ARISTOTLE UNIVERSITY OF THESSALONIKI

Department of
Electrical and Computer Engineering

DIPLOMA THESIS:

“Measurements and Analysis of a 20 kW Grid-Connected PV System”

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GRADE: Excellent (10/10)

INDEX

0. RESUMEN EN ESPAÑOL

0.1 Breve Descripción

Las principales tareas ejecutadas durante la realización del presente PFC se pueden resumir de acuerdo con los siguientes puntos:

- Realización de medidas eléctricas sobre un sistema fotovoltaico de 20 kWp conectado a red.
- Variación de la eficiencia de inversión en función de: época del año, temperatura, tipo de inversión, configuración de inversión, etc.
- Comparación de resultados experimentales con resultados de simulación vía PVSYST 4.1
- Evaluación con PVSYST de los rangos energéticos para el sistema fotovoltaico con distintas configuraciones de inversión

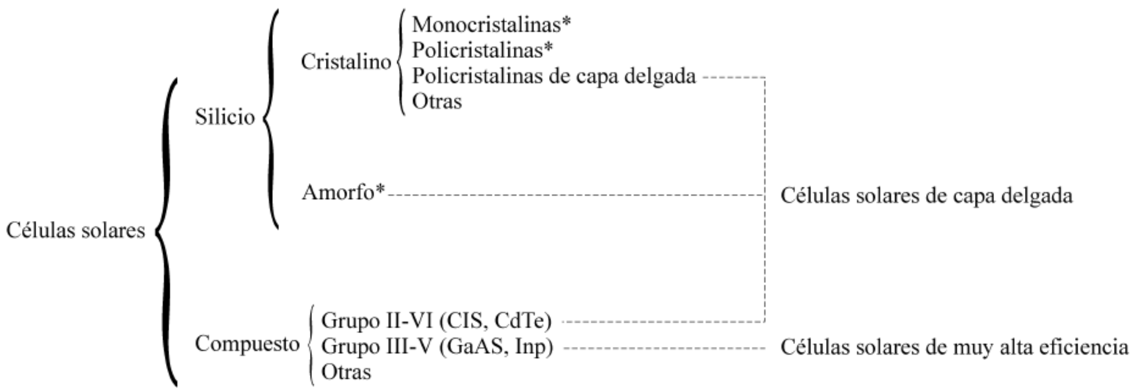
0.2 Introducción

Hace ya más de cien años (Becquerel, a mediados del siglo XIX) que se sabe que la radiación solar puede alterar el comportamiento eléctrico de ciertos materiales originando, bajo unas condiciones determinadas, una corriente eléctrica. Desde entonces se ha venido investigando sobre las formas eficientes de generar energía eléctrica a partir de la radiación solar, y al dispositivo básico utilizado para conseguirlo se le llama célula fotovoltaica, o célula solar.

El principio de funcionamiento de las células solares es el efecto fotovoltaico:

- La unión de dos elementos semiconductores, uno tipo n y otro tipo p, provoca una diferencia de potencial en las proximidades de esta unión.
- Los fotones transfieren la energía de la radiación solar incidente a los electrones de los semiconductores, liberándolos de la red cristalina a la que estaban unidos (generación electrón-hueco).
- La diferencia de potencial existente en la unión provoca un flujo ordenado de portadores (electrones y huecos) fotogenerados, originando una diferencia neta de potencial en la célula.
- Mediante los contactos existentes en la célula, puede disponerse un circuito exterior, por el que circulará una corriente eléctrica, la cual podrá entregar potencia eléctrica útil

Las células solares se clasifican en distintos tipos, de acuerdo con el siguiente esquema:

