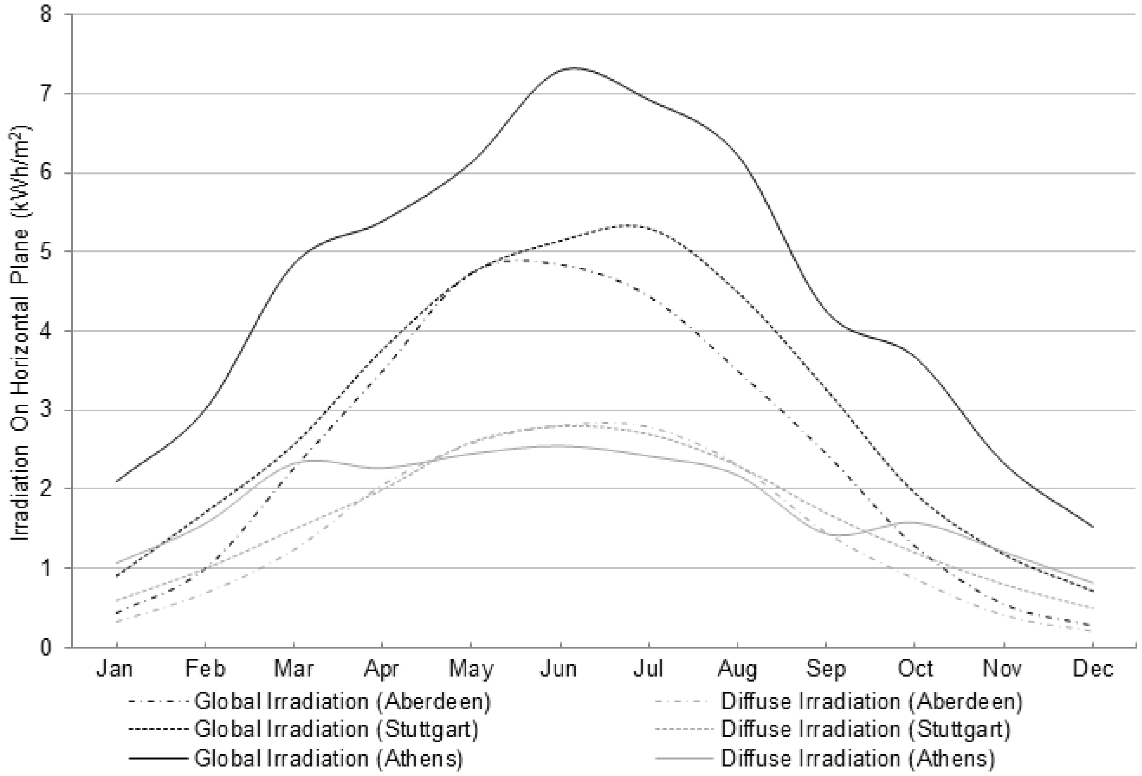

Figure 1. Daily Average Global and Diffuse Irradiation on Horizontal Plane in Athens, Stuttgart and Aberdeen.

The monthly global and diffuse irradiation on horizontal surfaces in the three selected cities is shown in figure 1. From this graph it can be derived that the global irradiation generally decreases with increasing latitude, yet a comparison of the annual climatic conditions shows that the north-south gradient is not as strong during the summer as it is during the winter, which is due to the influence of the longer day in the north. From the same figure it can be seen that the diffuse irradiation is affected positively by latitude in summer and the fraction of the diffuse to global irradiation increases in winter. Figure 2 displays the global irradiation incident on the inclined plane for systems both fixed at optimal inclination angles and mounted on two-axis trackers, from which it becomes clear that the energy generation increase induced by a two-axis tracker is inversely interrelated to the percentage of diffuse to global irradiation.

