A Place for PV, Tracked-PV and CPV

A Comparative Study of the Energy Production
from the Three Technologies According to the Available Solar Resources

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Abstract

The choices to generate electricity using solar energy are increasing from one year to the other. Today, amongst the main technologies, fixed crystalline Photovoltaic (PV), tracked crystalline PV and more recently Concentrator Photovoltaic (CPV) are just to name a few alternatives. A CPV system offers a much higher efficiency than conventional PV, but has the disadvantage that it only uses the direct fraction of the sun irradiation. Consequently, the higher the Direct Normal Irradiation (DNI), the more profitable a CPV system becomes. But where is the limit, and how does it compare to conventional tracked PV systems? This paper compares the relative energy yield of the three systems in several regions of the world while pointing out the advantages of each in order to try and to identify an appropriate interface between them. This interface is in no way regarded as an absolute limit but can help choosing a technology for a site, or vice versa. Additionally, other points of comparison such as the relative energy output per hectare are considered as well as an outlook for the coming years.

Introduction

This paper uses eight exemplary locations from Europe, Africa and the Middle East with different Global Horizontal Irradiation (GHI), diffuse irradiation ratio and therefore different Direct Normal Irradiation (DNI). This approach was chosen in order to understand the relationship between these factors and the output energy for different technologies. The considerations and results shown in this paper are merely regarding technical and energy efficiency matters. Any economical matter was explicitly not considered. All assumptions and results shown in this paper are approximations and do not have the purpose to be used for planning or decision making: they shall serve to give an idea about the performance of the different technologies according to the resources. Figure 1 shows the irradiation conditions considered and for indication also the names of towns with approximate corresponding characteristics[1]. Discussion of the accuracy of the data for each town is not part of this paper. The GHI values considered for the study range from about 1,000 kWh/m².a to 2,300 kWh/m².a and both integral parts of the GHI, the Direct Horizontal and the Diffuse Irradiation, are shown. The DNI on the other hand is a part of the Global Normal Irradiation (GNI) and is also represented here.

[1] Source: PVGIS

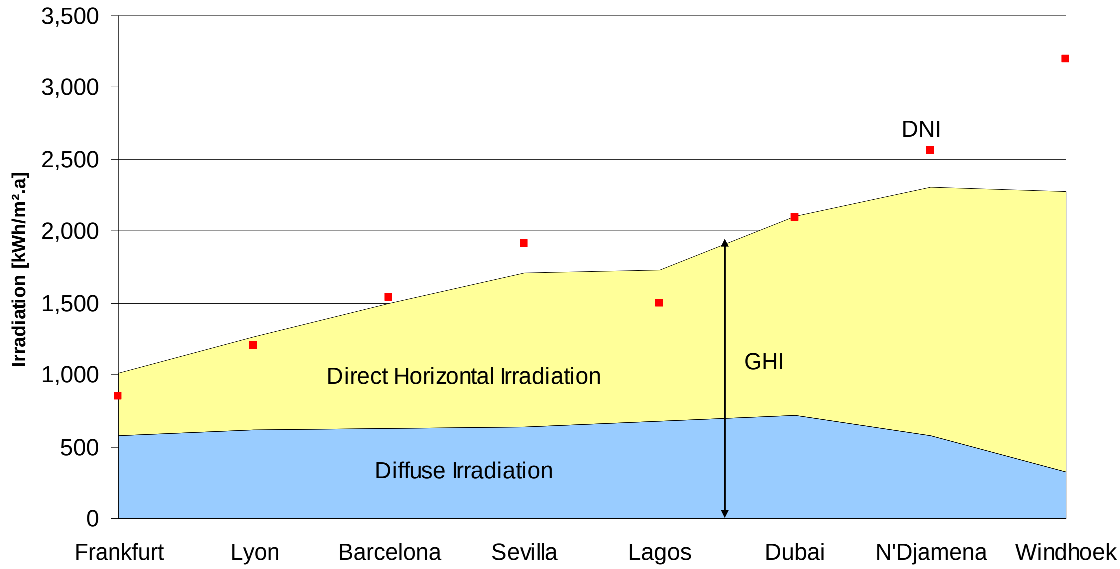

Figure 1: Range of Solar Irradiation considered for the study[2]

