PERFORMANCE EVALUATION OF DIFFERENT PV MODULE TECHNOLOGIES IN A GRID-CONNECTED PILOT PROJECT IN GREECE

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ABSTRACT: The need for increased penetration of Renewable Energy Sources and gradual decarbonisation of the energy supply chain is well established. Photovoltaic (PV) technology is constantly emerging as a key player in the green energy generation market. Numerous PV technologies are competing for market share, making the choice of the most suitable type of equipment essential for the viability of any application. In this study the real-life performance of four different PV technologies in actual southern Mediterranean climatic conditions was examined. A quality check of the recorded data throughout the monitoring period was carried out, followed by the calculation of the performance indices proposed by the IEC 61724 international standard on PV system performance monitoring and analysis. The outdoor evaluation has shown that grid-connected PV systems can have a major impact on the future energy mix of countries with high solar resources. The module technology that will claim a leading role in the PV industry will depend almost entirely on the future trends of manufacturing and production costs as well as, the BoS costs related to the final installation.

Keywords: Performance, Crystalline, Thin-film

1 INTRODUCTION

The enormous fluctuations of oil prices during the past 18 months [1] due to the instability of financial markets have highlighted more than ever the strong dependence of today's energy supply on oil. Apart from the well known environmental implications, an additional argument has been introduced for the further penetration of renewable energies in the energy market: minimisation of price volatility risks [2].

For the European region in particular, the Gas Crisis at the beginning of 2006 and subsequent interruptions of gas supply in 2008 and 2009 have explicitly demonstrated the high vulnerability of the energy supply chain. A possible remedy could lie on the diversification of supply countries and mainly on the diversification of energy sources.

Photovoltaics (PVs) constitute a key technological option to implement the shift towards a decarbonised energy supply. Solar resources in Europe and most of the world are abundant and cannot be monopolised. Furthermore, as technology advances and production volumes increase dramatically every year, market prices for PVs will further decrease, following the trend of the past years. It is worth mentioning that yearly growth rates over the last decade were in average more than 40% making PVs one of the fastest growing industries at present. Business analysts predict the market volume to reach €40 billion in 2010 and anticipate decreasing prices for the consumers, [2].

With relevant technology advancing, the scope of available PV modules is constantly expanding. There are two broad technological categories when it comes to commercially available PV cells: crystalline silicon and thin-film [3], [5]. These two cover almost all available solutions currently in the PV market. In 2009, crystalline silicon, either in monocrystalline or polycrystalline form, account for about 78% of all modules produced globally; the remaining is covered by thin-film modules, [13]. The family tree of the mentioned technologies is as follows, [5]:

- Crystalline Silicon (wafer based)
  - Monocrystalline silicon
  - Polycrystalline silicon
- Thin-film
  - Amorphous-Si (a-Si)
  - Tandem a-Si/microcrystalline
  - CIGS (Copper Indium Gallium Selenide)
  - CdTe (Cadmium Telluride)
  - Dye-Sensitised (TiO_2) - currently in experimental stage

Crystalline silicon PV cells are manufactured from thin silicon wafers. For the production of monocrystalline silicon cells, silicon is shaped in a cylindrical ingot form.

Thin slices with thickness of (0,2-0,3)mm are cut from these ingots and then formed into usually hexagonal shapes in order to cover as much of the modules aperture area as possible. Mass produced monocrystalline cells have an efficiency of 13% to 17% and are the most efficient cells yet to enter the PV market [3], [5]. Polycrystalline silicon is also produced from high purity molten silicon, only in this case it is formed through a casting process. A comparison between poly- and monocrystalline silicon cells in terms of efficiency shows that monocrystalline are (1,5-2,0)% more efficient than polycrystalline, but the latter are cheaper to produce. This is one of the main reasons that their market share is currently growing [3].

An alternative to the crystalline regime are thin film technologies. They are manufactured by depositing ultra thin layers of silicon with a thickness of (0,3 to 2,0)μm onto glass or stainless steel substrates [5]. Despite their lower efficiencies which lie between 6% and 12% thus implying larger array surface areas, they are much more resistant to any shading and high temperature effects. Moreover their production costs are significantly lower because of the usage of fewer raw material, a fact that encourages PV companies to invest in thin-film technologies in order to save on the silicon demand per Wp, [2].