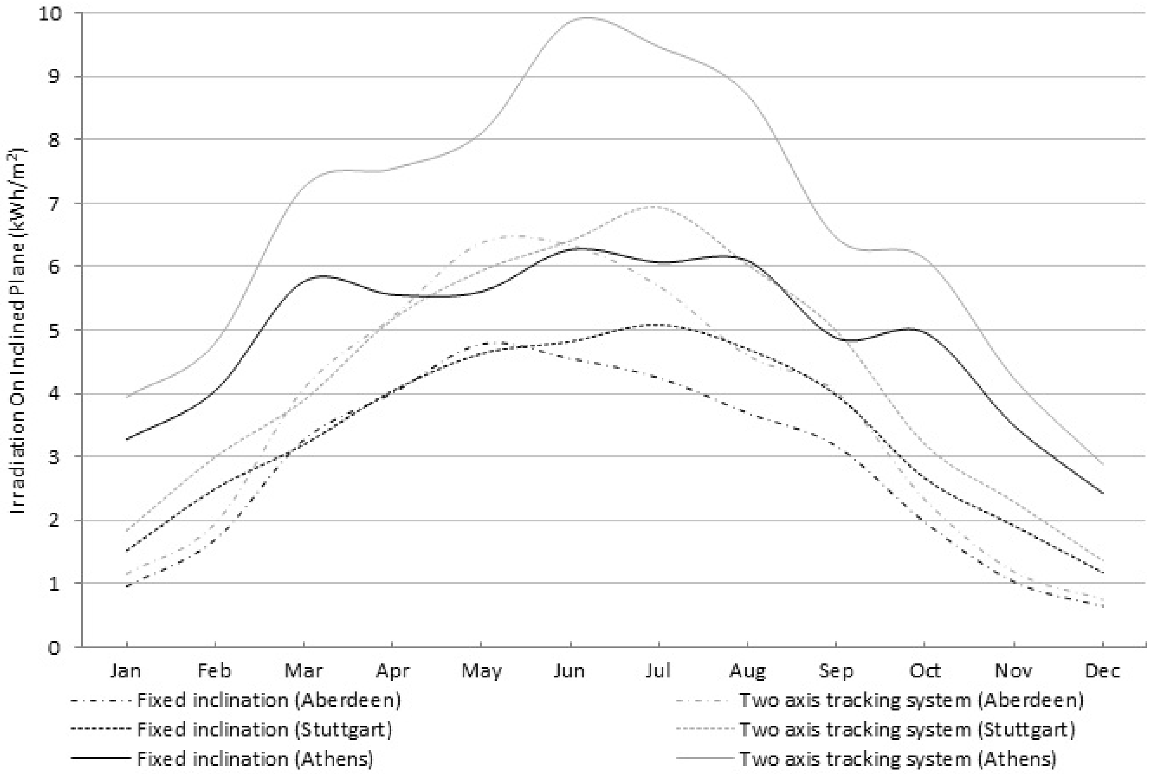

Figure 2. Daily Average Global and Diffuse Irradiation on Inclined Plane in Athens, Stuttgart and Aberdeen

Photovoltaic System

The installation under study consists of 32 Sun Tech Solar STP200-18/Ud polycrystalline panels, rated at each with an efficiency of 13.6%, thus resulting to a total installed power of 6.4kWp. The technical specifications ("Suntech Power Polycrystalline Solar Module Datasheets" 2010) of each panel are being displayed in table 2.

The system is grid connected via a Power One PVI-6000-OUTD 6.0kW inverter. This single phase inverter has a minimum power point (MPP) voltage of 90V and a maximum MPP voltage of 580V. The rated maximum efficiency of the inverter is 97% (Euro 96.4%). The photovoltaic system power output peaked at 5.85kW during the simulation; therefore a 6.0kW inverter is more than sufficient for the particular configuration and the most monetarily sound equipment choice.

The tracker under study 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 power consumption of 40kWh which is deducted from the annual electricity consumption.

Table 2: Suntech Power STP200-18/Ud panel specifications

V_{mpp}	26.2 V
I_{mpp}	7.63 A
V_{oc}	33.4 V
I_{sc}	8.12 A
R_{sh}	250 Ohm
R_s	0.227 Ohm
P	200±3%W_p
NOCT	45±2°C
μ_{Voc}	-116 mV/°C
μ_{Isc}	+0.045 %/°C
μ_{Pmpp}	-(0.47 ± 0.05)W/°C

Finally, a system performance degradation of 1% per annum and module mismatch losses of 2% were taken into account, as well as cable Ohmic losses which were estimated to be 94.7mOhm for the size of this installation.

Simulation

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. Also, the simulation of grid connected PV system with TRNSYS, provides a good agreement with the experimental results(Quesada, et al. 2011).

The single diode model of the PV module was initially developed by Townsend(Townsend 1989). The model was incorporated into TRNSYS by Eckstein (Eckstein 1990) and is also described by Duffie and Beckman(Duffie and Beckman 2006). According to that model, the module current I, at fixed temperature and solar irradiance, equals the light current I_L minus the diode current and the shunt resistance current:

$$I = I_L - I_o\left[\exp\left(q * \frac{V + I_m * R_s}{N_s * \gamma * k * T_c}\right) - 1\right] - \frac{V + I * R_S}{R_{sh}} \tag{1}$$

Where: V is the module voltage, I_o is the diode reverse saturation current, R_{sh} is the shunt resistance, R_s is the series resistance, γ is the diode quality factor, q is the electron charge = 1.602·10-19 Coulomb, k is the Boltzmann's constant = 1.381·10-23 J/K, N_s is the number of cells in series, 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 μ_{Isc}, temperature coefficient of open circuit voltage μ_{Voc}, current at maximum power point I_{mpp}, voltage at maximum power point V_{mpp}, series resistance and shunt resistance, which are specified by the manufacturer at Standard Test Conditions (STC). The STC are defined as: solar irradiance of 1 kW/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 2.

The model assumes that the PV array always operates at its maximum power point which means that the power output of the module is equal to its maximum power. The maximum power is derived by differentiating the power (V·I), with respect to voltage and setting the results equal to zero.

$$\frac{d(V * I)}{dV} = 0 \tag{2}$$

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 Io need to be defined.

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 ($\mu_{I,sc}$).

$$I_L = \frac{G_T}{G_{STC}}\left[I_{L,STC} + \mu_{Isc}\left(T_c - T_{c,STC}\right)\right] \tag{3}$$

The diode reverse saturation current Io varies with the cell temperature and is given by the following equation:

$$I_o = I_{o,STC}\left(\frac{T_c}{T_{c,STC}}\right)^3 \exp\left[\left(\frac{E_g * q}{\gamma * k}\right)\left(1 - \frac{T_{c,STC}}{T_c}\right)\right] \tag{4}$$

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 ηc of the module. The most common manner to determine the cell temperature Tc is using the Nominal Operating Cell Temperature (NOCT), which is defined as the cell temperature that results at an incident solar irradiance of 800W/m2, an ambient temperature of 20oC, a wind speed of 1m/s and no load operation, correlated to the ambient air temperature Tα as follows (Matte, et al. 2006):

$$T_c = T_a + (NOCT - 20°C)\frac{G_T}{800}\left[1 - \frac{n_c}{(\tau\alpha)}\right] \tag{5}$$

Where (τα) is the effective transmittance-absorptance product of the PV panel.