Table 1: Assumptions considered for the study

	PV	Tracked PV	CPV
Technology	Flat plate Polycrystalline	Flat plate Monocrystalline	Fresnel lenses III-V Tripple Junction cells
Standard Test Conditions (STC)	1000 W/m², 25°C cell temperature		850 W/m², 25°C ambient temperature
STC module efficiency*	13.5%	14.5%	25%
STC power of a 1 m² module	135 W	145 W	212 W
Module power on a "typical" summer day	115 W	120 W	250 W
Mounting System	fixed at latitude tilt	dual axis tracking	dual axis tracking
Module surface for 1 MW	7,400 m²	6,900 m²	4,700 m²
Terrain surface for 1 MW	2.5 ha	4.5 ha	2.4 ha
Typical annual Performance Ratio*	77%	79%	97%

* the STC module efficiency and the performance ratio for CPV in this table are in reference to DNI

For each one of these eight locations, brief simulations of the energy production were carried out for three technologies: polycrystalline modules installed at a fixed tilt corresponding to the site latitude, monocrystalline modules installed on dual-axis tracking systems (both crystalline modules are also referred to as "conventional PV" or

[2] Source: PVGIS

“flat plate PV”), and CPV modules likewise mounted on dual-axis tracking systems. The assumptions taken on the technologies for the purpose of this study are summarized in the Table 1.

The performance ratio stated in the table takes into account the losses in the systems with regards to module losses or gains due to deviation from laboratory conditions (mainly the temperature cell and the irradiation levels) and non-module losses (mainly inverters and cables). These values are based on averages obtained from field experience[3].

The performance ratio for a CPV system is much higher than for conventional flat plate PV mainly due to the fact that the standard test conditions can be achieved and even surpassed in the field. STC for CPV represent “real conditions” where the cells are already at 40-60°C, and the DNI with 850 W/m² is “sub-optimal” since it can reach higher values on the field. Especially the difference in cell temperature for conventional PV between laboratory and field conditions can easily bring 10-15% performance drop of the system. As a consequence, a CPV module can achieve a power of 120% of its nominal power on a typical hot summer day, whereas a PV module can hardly reach 80-85% of its nominal power that day. This can be seen in the table: although the nominal power of the CPV module is not twice the power of a flat plate PV, its real power on a clear days is easily more than double that of the PV.

Simulations

The conventional flat plate technology and the CPV considered for this study have different gains and losses through the energy conversion steps. Figure 2 shows the energy balance of a 1 MW system for a fixed flat plate PV and CPV from the available source through the conversion steps to the available energy at the inverter output. It is worth reminding that a fixed PV system uses the GHI increased by a factor to account for the irradiation on inclined surface, a tracked PV system uses the GNI whereas a CPV system uses the DNI only, being a part of the GNI.

The figures in blue present the concrete example of Dubai. It clearly shows that the flat plate technology has an advantage on the resources level since it uses the whole irradiation available, whereas a CPV uses only the direct fraction of the irradiation. This brings a reduction of 15% up to 50% compared with flat plate tracking systems, depending on the location. In the case represented below, although the GNI is much higher than the GHI, the useable irradiation is about 10% higher for the flat plate PV, and the available electricity at STC shows about the same difference. On the other hand, the outdoor real conditions are often better for the CPV system compared to the STC, so that the available energy at the inverter output is higher for a CPV system. The 5% efficiency drop observed for conventional PV systems refers to the different light spectrum as compared to laboratory conditions and to a slight drop in efficiency with decreasing irradiation. Moreover, conventional PV cells observe a drop of efficiency with increasing temperature, having a negative effect on the output as soon as module temperature exceeds the lukewarm 25°C laboratory conditions.

[3] Source: Concentrix for CPV field data, Lahmeyer for PV field data.