There are also cases where manufacturers produce hybrid versions of crystalline and thin-film technologies. Such a case is the Type A module installed at Halandri, which incorporates amorphous silicon onto monocrystalline silicon. According to the manufacturer, this particular design shows higher efficiency in warmer climates compared to plain monocrystalline modules. Such modules are regarded as niche products and aim to cover a specific part of the market.

Because of the large variety of available solutions, a need for controlled field testing of various PV technologies has emerged. Laboratory tests provide significant data concerning the performance of the available products but even the most demanding laboratory test cannot simulate the real life operation of a system that is intended to operate reliably for more than 20 years outdoors. Therefore it is believed that field tests such as the one presented here can provide significant know-how concerning the real life operation of PV systems.

2 PURPOSE OF THE STUDY

Amidst the worst financial crisis of recent years, renewable energies and PVs in particular constitute one of few attractive, not to mention sustainable, investment possibilities. In this context, numerous PV technologies are competing for market share, making the choice of the most suitable type of equipment essential for the viability of any application. However the system performance promised by the manufacturers of the system's components as well as the designers of the system itself, do not necessarily coincide with real life performance. The latter is one of the two main objects of study in this thesis project.

In order to gain insight in the operational behaviour of PV power stations in actual southern Mediterranean conditions, a performance evaluation study was carried upon a newly commissioned PV power station situated in Halandri, in the region of Attica. This experimental station, built in the offices of Phoenix Solar Greece, facilitates four different PV technologies, namely: high efficiency hybrid monocrystalline / amorphous-silicon (Type A), polycrystalline silicon (Type B), thin-film cadmium telluride CdTe (Type C) and Copper Indium Gallium Selenide CIGS (Type D) modules with each technology ultimately falling into one of the following categories: crystalline silicon (Types A and B) and thin-film modules (Types C and D). According to [2], [3], [4] and [5] these technologies currently constitute almost the totality of the available solutions in the PV market.

As will be subsequently shown in the detailed description of the photovoltaic system, the overall design of the station allows for a side-by-side subsystem comparison, disregarding in essence any power conversion, weather and other site implications, therefore proving to be an excellent research opportunity.

3 DESCRIPTION OF THE PV INSTALLATION

3.1 Site location and climate

The PV system under study is situated in the offices of Phoenix Solar Greece in Halandri (longitude 38° 01′′N, latitude 23° 48′′E), in the wider urban zone of Athens in Greece [6]. The climate is typical Mediterranean with hot dry summers and usually low rainfall totals.

An overview of the climatic data of the region for year 2009 is provided in Table 1.

Table 1: Climatic data for the wider urban zone of Athens in Greece for year 2009, [6]

Month	Record High [°C]	Avg High [°C]	Avg Low [°C]	Record Low [°C]	Avg rainy days
Jan	24	12,5	5,2	-4	12,6
Feb	23	13,5	5,4	-6	10,4
Mar	28	15,7	6,7	-1	10,2
Apr	32	20,2	9,6	0	8,1
May	36	26	13,9	6	6,2
Jun	46	31,1	18,2	14	3,7
Jul	48	33,5	20,8	16	1,9
Aug	46	33,2	20,7	16	1,7
Sep	39	29,2	17,3	12	3,3
Oct	37	23,3	13,4	7	7,2
Nov	28	18,1	9,8	-1	9,7
Dec	24	14,1	6,8	-4	12,1
Year	48	22,5	12,3	-6	87,1

3.2 System configuration and layout

The system is divided into four subsystems of different capacities. Each subsystem comprises of one type of PV module with each one representing a specific technology, i.e. Type A for high efficiency hybrid monocrystalline / amorphous-silicon, Type B for polycrystalline silicon, Type C for thin-film CdTe and Type D for thin-film CIGS. Three subsystems namely, Type A, Type C and Type D are connected to 3 identical inverters of 1,1kVA capacity each. Due to its higher nominal capacity, subsystem Type B is connected to the grid through a 1,7kVA inverter. All inverters comprise the string topology for direct connection to the grid.

An overview of the PV system at Halandri is shown in Figure 1 below.

Figure 1: PV arrays under evaluation in Athens

The overall system configuration is summarised in Table 2.