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 photovoltaic system performance is the performance ratio (PR)("Guidelines for the Assessment of Photovoltaic Plants, Document B, Analysis and Presentation of Monitoring Data. Issue 4-3" 1997, "Photovoltaic System Performance Monitoring—Guidelines for Measurement, Data Exchange and Analysis" 1998). This ratio, which describes the percentage of energy generated (E) by the PV system with respect to the ideal performance, was used in the present study and it is given as:

$$PR = \frac{E}{H_T * n_{STC}} \tag{6}$$

Where HT is the incident solar irradiation on the inclined PV module surface and ηSTC is the efficiency of the module under Standard Test Conditions.

In 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 with the following equation, assuming that both diffuse and ground reflected irradiance are isotropic:

$$G_T = (G - G_d)\frac{cos\theta}{cos\theta_z} + \frac{G_d * (1 + cos\beta)}{2} + \frac{G * \rho * (1 - cos\beta)}{2} \tag{7}$$

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

It is clear that a two-axis tracker will not only reduce the incidence angle θ to zero but also has an effect on the diffuse and reflected radiation by affecting the slope angle β. The calculation of the solar incidence angle θ is important because the total solar irradiance on the inclined surface is proportional to cosθ, as can be seen from equation 7. This angle is calculated from solar position coordinates (solar altitude angle (h), solar azimuth angle (α)), as well as the surface orientation (γ) and slope (β), using the well-known equations from solar geometry (Axaopoulos 2011).

Thus, the program calculates at each time step of the simulation the incident solar irradiation on the PV modules and the electricity generated by the PV system by using the appropriate system parameters and the meteorological data from the three European locations. For fixed mount photovoltaic systems facing south, extensive research has been made trying to determine the optimal slope angle with researchers in good agreement regarding the monthly optimal tilt(Benghanem 2011, Gunerhan and Hepbasli 2007, Jimenez 2009, Gopinathan, et al. 2007). Tian Pau Chang (Chang 2009) calculated the annual optimal tilt angle (β) of a solar collector in the northern hemisphere correlated to the geographic latitude (φ) and found it to be equal to 0.764φ + 2.14°, φ ≤ 65°. Assuming that the tilt angle of the fixed system is not adjustable, when performing calculations regarding a fixed inclination system the annual optimal inclination for each location was used.

Economic analysis

A simple economic analysis appraisal is undertaken for electrical energy generated, based on Life Cycle Cost method. This method is widely applied for determining energy systems economics. With this method all costs and benefits are discounted to their present values. The appraisal requires the synthesis of both photovoltaic system performance results and a number of economic parameters. Required performance data have been calculated using the aforementioned simulation model. The set of presumed economic parameters are shown in Table 3. Since most of the economic parameters change with time and geographic area and is difficult to make reliable predictions about future trends in the value of money, a sensitivity analysis based on net present value is undertaken to evaluate the economics of energy generated under various investment costs and feed in tariff price fluctuations.

The net cash flow of each year is:

$$CF_T = [ES * (FIT * (1 + i_{FIT})^{T-1})] - PP_T - MC * (1 + i_{MC})^{T-1} \tag{8}$$

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 with the following formula:

$$PP = CS * \left(i_{bl} + \frac{i_{bl}}{(1 + i_{bl})^{Y} - 1}\right) \tag{9}$$

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 25 year period. The NPV is the sum of the present worth discounted at a rate of d and is given by the following equation:

$$NPV = \sum_{T=1}^{T=25} \frac{CF_T}{(1+d)^T} \quad (10)$$

The economic viability of the systems is being calculated with the help of a spreadsheet which can be used to calculate and ultimately compare the economic viability of any grid-connected photovoltaic system under multiple economic parameters, as long as the annual energy generated has been calculated.

Table 3: Economic data

Economic parameters used	Athens		Stuttgart		Aberdeen	
	Fixed inclination	Two-Axis Tracking	Fixed inclination	Two-Axis Tracking	Fixed inclination	Two-Axis Tracking
Capital cost	13700€	18600€	14700€	20880€	14180€	20360€
Maintenance and operating costs	274€	372€	294€	418€	425€	611€
Annual maintenance and operating costs inflation rate	5%	5%	3%	3%	5%	5%
Bank savings interest rate	3%	3%	3%	3%	3.5%	3.5%
Bank loan interest rate	5.5%	5.5%	5%	5%	4.5%	4.5%
Discount rate	5%	5%	5%	5%	5%	5%
Feed In Tariff (FIT)	0.25€/kWh	0.25€/kWh	0.1271€/kWh	0.1271€/kWh	0.11€/kWh	0.11€/kWh
FIT increase rate per annum	0.9%	0.9%	1.2%	1.2%	4%	4%

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 15 years and the period of the financial analysis is 25 years. Bank lending and deposit interest rates are the average extracted from numerous banks, which is also in line with the data provided by official statistic services (CIA 2011).