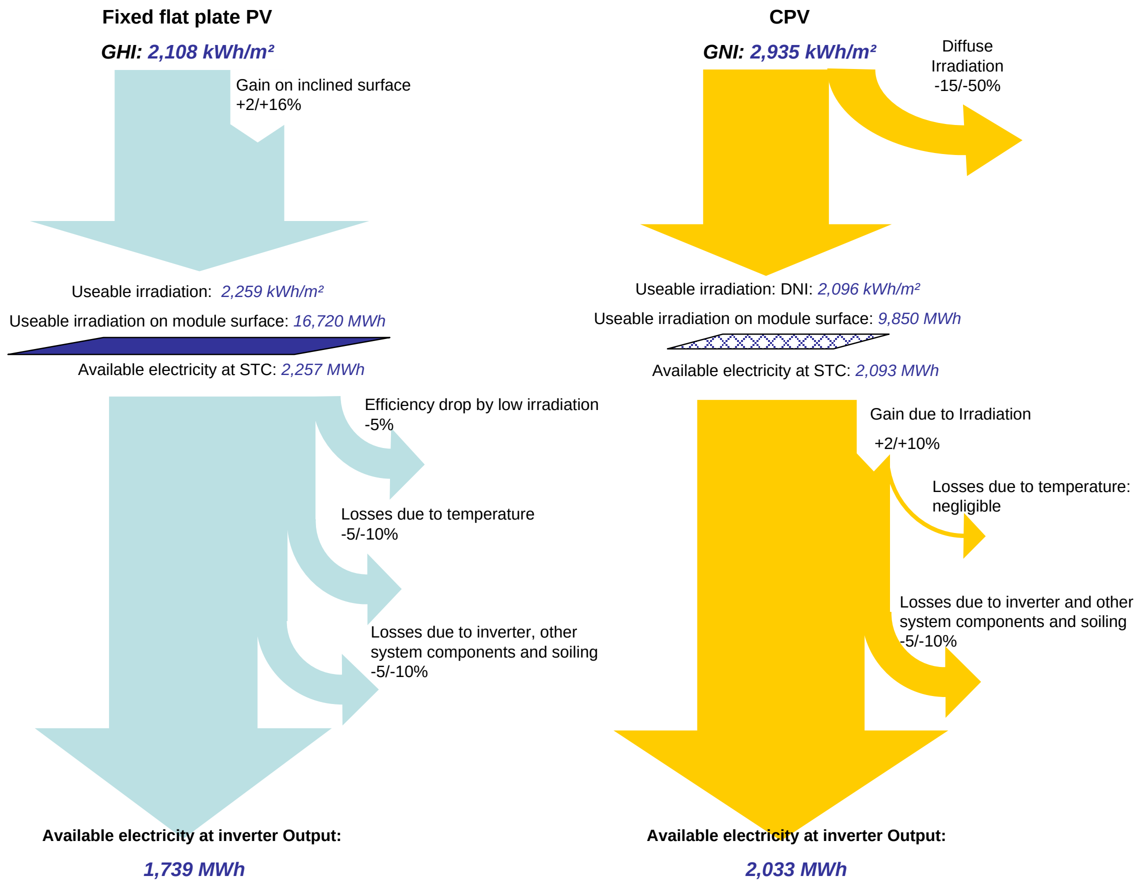

Figure 2: Energy Balance of a fixed flat plate PV and a CPV system (example of Dubai)

This energy balance approach was duplicated for all the locations considered above in order to understand the relationship between the resources and the electricity output of each technology. The first analysis which is carried out is the direct comparison between the yield ratio [kWh/kWp.a] and the incoming GHI and DNI. This is depicted in Figure 3 and Figure 4, respectively. The comparison of the yield ratio, also referred to as “full-load hours” in the conventional energy sector, allows a quick comparison of the specific electricity generation.

As it can be seen on the first figure, it is hard to recognize a clear advantage of the CPV technology versus the conventional tracked flat-plate technology when a GHI below 2,300 kWh/m².a is considered. However, it can be seen that CPV shows an advantage for DNI higher than 2,500 kWh/m².