Table 2: Main PV subsystems' characteristics

Module Type	Techno-logy	Nominal Power, [Wp]	Number of Modules	Area, [m^2]	Total Nom. Capacity, [kW]
A	Hybrid mono / a-Si	210	5	6,30	1,050
B	Poly Si	270	6	11,64	1,620
C	CdTe	75	15	10,80	1,125
D	CIGS	182	6	11,79	1,092

The modules in each array are connected differently depending on their electrical characteristics which are presented in Table 3. In the first array there are 5 Type A modules connected in series. For the second array there are 6 in total Type B modules all of which are connected in series constituting a single string. For the third array there are 15 Type C modules which are broken down in strings of 5. The 3 resulting strings are subsequently connected in parallel. The fourth and last array consists of 6 Type C modules connected in series.

The electrical layout of the installation is outlined in Figure 2. Type A, B and C modules are installed on fixed mounting structures, at a 20° tilt angle and are facing due south. Type D modules are installed horizontally 30cm above the ground according to the manufacturer's specifications.

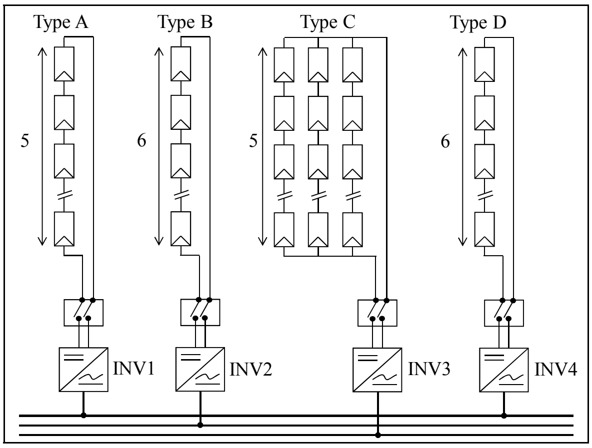

Figure 2: Electrical layout of the PV installation.

A summary of the main electrical characteristics of each module type is presented in Table 3 below.

Table 3: Electrical characteristics of modules under Standard Testing Conditions

Module Type	Open-circuit voltage, [V]	Short-circuit current, [A]	Voltage at max power, [V]	Current at max power, [A]	Module Efficiency, [%]
A	50,90	5,57	41,3	5,09	16,70
B	44,00	8,09	35,00	7,71	13,90
C	89,60	1,23	68,20	1,10	10,42
D	96,70	2,76	73,90	2,46	9,26

3.3 Measured parameters

All parameters measured on site were recorded with a 5 minute sampling interval and are presented in Table 4. According to the guidelines provided by [7], this value lies within the proposed limits of 1 to 10 minutes. With the chosen interval all parameters could be adequately monitored without substantially increasing the bulk of recorded data.

Table 4: Parameters measured on site

Parameter	Symbol	Unit
Plane-of-Array Irradiance	G_I	$\frac{W}{m^2}$
Ambient air temperature	T_{amb}	°C
Wind Speed	S_W	$\frac{m}{s}$
Module Temperature	T_{mod}	°C
Array Output Voltage [DC/AC]	V_A	V
Array Output Current [DC/AC]	I_A	A
Utility Voltage [AC]	V_U	V

4 PERFORMANCE ANALYSIS

4.1 Measured values

The performance parameters that were calculated for the evaluation of the four PV technologies installed at the Halandri PV station are, as suggested by [7], those shown in Table 5 where:

- E_A is electrical energy produced by each subsystem (AC side)
- A_A is the surface occupied by each subsystem
- G_{STC} is the plane-of-array irradiance under Standard Testing Conditions
- H is the plane-of-array irradiation.

Table 5: Performance evaluation parameters according to IEC 61724

Parameter	Symbol	Formula	Unit
Array Yield	Y_A	$Y_A = \frac{E_A}{P_{A0}}$	$\frac{kWh}{kW}$
Reference Yield	Y_r	$Y_r = \frac{H}{G_{STC}}$	$\frac{kWh}{kW}$
Array Capture Losses	L_C	$L_C = Y_r - Y_A$	$\frac{kWh}{kW}$
Mean Array Efficiency	η_{Amean}	$\eta_{Amean} = \frac{E_A}{A_A \cdot H}$	-
Performance Ratio	PR	$PR = \frac{E_A \cdot G_{STC}}{P_{A0} \cdot H}$	-

The monitoring period for this study was from February to August 2010 for array Type A, B and C and from July to August 2010 for array Type D. Monthly plots of the evaluating parameters are apposed next. It should be pointed out that the Type C modules were replaced during the first week of June due to lower than expected performance which is reflected in the following figures.

