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PV Energy Production Over Greece: Comparison of Predicted and Measured Data of Medium-Scale Photovoltaic Parks

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Abstract

The aim of this study is to explore the real PV energy production over Greece and to investigate the calculation accuracy of different approaches concerning the energy production of a medium-scale PV park. In Greece there are many photovoltaic parks installed with a named power up to 100kWp, due to favourable Feed-in-Tariff sales price according to recent Greek regulation. Considerable differences between real and predicted data of typical 100 kWp PV systems were observed for almost all prefectures of Greece. However, no significant differentiations were found between two known software packages used for the purposes of the study. In order to examine deeper this inconsistency, two different climate databases were used in numerous simulations for more than 50 sites all over Greece. These results were compared with real data derived from more than 200 existing 100kWp Photovoltaic Parks in Greece. Conclusions of great importance for possible investors, banks, suppliers and Authorities are derived, as large deviations were proved to exist in a constant basis.

1. Introduction

Energy is an essential ingredient of socio-economic development and economic growth. Renewable energy provides a variable and environmental friendly option and national energy security at a time when decreasing global reserves of fossil fuels threatens the long-term sustainability of global economy [1]. Renewable technologies are considered as clean sources of energy and optimal use of these resources minimises environmental impacts, produce minimum secondary wastes and are sustainable based on current and future economic and social societal needs [2]. Renewable energy technologies provide an excellent opportunity for mitigation of greenhouse gas emission and reducing global warming through substituting conventional energy sources. The concept of the PV energy evaluation is not something new. Monthly maps of solar radiation are an important pre-requisite for solar energy applications, as they can illustrate optimal regions for locating solar energy conversion systems such as solar PV or thermal power plants. Ideally these maps should be based on a dense array of surface pyranometers, but due to costs, only a few instruments can be practically employed. To extend this limited data set, several methods have been used, including interpolation and derivation of solar radiation from sunshine duration or cloud cover [3,4]. One alternative solution is to use satellite-derived solar radiation data. These data have an advantage over radiation data from ground-based measurements in terms of better temporal and spatial coverage. The best way to evaluate solar systems is to use information of solar irradiance, measured throughout the time [5]. There exist different global irradiation databases available, such as meteonorm [6], European Atlas of solar irradiation [7], PVgis, or Censolar [8]. However, some mismatches between different sources are observed [9]. It's true that there are many corresponding studies concerning the solar irradiation of different countries and there are also many comparisons between predicted and measured data like the Turkish example [10], the Egypt's example [11] and the Pakistan's example [12]. A lot of models for forecasting the solar radiation exist, which conclude to solar radiation maps of Greece. However, until now there are not any real energy data derived from medium scale PV parks per region in Greece. For the purposes of this study real measurements have been taken from more than 200 already installed PV parks in Greece. Then, these data are compared to simulated results derived from the implementation of known software packages using different meteorological databases for the same sites that the measurements were taken. As known, solar radiation values of every country are illustrated in maps providing a helpful tool and a useful approach of relative studies. In this paper, an attempt to create illustrative PV energy production maps based on real data is made. Finally, an attempt to provide rational explanations concerning the deviations between theoretical and real data for all the above mentioned sites in Greece is made, so that anyone (investors, Authorities, Banks, etc) may have at once a quite accurate result for more reliable studies and investments.

2. Proposed methodology

The proposed methodology consists of 4 steps, as shown in Fig. 1. Initially, in Step 1 by means of PVsyst 5.2 Preliminary design [13] a typical and verified project design for an indicative medium-scale (100kWp) photovoltaic park is realised. The energy production of this typical 100kWp project is simulated in each prefecture of Greece. Using the "Preliminary Design" mode of PVsyst 5.2 the system yield evaluations are performed instantaneously in monthly values, using only a very few general system characteristics, without specifying specific system components. Fifty three simulations are totally performed in this step, exactly as many as the Prefectures of Greece.