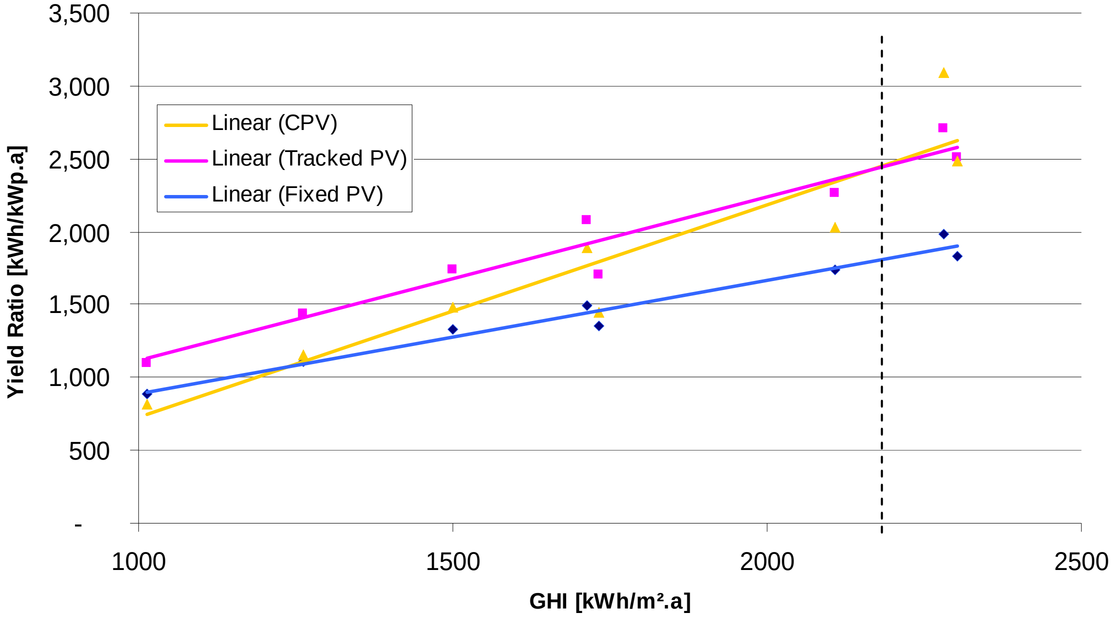

Figure 3: Yield Ratio vs. GHI

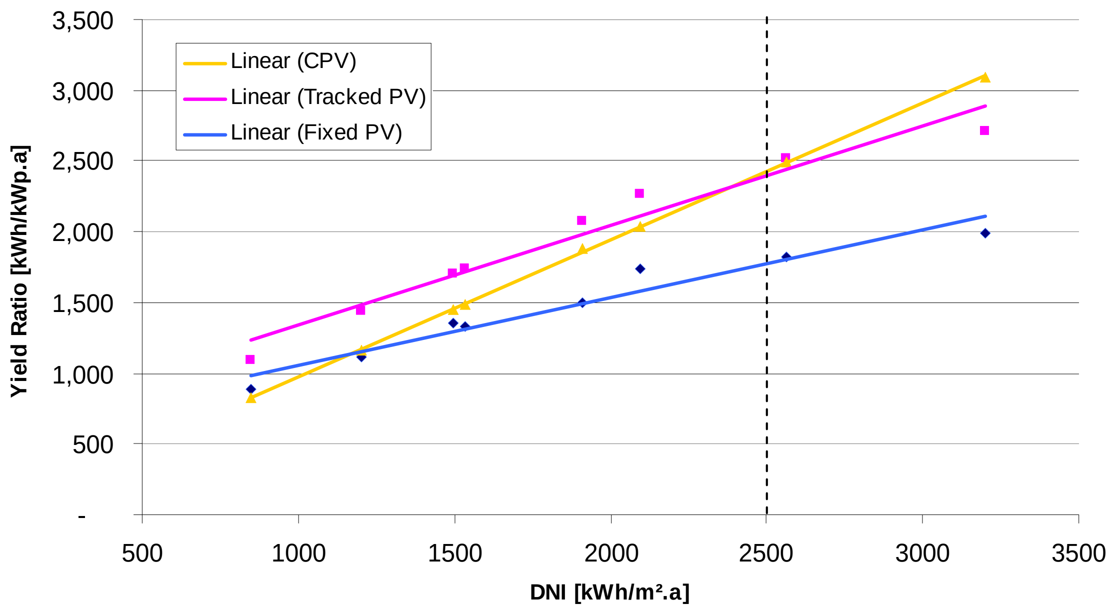

Figure 4: Yield Ratio vs. DNI

Since CPV systems only use the direct part of the normal irradiation (i.e. the DNI), the technology becomes more interesting when the ratio DNI/GHI increases. Moreover, since the DNI is not only a function of GHI but also – and in majority – a function of direct irradiation ratio, both entries have to be considered. The relation between DNI/GHI ratio and direct irradiation is depicted in Figure 5. This figure shows for the eight different locations how the ratio DNI/GHI increases as the diffuse irradiation ratio decreases. As expected, the lower the proportion of diffuse irradiation, the higher the DNI/GHI ratio. It can be said that for locations with the proportion of diffuse light of less than 35-40% of the GHI, the DNI is larger than the GHI.