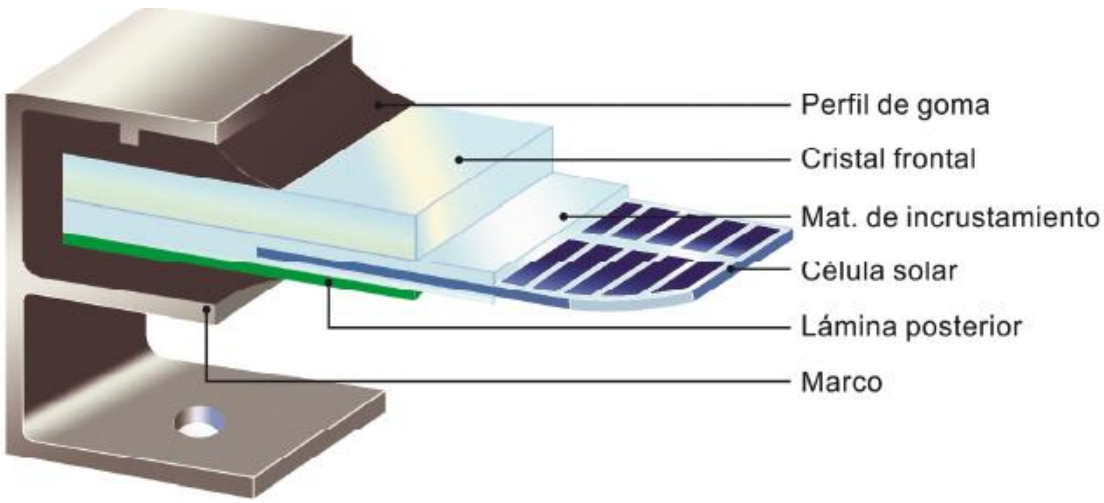


* Tecnologías más comunes y extendidas comercialmente

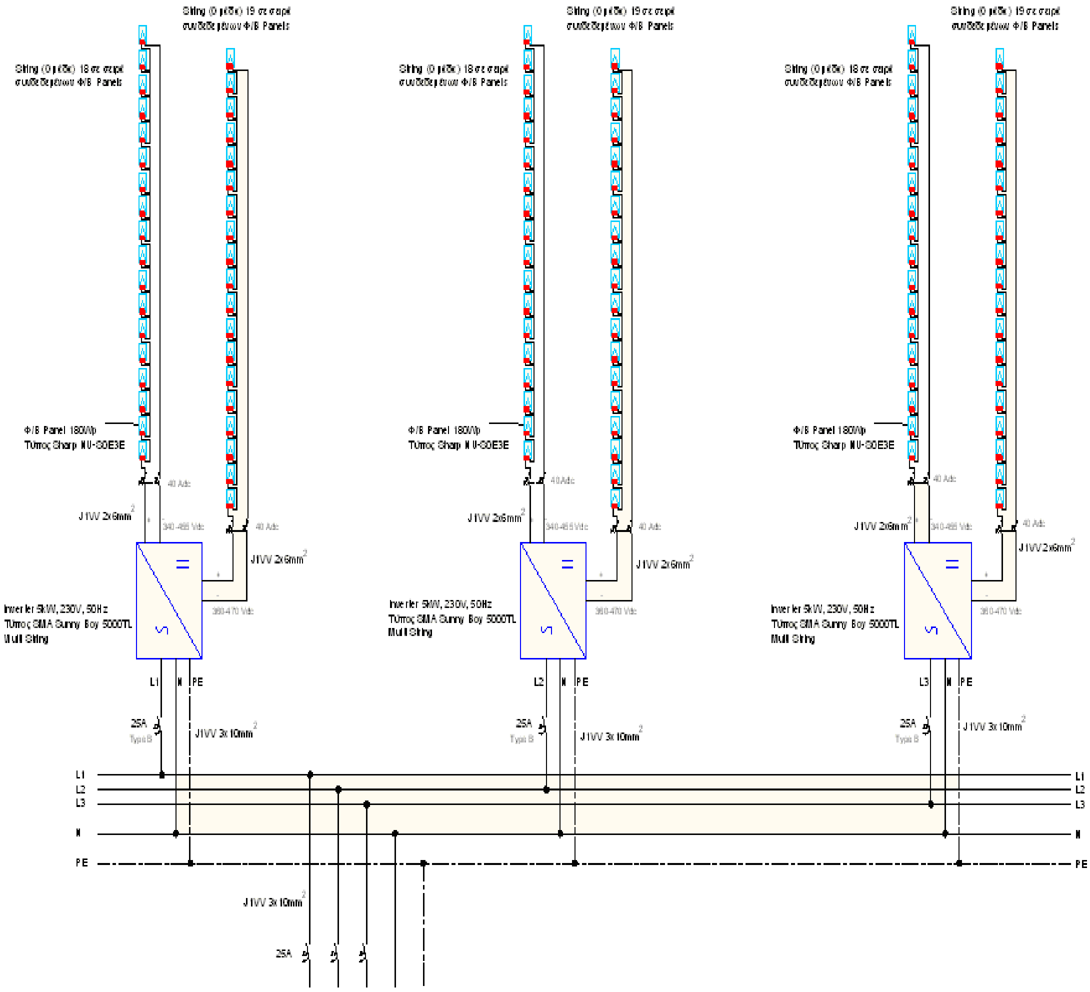
Para su manejo y utilización práctica, las células solares se unen entre sí en lo que se denomina un módulo fotovoltaico o módulo FV, resultando una estructura compacta, manejable y resistente.