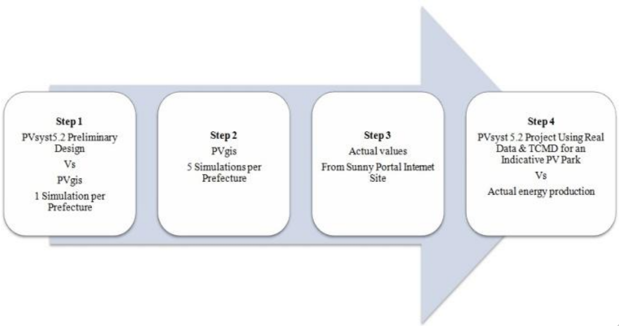

Figure 1: The five steps of proposed methodology

On the other hand PVgis is a database of solar radiation and temperature data, combined with a web interface that lets a user to calculate the energy output of photovoltaic (PV) systems. PVgis [14] is also a scientific tool that allows us to do research on the performance of PV systems over large geographical areas and estimate the potential for solar energy deployment in Europe [15]. Fifty three simulations, at the same sites with PVsyst 5.2 were performed. Step 1 concludes to a point by point comparison between PVsyst 5.2 and PVgis.
In Step 2, 265 simulations of PVgis (5 simulations in each prefecture) concerning the electrical energy are performed. Five simulations in each prefecture have been taken in order to find out -with an acceptable accuracy- the average energy produced.
In Step 3, the energy values resulted from the above software packages are compared with the actual values derived from the Sunny Portal internet site. In this internet site (SMA) there are diagrams, which provide the annual energy production of each PV Park through its operational time. Real data from more than 200 similar size PV parks using fixed mounting systems are retrieved. Their distribution reaches up to 17 measurements in each prefecture.
More specifically and in order to investigate the difference between the predicted and the real energy produced by the PV parks, the predicted energy must be calculated with the highest possible accuracy (Step 4), thus real and detailed equipment data (panels, inverters, cables, mounting system, etc) as well as accurate meteorological data must be used for running the PVsyst 5.2 project software. Meteorological data of high accuracy are derived from the Technical Chamber of Greece "TCMD" [16]. As expected, the results of this analysis are, beside the comparison between the real and the predicted data, the comparison between the prediction accuracy of the two programmes themselves.

3. Results

3.1 Results of Step 1: Comparison between PVsyst 5.2 Preliminary Design and PVgis on common PV sites

In Step 1, PVsyst 5.2 Preliminary Design results and PVgis results are compared. Both softwares are used worldwide by architects, engineers, researchers etc, because they allow a quick evaluation of a PV system yield to be performed using the exact location of the photovoltaic park.
As opposed to PVsyst, the PVgis software has its own database of solar radiation and temperature data. PVsyst does not include a climate database, so the PVgis's database is imported. The calculation is made using these two simulation softwares, for the same geographical point with the same climate database. Fifty three (53) simulations were performed, one for each prefecture of Greece.
For each prefecture, a typical photovoltaic park of 100kWp nominal power is considered, using a standard polycrystalline module type, a typical single phase inverter, on a fixed mounting system properly installed for adequate ventilation of the panels. The results of these simulations are gathered in Table 1.

Table 1. Comparison between PVsyst 5.2 Preliminary Design versus PVgis

Prefecture	PVgis output in kWh/kWp	PVsyst output in kWh/kWp
Corinthia	1390	1372
Achaea	1310	1298
Elis	1310	1304
Arcadia	1390	1366
Messenia	1320	1319
Argolis	1380	1365
Lakonia	1360	1355
Aetolia	1250	1246
Evritania	1300	1279
Fhthiotis	1270	1253
Phocis	1290	1279
Voeotia	1400	1390
Attica	1440	1434
Euboea	1400	1388
Arta	1250	1239
Ioannina	1280	1265
Preveza	1230	1224
Thesprotia	1240	1233
Karditsa	1270	1256
Trikala	1280	1268
Larissa	1270	1260
Magnesia	1320	1306
Evros	1240	1214
Xanthi	1230	1206
Rodopi	1230	1205
Grevena	1330	1299
Kozani	1350	1316