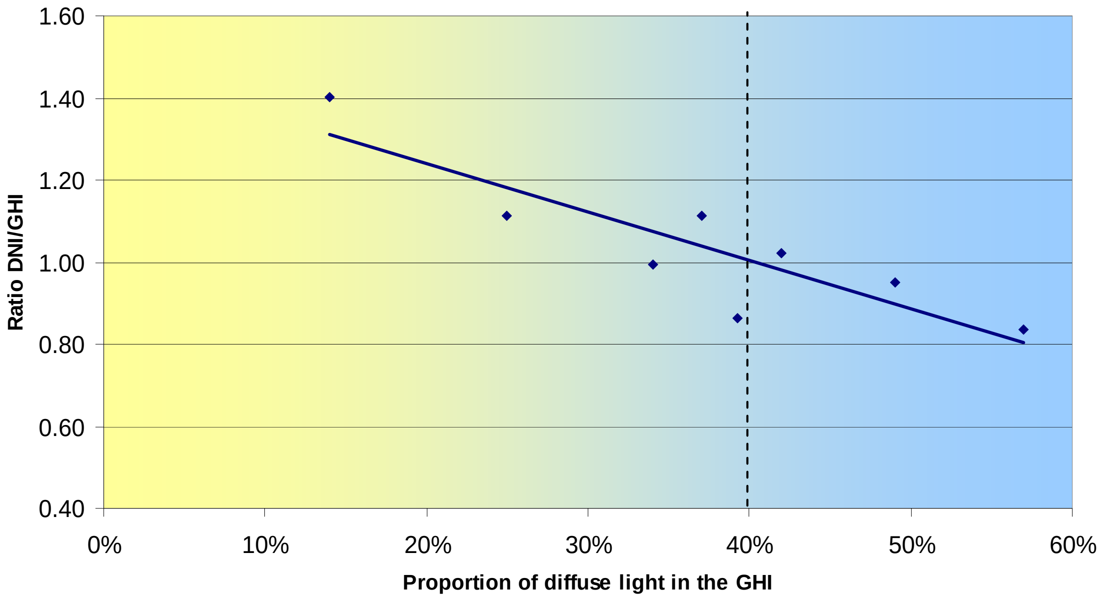

Figure 5: Trend of the DNI/GHI Ratio vs. Diffuse Irradiation Ratio

Based on the finding above a study of the yield ratio versus direct irradiation ratio (direct horizontal irradiation over global horizontal irradiation) was carried out and the results are shown below. It can be seen that at a diffuse fraction of 25-30% and below, a CPV system shows a surplus in yield ratio versus tracked flat plate PV.