Los módulos FV con células de silicio cristalino suelen comercializarse como unidades de 12 ó 24 voltios y con potencias de hasta 100 vatios, o más, de modo que en determinadas aplicaciones será necesario asociar varias de estas unidades para satisfacer los requerimientos eléctricos de tensión, corriente y potencia.

En la siguiente figura se puede observar el corte transversal de uno de estos módulos, en el que se observa el sistema de encapsulado y el enmarcado final:



0.3 Descripción del sistema bajo estudio



Localizado en Katerini, la capital de la prefactura de Pieria (Macedonia Central, Grecia), entre el Monte Olimpos y el Golfo de Termaikos, a una altitud de 14 m., el array FV existente se compone de 111 módulos de silicio mono-cristalino Sharp, produciendo una capacidad total de potencia pico de 19.98 kW.

El campo solar se divide en tres sub-arrays de 37 módulos con inclinación de 30º (óptimo para Katerini). Cada sub-array se divide a su vez en dos Strings:

- String A: 19 módulos conectados en serie.
- String B: 18 módulos conectados en serie.

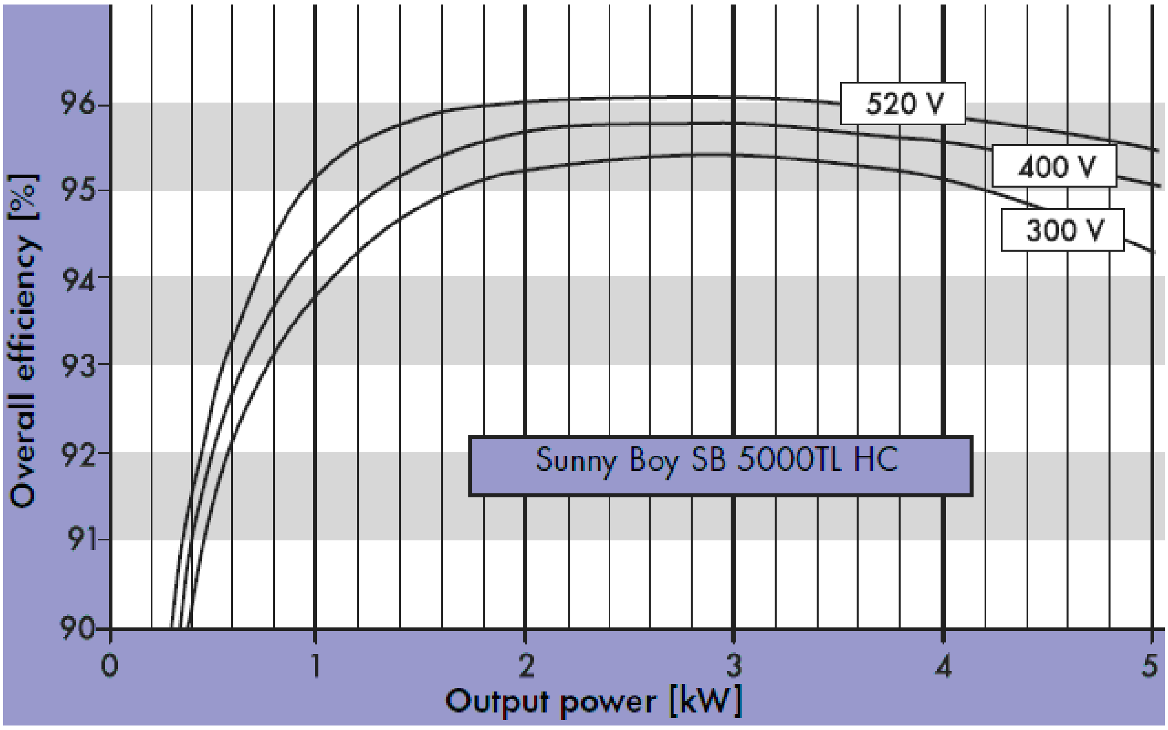
La eficiencia de inversión (3x5 kW) está diseñada para operar entre 220 y 240 V con una frecuencia de red de 50 Hz.