Results and discussion

In the following paragraphs, the annual energy generation performance of the photovoltaic systems is being presented, divided into three subsections, one for each country. The energy generation percentage increase and the performance ratio increase have also been calculated. The energy generation results are followed by an economic analysis of both the fixed inclination and two-axis tracking photovoltaic systems, divided into three subsections, one for each country. A spider diagram displays how feed in tariff (FIT) price and capital cost changes would affect the NPV of the economic investments, the NPV 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 parallels legislation subsidies would have on these two major economic figures.

Energy generation

From figures 3, 4 and 5, it becomes apparent that the energy generated by the tracking system is greater than that of the fixed system, particularly during the summertime period between the two equinoxes. Outside of that period, it decreases significantly as latitude increases. Consequently, in January and December in Aberdeen, the energy generated by the tracking system is almost identical to that of the fixed system because the portion of diffuse radiation of the global radiation is very large (figure 1). It is also noteworthy to mention that in Aberdeen the utilization of a two-axis tracker increases the annual energy generation more than in Stuttgart because of the long summertime days and extended sunshine hours during that period. Therefore, it becomes apparent that even if the annual diffuse to global irradiation ratio increases, the annual energy generation percentage increase that a two-axis tracking system would yield will not necessarily shrink as it is dependent on more than one parameter.

Athens, Greece

Due to the southern latitude and the sunlit climate of the region, the utilization of a two-axis tracker improves the annual energy generation of a PV system installed in Athens by 34.8%. The performance ratio increased by 0.8%. Although the largest energy generation increases from using a two-axis tracker occurs during the summer months, a significant increase is evident during the winter months as well.

Table 4: Annual energy generation of system at 38.0N, 23.675E (Athens)

	Fixed Inclination (β=31°)	Two-Axis Tracking
Annual Energy generation	9285,1 kWh	12599 kWh
Annual Performance Ratio	80.6%	81.4%
Annual Energy Generation Percentage Increase	34.8%	
Annual Performance Ratio Percentage Increase	0.8%	
Annual Diffuse to Global Irradiation Ratio	40.7%	

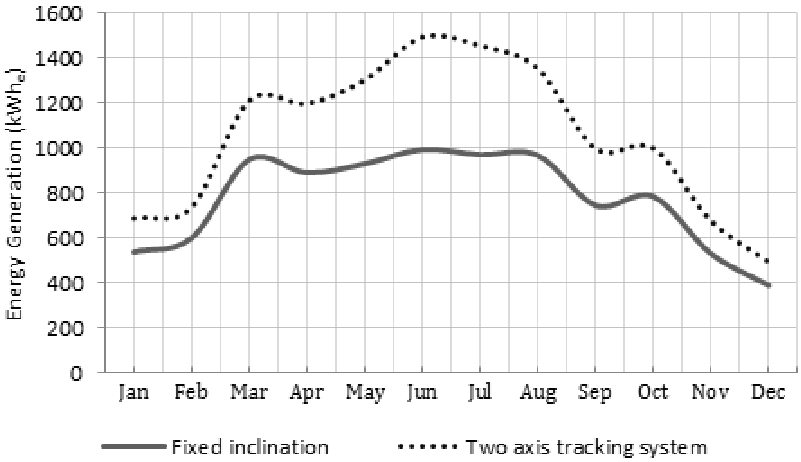

Figure 3. Monthly Energy Generation (Athens)

Stuttgart, Germany

The annual solar irradiation on a horizontal surface in Germany varies between 780kWh/m^2 and 1240kWh/m^2 while the average sunshine hours diverge between 1300 and 2000 per annum(Tereci, et al. 2009). Enjoying a mean of about 1700 sunshine hours per annum, the city of Stuttgart can be considered a median location for Germany. Even though the annual performance ratio increases by 1.1%, the annual energy generation percentage increase is 28.7%. During the winter months the short days account for a minor generation increase, which increase explodes during the summer because of the many sunshine hours and relatively low environmental temperatures.

Table 5: Annual energy generation of system at 48.83N, 9.2E (Stuttgart)

	Fixed Inclination (β=39°)	Two-Axis Tracking
Annual Energy Generation	6614,4 kWh	8510 kWh
Annual Performance Ratio	84.4%	85.5%
Annual Energy Generation Percentage Increase	28.7%	
Annual Performance Ratio Percentage Increase	1.1%	
Annual Diffuse to Global Irradiation Ratio	55.0%	

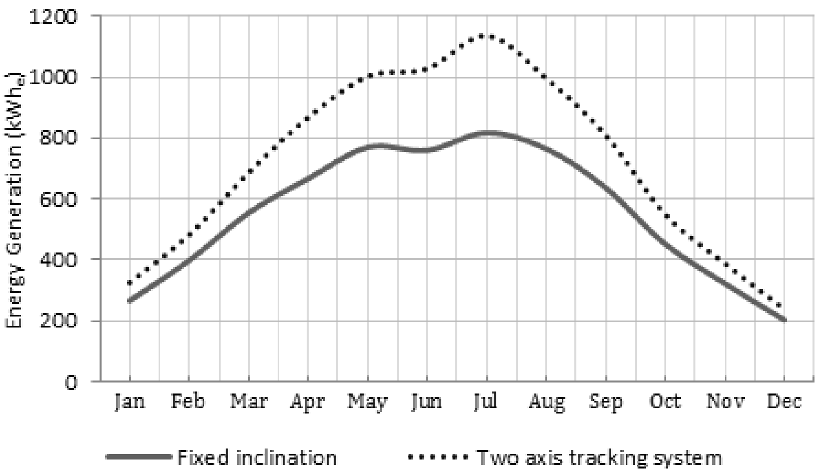

Figure 4. Monthly Energy Generation (Stuttgart)