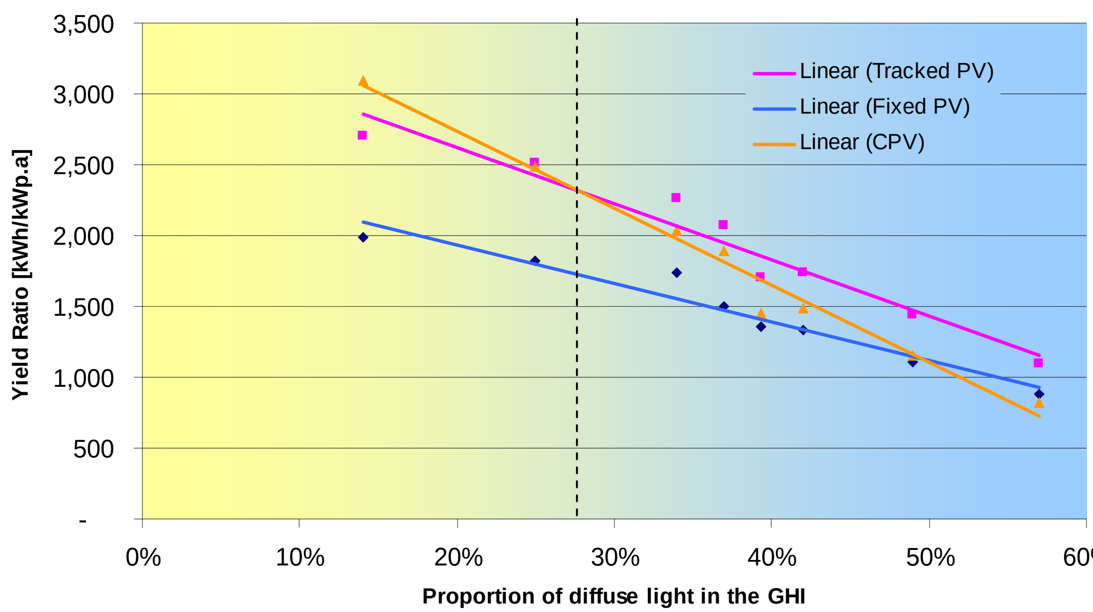

Figure 6: Yield Ratio vs. Diffuse Irradiation Ratio

Analyzing the overall system efficiency (Output Energy over Incoming Energy) as shown in Figure 7, the CPV technology shows clearly better results than flat plate PV, and this even in regions with low DNI and low irradiation. These values greatly increase with increasing GHI and approach figures around 18% as opposed to 10-11% for flat plate PV. This is not only due to the higher module efficiency (25% for CPV against 13-14% for conventional flat plate, hence the reduced size of modules for the same power), but also to the system performance as opposed to STC as already stated above. It is important to note that the shown system efficiency is considered in reference to the global irradiation. Should the DNI alone be considered the efficiency of CPV systems would be 10% to 50% higher depending on the diffuse irradiation ratio.

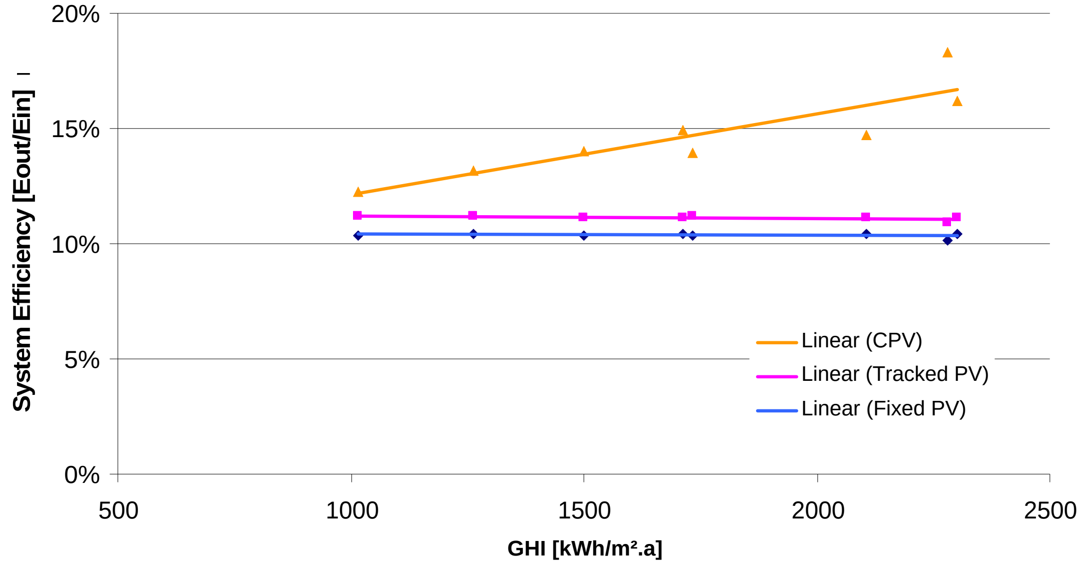

Figure 7: System Efficiency

Another advantage of CPV is the yield per hectare. Since CPV modules have a higher efficiency, the ground area required is accordingly less. This is indicated in Figure 8 below.