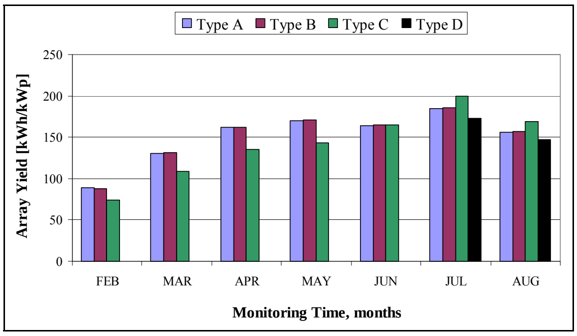

Figure 3: Monthly array yields

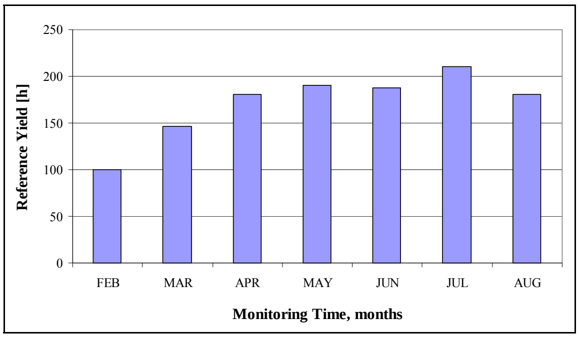

Figure 4: Monthly reference yield, i.e. monthly peak sun hours

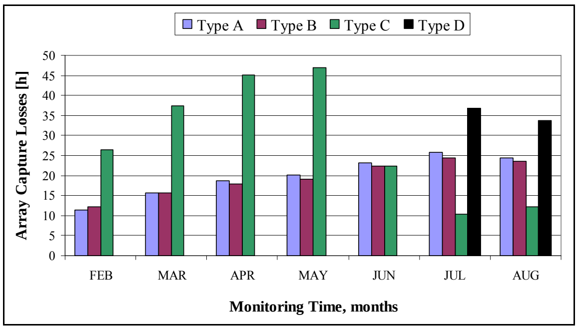

Figure 5: Monthly array capture losses

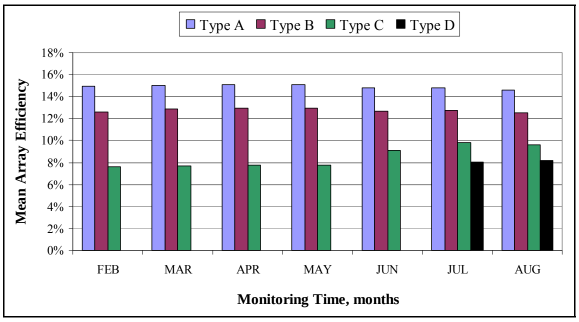

Figure 6: Mean array efficiency during each month

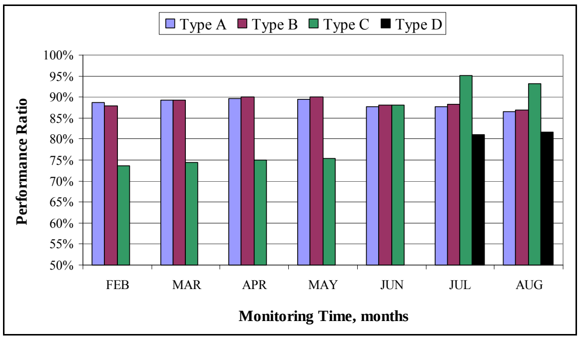

Figure 7: Monthly Performance Ratios

4.2 Comparison with simulated values and literature

A simulation of Type A, B and C subsystems for the time interval of February until August was carried out using a dedicated software package for photovoltaic systems. Type D modules are not yet included in this particular database so they were not involved in this part of the analysis. The meteorological data used for the simulation were hourly synthetic data for the region of Athens from 1990. Thus, the total plane-of-array irradiation taken into account by the software was $1121\,kWh/m^2$ instead of the $1196\,kWh/m^2$ which were recorded by the measuring equipment, i.e. 7% less. The results are presented in Table 6. Especially for Type C modules there are two rows, one for each batch. The original batch denoted as C1 was monitored from February to May while the new one, denoted C2, was monitored from June till the end of August.