Aberdeen, United Kingdom

Despite the maritime climate of Scotland, Aberdeen enjoys less than 1400 sunshine hours per annum while the high latitude makes for short days during the winter and large days during the summer months. Most of the energy generation during the winter months comes from diffuse radiation and therefore the use of a tracker yields no performance increase. On the contrary, a high energy generation increase of over 33% occurs during the summer months. The annual energy generation increase percentage from the use of a two-axis tracker is 30.4% and the annual performance ratio increase is 1.3%.

Table 6: Annual energy generation of system at 57.17N,2.08W (Aberdeen)

	Fixed Inclination (β=46°)	Two-Axis Tracking
Annual Energy Generation	5645,4 kWh	7362 kWh
Annual Performance Ratio	85.1%	86.4%
Annual Energy Generation Percentage Increase	30.4%	
Annual Performance Ratio Percentage Increase	1.3%	
Annual Diffuse to Global Irradiation Ratio	60.5%	

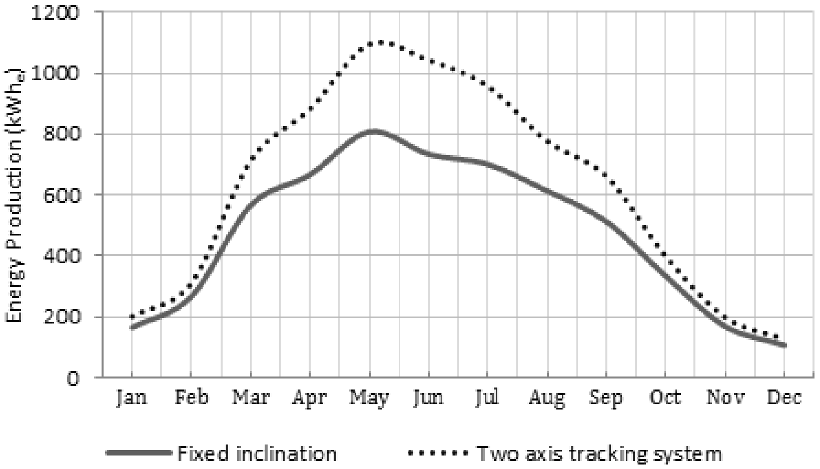

Figure 5. Monthly Energy Generation (Aberdeen)