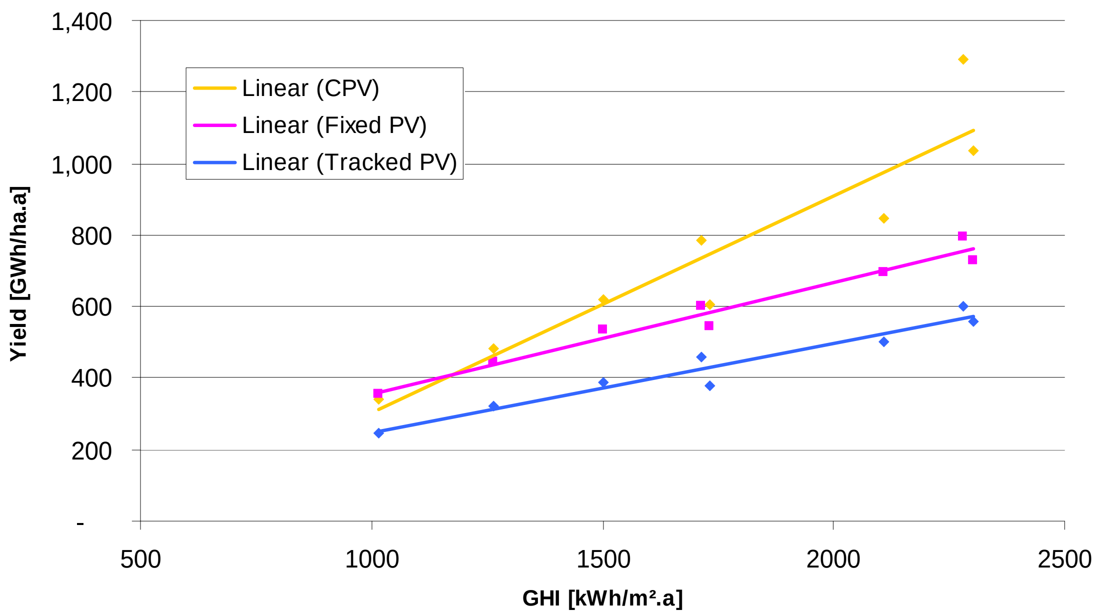

Figure 8: Yield per Hectare

For GHI of 1700 kWh/m².a and above, the yield per hectare for CPV is almost twice that of tracked PV systems. It has to be noted that this advantage increases with increasing irradiation.

Conclusions

As it was observed in the different results, the higher the GHI or DNI, the more interesting the CPV technology becomes. It can be generally stated that CPV systems have a clear advantage over flat plate PV with regards to overall system efficiency and yield per hectare for GHI values of 1,500 kWh/m².a and above. This means that even in a country where the DNI is much lower than the GHI, such as Germany, the system efficiency of CPV systems is higher than for conventional flat plate PV. Hence, a CPV system can be considered as more efficient in almost any situation where PV can be implemented. Furthermore, with the increase in efficiency of CPV systems in the coming years, it can be expected that the gap with conventional technology will further increase.

Nevertheless, when the yield ratio is considered, which can also be regarded as the full-load hours frequently referred to in any conventional power generation unit, a CPV system shows better results than a tracked PV only in regions with very high GHI or DNI values of 2,300 and 2,500 kWh/m².a respectively. This confines the benefit of CPV to only limited regions worldwide.

Furthermore, as it was stated before, the higher the DNI/GHI ratio, the better it is for CPV as opposed to conventional PV. With this regards, for regions were both the GHI and the DNI are relatively well known, Figure 9 is indicating where CPV becomes attractive considering different DNI/GHI ratios. With a ratio from around 0.80 and above, a CPV system outperforms a fixed PV system, whereas by a ratio of 1.20 and above, a CPV system also overtakes tracked PV systems. The point shown on the far right in this figure corresponds to the location of Windhoek considered above. This place has not only a high GHI but also a very high direct irradiation fraction.