Prefecture	PVgis output in kWh/kWp	PVsyst output in kWh/kWp
Kastoria	1370	1326
Florina	1310	1281
Pella	1270	1256
Imathia	1270	1249
Pieria	1340	1332
Kilki	1260	1239
Thessaloniki	1290	1263
Chalkidiki	1330	1310
Serres	1230	1216
Kavala	1230	1207
Drama	1240	1213
Chania	1400	1393
Rethymno	1430	1421
Heraklion	1440	1430
Lasithi	1470	1476
Corfu	1310	1301
Lefkada	1250	1250
Kefalonia	1290	1283
Zakynthos	1290	1285
Cyclades	1450	1436
Rodhes	1540	1555
Dodecanese	1530	1535
Samos	1450	1444
Chios	1440	1426
Lesbos	1410	1387
Limnos	1320	1300

From Table 1 it is easily figured out that for the same site of each region the simulation results calculated by the two softwares are practically the same. In most cases PVgis is giving slightly higher amount of photovoltaic electric energy potential than PVsyst 5.2 Preliminary Design.

3.2 Results of Step 2: Improved calculation results by the use of PVgis

As stated in Step 2, there was no important difference between the results of the two simulation softwares, so for this step the PVgis software is used.

It is known that every region has different climate (meteorological and microclimate). So, in order to obtain more reliable data per region, i.e. an annual energy production average, the PVgis software is used considering five different sites per Prefecture or Island. More than 260 calculations have been performed all over Greece, the averages of which (per prefecture) are presented in Table 2.

The results are presented with increasing values in terms of Produced Energy.

Table 2. Theoretical energy yielded by PV parks in Greece according to PVgis - Average of five (5) sites per prefecture

Prefecture	Produced Energy (kWh/kW p.y)
Drama	1118
Evros	1144
Rhodope	1144
Xanthi	1148
Lefkada	1154
Kavala	1156
Serres	1162
Kilkis	1188
Kefalonia	1190
Thessaloniki	1200
Zakynthos	1210
Corfu	1214
Pella	1214
Imathia	1234
Limnos	1236
Arta	1242
Preveza	1246
Ioannina	1250
Chalkidiki	1250
Grevena	1254
Thesprotia	1260
Pieria	1262
Larissa	1264
Aetolia	1272
Karditsa	1274
Kozani	1274
Evrytania	1276

Prefecture	Produced Energy (kWh/kW p.y)
Trikala	1276
Florina	1282
Kastoria	1294
Rethymno	1300
Arcadia	1304
Magnesia	1308
Lesbos	1310
Fhthiotis	1312
Elis	1316
Phocis	1322
Chania	1326
Cyclades	1334
Achaea	1346
Samos	1348
Messenia	1350
Chios	1362
Heraklion	1370
Laconia	1374
Argolis	1380
Voeotia	1380
Dodecanese	1386
Lasithi	1388
Corinthia	1392
Euboea	1408
Rhodes	1416
Attica	1446

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According to the PVgis simulation software, the energy yielded by PV parks in northern Greece and specifically in Drama, Evros and Xanthi is the lowest in the country and is approximately 1120 kWh/kWp to 1150 kWh/kWp for fixed mounting systems. The regions with the highest PV energy potential are Euboea, the island of Rhodes and Attica reaching higher values, from 1408 kWh/kWp up to 1450 kWh/kWp.
In order to obtain a better feeling of the simulated results, a coloured map is created using the data of Table 2. This is the first attempt of a Photovoltaic Energy Map of Greece and is presented in Figure 2. The map presents with colours the energy production capability of each region, mainly because of the different meteorological and local microclimate data.