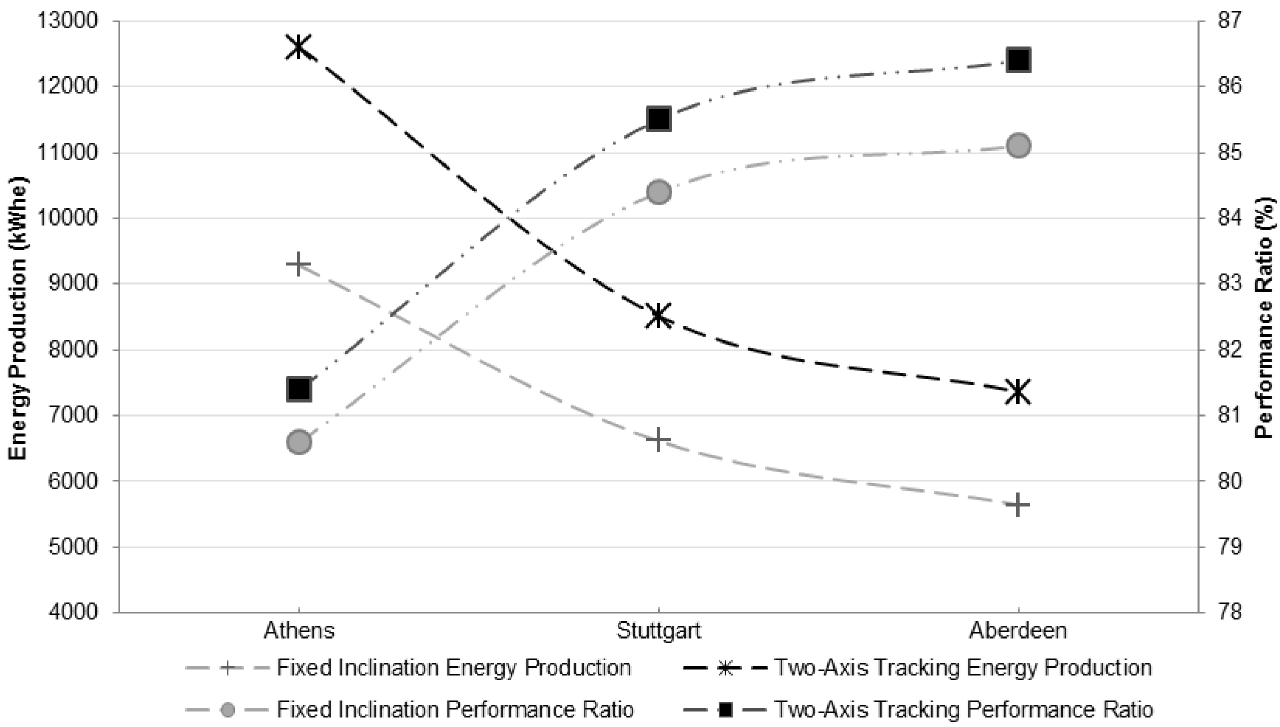

Figure 6. Annual Energy Generation and Performance Ratio at every location

Figure 6 displays the annual energy generation and performance ratio of both the fixed inclination and two axis tracking systems at all three locations. Although energy generation declines as latitude increases, the lower temperatures increase the performance ratio of the systems.

Economic Analysis

Figures 7, 8 and 9 display the economic viability of investing in a small scale photovoltaic energy generation system in each of the three locations and how future FIT and capital cost variations would affect the NPV of the investment, with the current analysis results being the reference point. The diagrams also display the effect possible future government subsidies regarding the FIT price and capital funding could have on the economic viability of the systems. These diagrams displayed that investing on small scale photovoltaic energy generation near Athens remains a viable financial investment even after the severe feed in tariff reduction which took place in August 2012, reducing the price per kWh from 0.395€ to 0.25€. 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 25-year economic analysis increases considerably. On the contrary, the recent major FIT price drops in Germany and the United Kingdom and in conjunction with the considerably lower annual energy generation in contrast to that of Athens, Greece, made economic investments in small photovoltaic energy generation systems in Stuttgart and Scotland highly unattractive.

Table 7: Economic Analysis Results

	Athens		Stuttgart		Aberdeen	
	Fixed Inclination	Two-Axis Tracking	Fixed Inclination	Two-Axis Tracking	Fixed Inclination	Two-Axis Tracking
NPV (PV System)	11.453 €	15.525 €	-8.337 €	-13.452 €	-12.131 €	-18.977 €
NPV (Bank Deposit)	5.122 €	6.954 €	5.496 €	7.806 €	6.185 €	8.881 €

A recent study also displayed that PV generation is not viable in Ireland either, also because of the declining FITs and high capital cost (Li, et al. 2011). It can also be derived that under the current economic parameters the utilization of a two-axis tracker at northern latitudes not only does not help increase the NPV of an investment but decreases it even further, a result of the large capital cost a two-axis tracker imposes. These outcomes are worrisome as intense R&D on PV technologies took place during the past decade primarily thanks to government subsidies (Gonçalves da Silva 2010, Lior 2012). Furthermore, forecasts which date only 3 years old were expecting considerable economic support 10 to 20 years into the future (Raugei and Frankl 2009, Lior 2010).

Athens, Greece

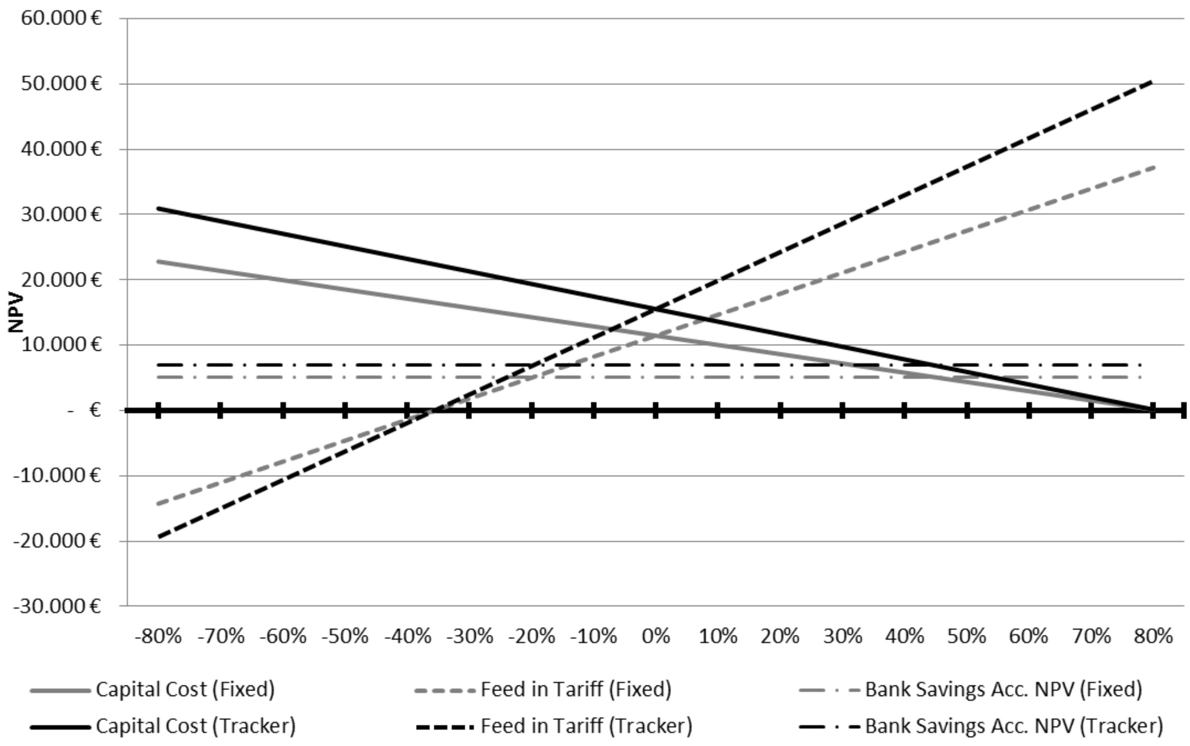

Figure 7. Economic Analysis Spider Diagram (Athens)