Table 6: Measured and simulated values for the period February to August 2010

Type	Simulated values			Measured values		
	H $\left[\frac{kWh}{m^2}\right]$	Y_A $\left[\frac{kWh}{kWp}\right]$	PR [%]	H $\left[\frac{kWh}{m^2}\right]$	Y_A $\left[\frac{kWh}{kWp}\right]$	PR [%]
A	1121	940	81,0	1196	1056	88,3
B	1121	921	79,4	1196	1060	88,6
C1	507	463	84,6	617	461	74,6
C2	568	456	80,3	578	533	92,1

For the overall monitoring period, the Type A modules outperformed the simulated values in terms of total yield by 12,3%. The corresponding value for Type B modules was 15,1%. The first batch of Type C modules underperformed compared to the simulated values by 1% while the second batch over performed by 16,8%.

When comparing these values to similar studies [8], [9] conducted under comparable climatic conditions, the PV system at hand produced approximately 5% more in terms of total yield for Type A.

Concerning the PR, after consulting relevant work which was presented in 2004 and aimed in being used as a tool for assessing a PV station's PR [9], it was concluded that for stations built after 1998, an acceptable average value for the PR is 74%. Later studies, [10], have raised that value to 80% for large grid-connected installations that were commissioned after 2005. Therefore the produced PR values of Types A, B and D (measured average value of 81,4%) are deemed satisfactory. As for the first batch of Type C the produced PR value was lower than expected. The second batch however proved to be superior as can be seen in Figure 6.

5 CONCLUSIONS

The performance analysis of four PV technologies provided insight in the operational behaviour in actual southern Mediterranean conditions. The Type A and B arrays, which correspond to hybrid monocrystalline with amorphous silicon and polycrystalline PV modules respectively, performed satisfactorily throughout the monitoring period. Their yields and performance ratios were equal or superior to values published in relevant studies for similar climatic conditions [8].

The first batch of the Type C modules performed slightly lower than expected in terms of yield and performance ratio, both compared to literature values and Type A and B. As explained in earlier work, [11], concerning the same PV installation, it is assumed that production capacities might have been manufactured according to older specifications. In that case Type C's performance would seem more reasonable when compared to the trend of Type C modules' efficiency displayed in [12].

Another interesting aspect in this case is the fact that the original batch of Type C modules was left exposed to sunlight in an open-circuit state for more than 60 days due to various delays of the permit acquisition procedure. According to the manufacturer, this can prove to be a liability in terms of module performance. The new batch which was installed and connected to the grid within a few hours, is exhibiting outstanding performance even under extremely high ambient temperatures of more than 40°C. The monitoring period of three months is not in any case sufficient to draw safe conclusions; however there is a clear indication that the time interval between installation and grid connection plays an important role in this type of PV modules. All installers are therefore advised to proceed immediately with the grid connection as soon as the modules are in place.

As a final comment on the performance of the four types it can be said that the crystalline types which have been developed longer than any thin-film technology, have shown signs of consistency in their performance which is indeed close to the theoretical module characteristics. Thin-film technologies have come in the PV scene later on and a lot of research has been dedicated in their development. Current market trends indicate that their share is constantly rising worldwide. In the Mediterranean region the latest thin-film modules seem to have an application area if the results produced during the last three months of the monitoring period prove representative. In the end, apart from specific technological requirements, it's the market price of each module that will play an important role to the viability of any given PV project.

To conclude, the outdoor evaluation has shown that grid-connected PV systems can have a major impact on the future energy mix of countries with high solar resources. With projected specific annual yields in the proximity of 1500kWh/kWp or more, it is strongly believed that they can gradually increase their market share and be established as a key player of the future energy supply chain. Which one of the tested technologies will claim the leading role in this shift will depend almost entirely on the decrease rate of production costs and consequently retail prices. The next two to three years will be crucial for the determination of the leading technology as grid parity for PVs constantly approaches.

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