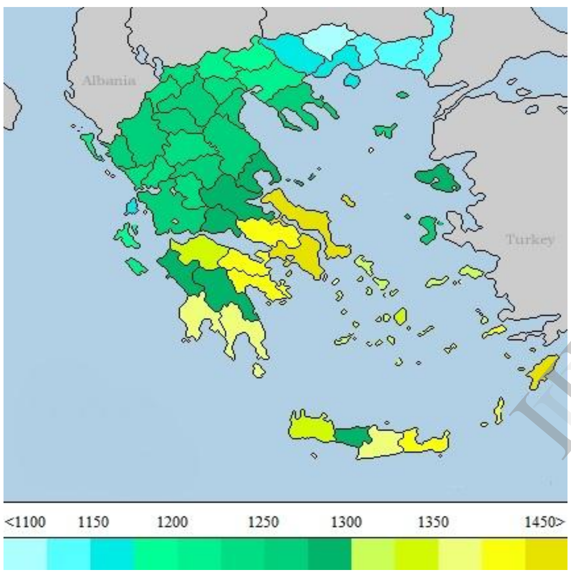


Figure 2. Energy map of Greece using PVgis software. Prices are in kWh/kWp

3.3 Results of Step 3: Actual average energy produced by medium low voltage scale PV parks in Greek areas

Following the main aim of this investigation, which is the creation of an updated Photovoltaic Energy map based on actual measurements, we proceeded in Step 3. Retrieving necessary information from Sunny Portal Internet site, an adequate sample from each prefecture is collected. The result of this analysis, after the appropriate processing, is the annual average PV energy potential of each site.
In this step, more than two hundreds thirty (233) operating Photovoltaic parks with fixed mounting systems and with nominal power from 10kWp up to 100kWp have been measured. The measured data were analysed and two hundreds and one (201) of them were found adequate, long lasting and reliable for further treatment. This fact led us to take into consideration different sample from each site according to the provided data. More specifically, there were cases that information from seventeen (17) PV installations in one area has been retrieved. The data are presented in table 3.

Table 3. Real annual average energy yielded by 201 PV parks in Greece

Prefecture	Produced Energy (kWh/kWp.y)	Prefecture	Produced Energy (kWh/kWp.y)
Chalkidiki	1380	Aetolia	1550
Pieria	1420	Corinthia	1560
Kavala	1440	Argolis	1570
Imathia	1440	Attica	1570
Serres	1450	Rethymno	1580
Evrytania	1450	Arcadia	1580
Kastoria	1450	Messenia	1580
Florina	1460	Euboea	1580
Fhthiotis	1460	Phocis	1590
Evros	1470	Arta	1620
Thessaloniki	1480	Chania	1626
Karditsa	1480	Ioannina	1670
Larissa	1490	Elis	1670
Magnesia	1490	Laconia	1670
Xanthi	1500	Achaea	1680
Drama	1510	Heraklion	1710
Kilkis	1510	Lasithi	1750
Kozani	1520	Rhodes	1780
Voeotia	1520	Dodecanese	1810
Pella	1550		

According to the measurements of real energy collected from medium scale low voltage PV parks, prefectures with the lowest photovoltaic energy potential are Chalkidiki, Pieria, Kavala and Imathia with an energy amount of 1380 kWh/kWp up to 1440 kWh/kWp.
The highest energy potential is measured in the islands of the Aegean's sea, in Rhodes, in Crete and in the most prefectures of Pelloponisos, with an energy value of approximately from 1670 kWh/kWp to 1810 kWh/kWp. According to the data of Table 4 a coloured map is illustrated, as shown in Figure 3, showing with colours a real energy range expected to be produced in each region of Greece, when a PV system is used.
It is important that the Energy maps illustrated in Fig.2 (simulated data) and Fig.3 (real data) have almost the same distribution. The more north and east the site in Greece is, the more Energy is produced.

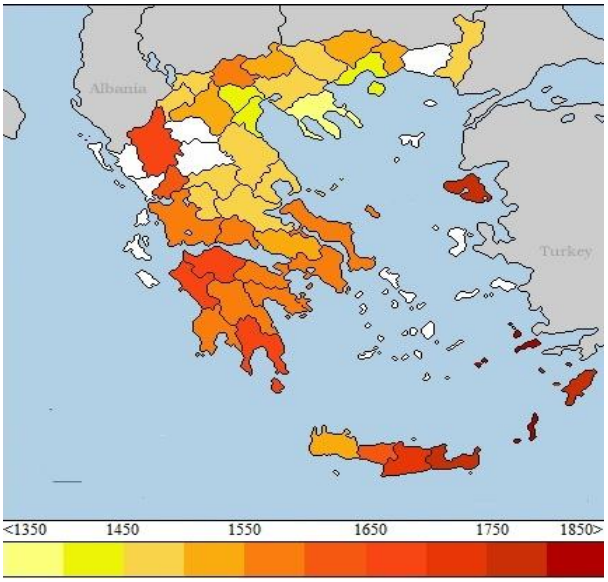


Figure 3. Photovoltaic Energy map of Greece using real data. Prices are in kWh/kWp