Figure 7 clearly shows that despite the FIT price reduction down to 0.25€/kWh, small scale photovoltaic grid connected energy generation systems remain an advantageous monetary investment in Greece. Starting from February 2013, the FIT price faces a reduction of 0.45% per 6 months and thus it will gradually drop down to 0.1986€/kWh by the February of 2015, a total decrease of 20% compared to the current price. Despite that decrease, grid connected systems will remain a viable investment until the end of 2015; however, a simple bank deposit would pose identical investment value relying on interest income alone. As the investment risk of a bank deposit is virtually zero, it is highly unlikely for a PV system to be realized as a monetary investment beyond that point.

Stuttgart, Germany

FIT price for ground mounted, grid connected installations in Germany faced a significant drop of 37% since 2010 and 55.8% since 2006. After the recent FIT price reductions and with the current FIT rate of 0.1271€/kWh (October 2012 - standalone systems), small scale photovoltaic energy generation power stations are not a viable economic investment in Germany unless considerable subsidies were to be offered. Due to the significant capital cost, the use of a two-axis tracker decreases the NPV value of the investment even lower than that of a fixed inclination system.

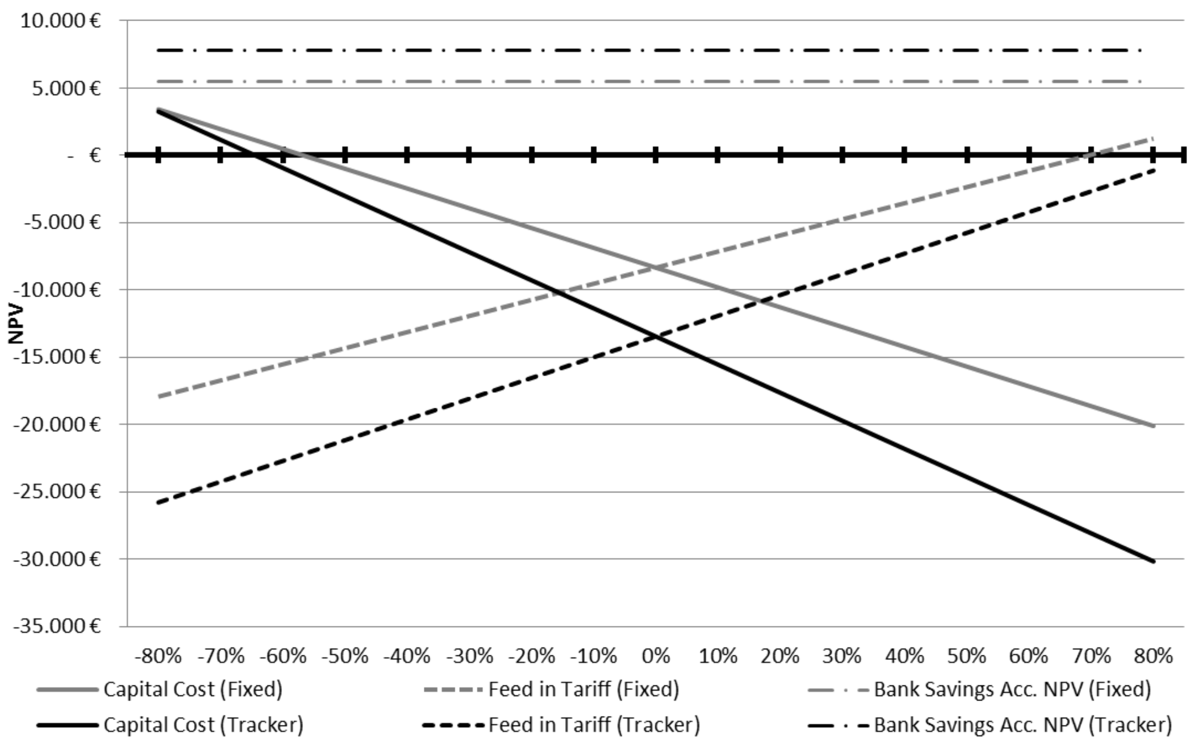

Figure 8. Economic Analysis Spider Diagram (Stuttgart)

If the 2006 FIT rates were to apply again (0.406€/kWh) and if all other economic variables remain stable, the NPV of the fixed inclination system would increase to 17.937€ and of the two-axis tracking system to 20.351€, which would make small photovoltaic energy generation systems a competitive monetary investment with a discounted profit over 25 years about 3 times higher than a bank savings account deposit equal to the initial capital cost (figure 8).