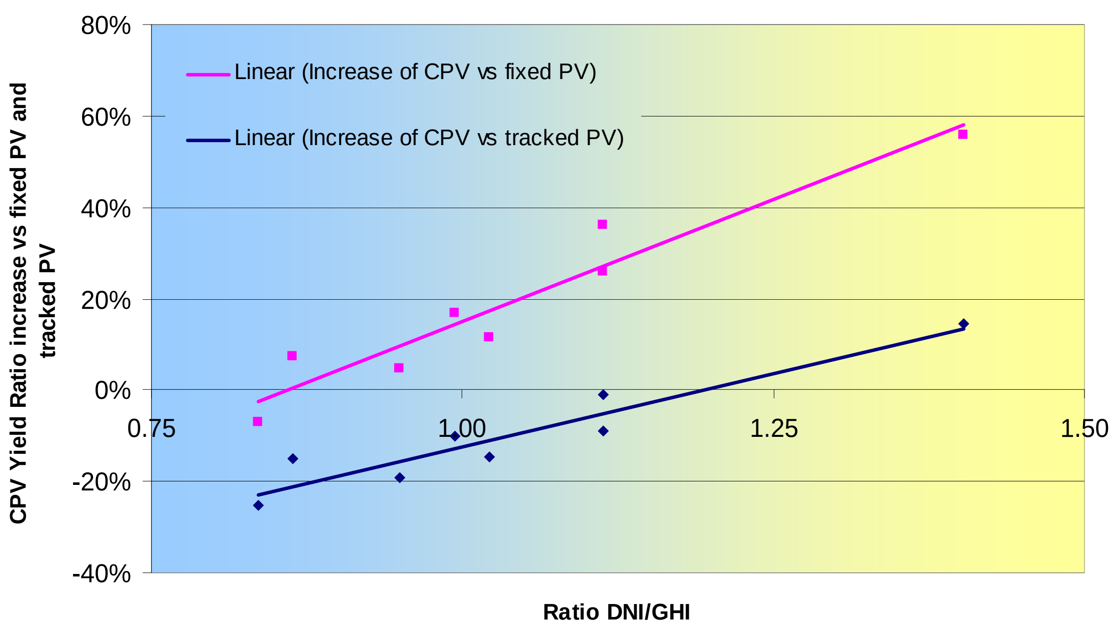

Figure 9: Increase of CPV Yield Ratio against conventional flat plate

Finally, since the DNI for a given region might not be known, the last figure presented within the frame of this study, Figure 10 shows the most appropriate technology according to GHI and diffuse irradiation ratio. For the purpose of this paper, the implementation was regarded as advantageous relative to PV when the increase in Yield ratio was more than 30%. The figure also shows the approximate position of each of the location considered in this study. As mentioned before, all the data were taken from PVGIS so as to have a consistent source for the different locations, but the accuracy of the specific locations has to be considered. For instance, real data coming from the location of Sevilla[4] are shown with the red point "Sevilla$_R$". The irradiation is similar but the diffuse irradiation ratio is much lower making the site favorable for CPV.
The figure represented here can hence be used to determine whether a potential site for which data are available can be eligible for CPV.

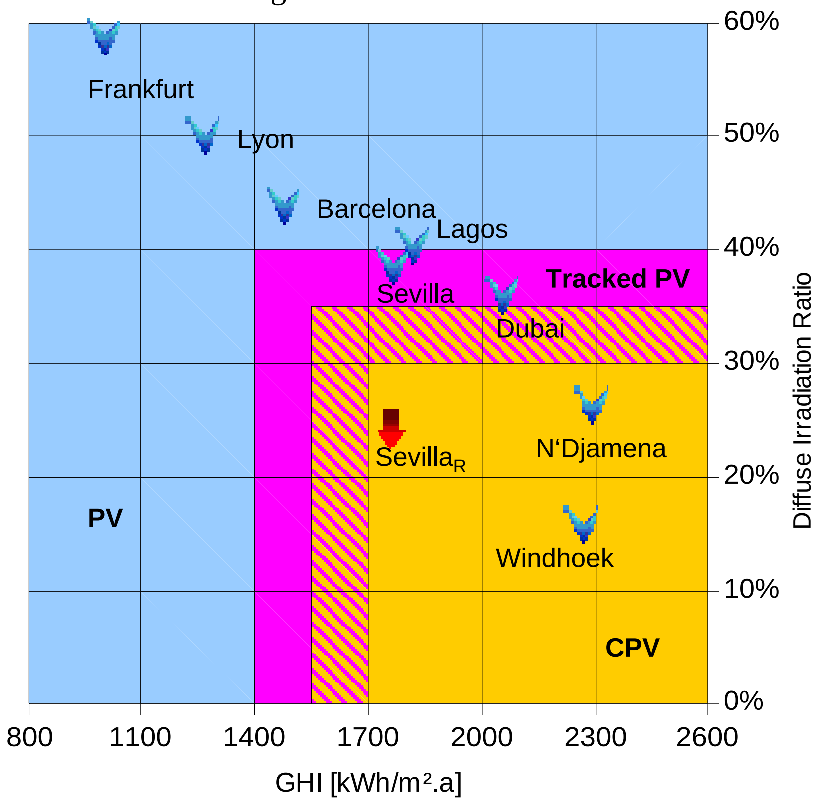

Figure 10: Suggested implementation of PV, Tracked PV, and CPV

It is important to note however that any decision in the investment of a PV, tracked PV or CPV system ultimately depends on the electricity generation costs or Levelised Costs of Electricity (LCOE in €/kWh). With this regard, the figure would look much different if these costs were considered. For instance, although today the LCOE from CPV are higher than PV because serial production has not brought economies of scale yet, it is likely that the tendency will reverse in the coming years with the CPV market rapidly developing.

[4] Source of data: Concentrix Solar GmbH

Literature

- Photovoltaic Geographical Information System (PVGIS), The European Commission. Online dynamic map of Europe and Africa. http://sunbird.jrc.it/ pvgis/
- Concentrix Solar GmbH, http://www.concentrix-solar.de/

List of Abbreviations

CPV	Concentrator Photovoltaic
DNI	Direct Normal Irradiation
GHI	Global Horizontal Irradiation
GNI	Global Normal Irradiation
LCOE	Levelised Cost of Electricity
PV	Photovoltaic
STC	Standard Test Conditions

List of figures and tables