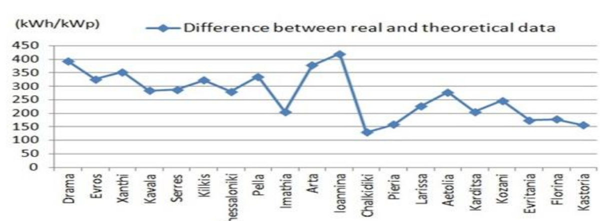
The main result, however, between the two maps is that there is a significant constant difference between the predicted and the real (measured) data, showing the last ones always higher than the former ones, as it will be analytically presented in the results discussion section. It is worth noting that the highest energy value simulated by PVgis software is almost the lowest real value according to the measurements.

3.3.1 Steps 2 & 3 results comparison and discussion

The comparison between the PVgis simulation results and the real energy data collected from the measurements of medium scale PV parks existed in Greece showed remarkable differences, as it is analytically presented in Table 4. The second column presents the average of five energy simulations using PVgis software, while the third column contains the measured energy data of PV parks in these Prefectures. On the last column the differences between PVgis and real data are presented (in %).

Table 4: Percentage differences between average of five points coming from PVGIS and real data concerning each region of Greece

Prefecture	STEP 2 PVGIS average of 5 points (kWh/kWp)	STEP 3 Real energy data (kWh/kWp)	Difference in percentage (%)
Drama	1118	1510	35,06
Evros	1144	1470	28,49
Rhodope	1144		
Xanthi	1148	1500	30,66
Lefkada	1154		
Kavala	1156	1440	24,56
Serres	1162	1450	24,78
Kilkis	1188	1510	27,10
Kefalonia	1190		
Thessaloniki	1200	1480	23,33
Zakynthos	1210		
Corfu	1214		
Pella	1214	1550	27,67
Imathia	1234	1440	16,69
Limnos	1236		
Arta	1242	1620	30,43
Preveza	1246		
Ioannina	1250	1670	33,6
Chalkidiki	1250	1380	10,4
Grevena	1254		
Thesprotia	1260		
Pieria	1262	1420	12,52
Larissa	1264	1490	17,88
Aetolia	1272	1550	21,85
Karditsa	1274	1480	16,17
Kozani	1274	1520	19,31
Evritania	1276	1450	13,64
Trikala	1276		
Florina	1282	1460	13,88
Kastoria	1294	1450	12,05
Rethymno	1300	1580	21,54
Arcadia	1304	1580	21,16
Magnesia	1308	1490	13,91
Lesbos	1310		
Fhthiotis	1312	1460	11,28
Elis	1316	1670	26,90
Phocis	1322	1590	20,27
Chania	1326	1626	22,62
Cyclades	1334		
Achaea	1346	1680	24,81
Samos	1348		
Messenia	1350	1580	17,04
Chios	1362		
Heraklion	1370	1710	24,82
Lakonia	1374	1670	21,54
Argolis	1380	1570	13,77
Voeotia	1380	1520	10,14
Dodecanese	1386	1810	30,59
Lasithi	1388	1750	26,08
Corinthia	1392	1560	12,07
Euboea	1408	1580	12,22
Rhodes	1416	1780	25,71
Attica	1446	1570	8,58



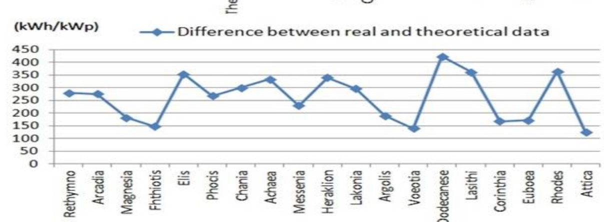


Figure 4: Differences between PVgis' average of five simulation results and actual measurements

Concerning the energy between the software simulation results and the real energy data gathered from the measurements of the medium scale PV parks, it is obvious that the software tool provides substantially lower energy potential in comparison to the real measurements.

The difference ranges from 8,6% in Attica (124 kWh/kWp difference in energy) up to 35,06% in Drama (392 kWh/kWp difference in absolute values). The average difference between measured and predicted data is still significant reaching 20,65%.