Aberdeen, United Kingdom

In the United Kingdom, the FIT price effective from the 3rd of October 2012 for 4-10kWp photovoltaic grid connected energy generation systems faces a massive drop of 55.5%. Before the FIT price drop, the investment in a photovoltaic energy generation system was advantageous, with a 25-year analysis NPV of 18369.8€ for a fixed inclination system and 19781.8€ for a system utilizing a two-axis tracker. With the new FIT price of 0.11€/kWh (1GBP = 1.24EUR) it becomes evident that investing on photovoltaic energy generation stations in Scotland no longer is a sound economic investment (figure 9).

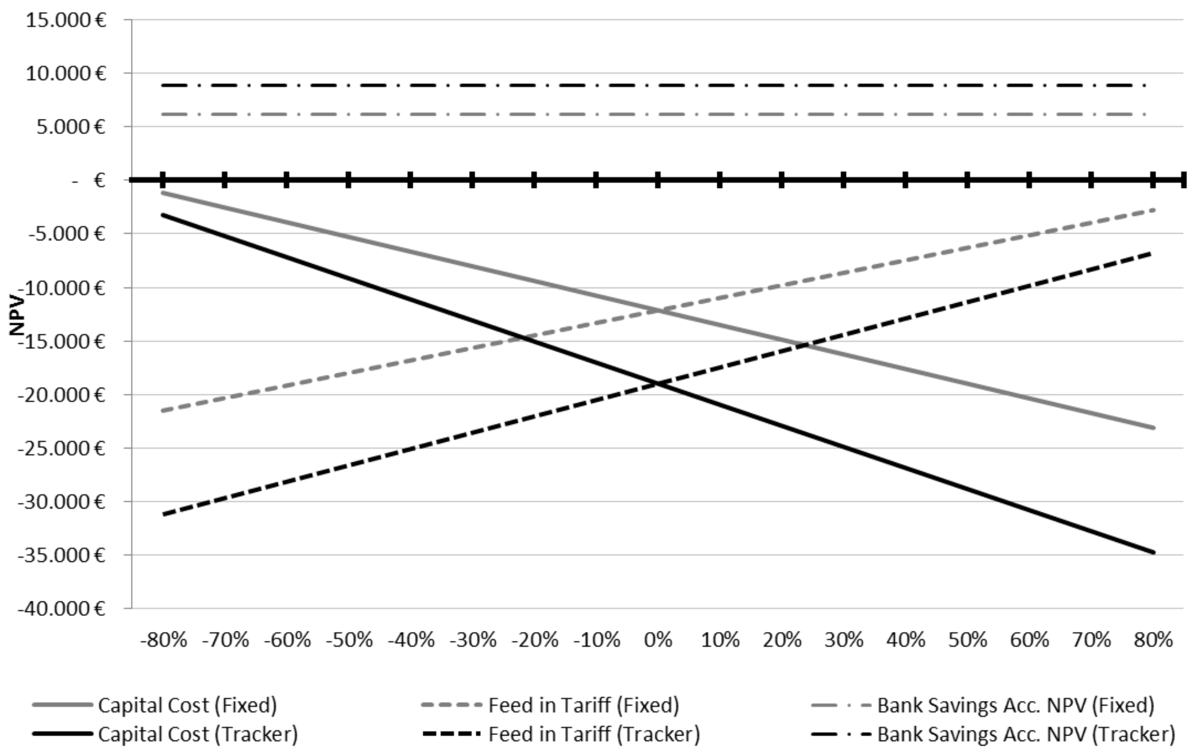

Figure 9. Economic Analysis Spider Diagram (Aberdeen)

Conclusion

The potential energetic benefits from the implementation of a two-axis tracker on photovoltaic systems installed in three regions in Europe are investigated in this paper. An economic analysis has also been performed for each of the three regions. The results of this comparative study lead to the following main conclusions:

1. At higher latitudes, the diffuse irradiation is nearly equal to the global irradiation during each winter; therefore, the use of a tracking device is virtually obsolete. The diffuse irradiation during the summer is also affected positively as the latitude increases.

2. The utilization of a two-axis tracker yields better results during the summer months at every location due to the longer path of the sun on the celestial sphere by taking advantage of the optimum incidence angle. As latitude increases this phenomenon is further enhanced.

3. 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.

4. While the fraction of diffuse to global irradiation has a substantial diminishing effect on the annual energy generation percentage increase a two-axis tracking system would yield

over a fixed inclination system, however the distribution of sunshine hours during the course of a year is equally important.

5. With the feed in tariff rates effective today, small scale energy generation photovoltaic stations will remain a viable economic investment in Athens until the February of 2015, at which point the investment in a stand-alone photovoltaic system would be of equal worth to a simple bank deposit. The recent feed in tariff reductions of August 2012 however undoubtedly greatly reduced the appeal of investing on photovoltaics. The utilization of a two-axis tracker further increases the net present value of the investment over a 25 year analysis period.

6. The constant reductions of the feed in tariff rates during the past few years turned land-based energy generation photovoltaic systems into an unappealing business investment in Germany. With the feed in tariff rates effective from March 2012, investments in energy generation photovoltaic stations became unprofitable in Scotland.

7. Considerable government subsidies must be introduced for the photovoltaic stations to become viable economic investments in the UK and Germany once again, as in most other EU countries.

8. Strong R&D on photovoltaic 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.

9. 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 generation increase the two-axis tracker imposes.

10. Investing on grid connected photovoltaic systems critically depends not only on the climatic conditions of the area but also on the national legislation and regional energy prices.

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