This difference is usually not taken into account from the majority of the PV system designers and installers. It is a common practice for banks, investors and authorities to use the predicted data derived from such software tools directly, without taking into account the real, measured data of similar or even identical operating PV systems.

3.4 Results of Step 4: PVsyst 5.2 Project, using real equipment & Technical Chamber's meteorological data for an indicative PV Park

Between step 2 and 3 an important difference among the real and simulated data was observed. In this step (4) an attempt to find out the reasons of this difference is made. In order to get a safer and more accurate simulation result, it is necessary to use PVsyst 5.2 Project software, using real components (panels and inverters) so that to simulate the annual PV energy production of a specific Photovoltaic park.

For this purpose, a PV park located in Serres named PV Electrogreen 99.63(STP270) is being chosen. Suntech STP270-24/Vd is the PV module that has been used for this park accompanied with nine (9) Sunny Mini Central 11000TL single phase inverters. Running the PVsyst 5.2 Project software tool with the same meteorological data of PVgis' database, the result is 1205 kWh/kWp/year. On the other hand, according to the sunny portal internet site, the photovoltaic park has an average of 1529 kWh/kWp/year. The significant difference of 26.88% indicates that more improved data must be used. In order to accomplish this, accurate and reliable meteorological data from the Technical Chamber of Greece [16] concerning the Global solar irradiation, the diffuse irradiation, the temperature and the wind velocity in the prefecture of Serres are used as input instead of those of PVgis.

As expected, the meteorological database input affects the simulation result significantly. More specifically, the new energy yielded by the photovoltaic park according to the PVsyst project is 1322 kWh/kWp/year, thus a smaller difference of 15,66% to the real data. So, using the Technical Chamber of Greece meteorological data the difference is improved by 41.7%.

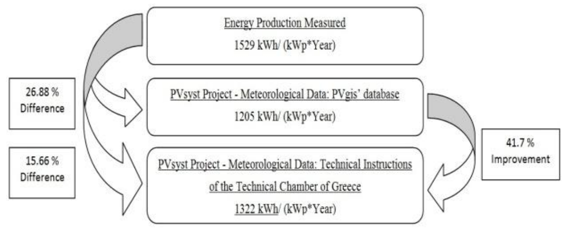


Figure 6: Photovoltaic Energy Production Improvement

To sum up, it is obvious that by using more specified data such as the exact location of the PV park, the specific type of equipment to be used (modules and the inverters exact types) and the accurate real meteorological data, the predicted energy results come closer to the actual (measured) photovoltaic energy produced by a PV park.

Furthermore, the difference that still remains after the detailed simulation can be explained as follows:

a) due to the general and specific losses of a real system,
b) due to the particular meteorological data of the specific area (microclima),
c) due to design parameters adopted,
d) due to the specific quality of components used by each PV park.

4. Conclusions

This extended research reveals that the actual and measured energy production of medium scale low voltage photovoltaic parks is significantly higher than the energy estimated by the software tools that have been used (PVsyst 5.2 preliminary version, PVsyst 5.2 project tool and PVgis). A significant number of annual consistent measurements (201) at Photovoltaic plants of rated power 20-100kWp all over Greece revealed that the energy produced by medium scale low voltage PV parks varies between 1380 kWh/kWp and 1810 kWh/kWp for fixed mounting systems while the simulation results vary between 1118 kWh/kWp and 1446 kWh/kWp. In order to get a more safe and more reliable prediction of the annual electric energy yield of an examined site (with low declination compared to actual values), the solution that must be followed is the use of PVsyst Project combined with the use of detailed components (panels, inverters) of the PV park under study and accurate meteorological data (for Greece: Technical Instructions of the Technical Chamber of Greece). Using this combination the prediction error was reduced by 41,7%, however

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this was still 15,66% less than the real energy production. Definitely, this difference, even when simulating with accurate data, could be a safe margin for any energy predictions concerning the energy yield of a PV park. However, this difference is huge enough and must be always taken into account by researchers and engineers during business plans development and decision support from investors side, by the banks when approving the loans, by insurance companies and by the PV system integrators.

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