0.4 Procesamiento de Datos

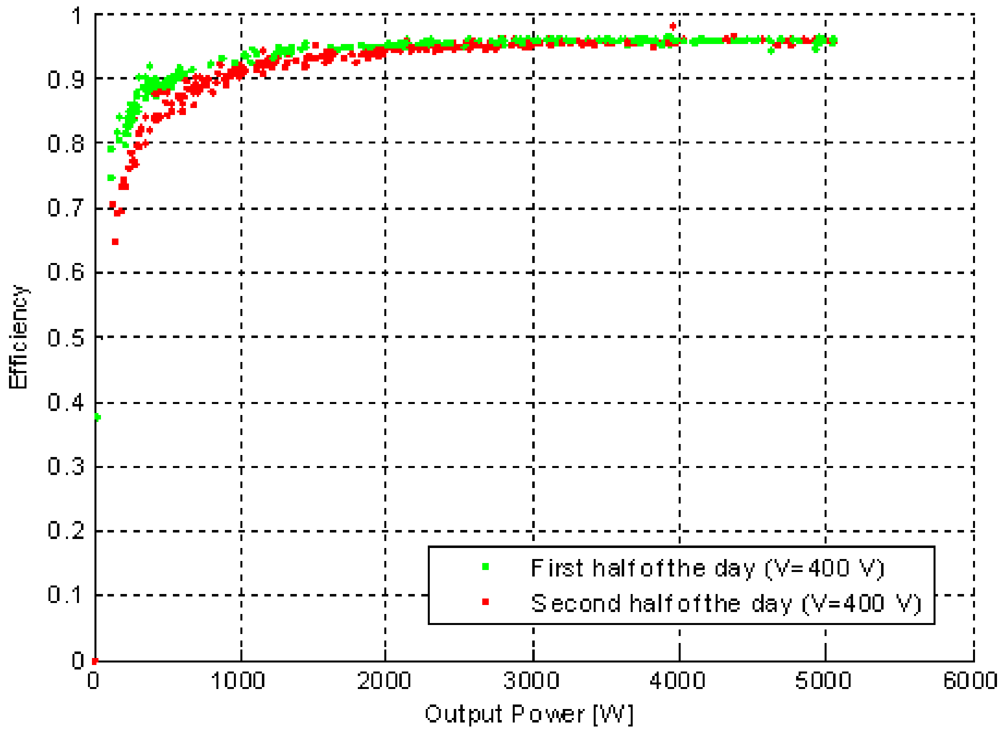
- La monitorización del sistema, se hace a través del inversor SMA Sunny Boy 5000, con un dispositivo que registra todos los datos relativos a las prestaciones del sistema (en un fichero .xls).
- Los datos disponibles recopilados para el presente análisis son los comprendidos entre las fechas: 10/03/2008 – 25/09/2008
- Para procesar tal cantidad de datos, el .xls original se convirtió en una hiper-matriz MATLAB, facilitando así el análisis y representación de las medidas tomadas.

0.5 Eficiencia de Inversión

Según el fabricante, la eficiencia del SunnyBoy 5000 depende principalmente de la tensión de entrada de los Strings PV conectados. De esta manera, cuanto mayor es el voltaje de entrada, mayor será la eficiencia:



Experimentalmente, la curva obtenida para nuestros inversores es la siguiente:

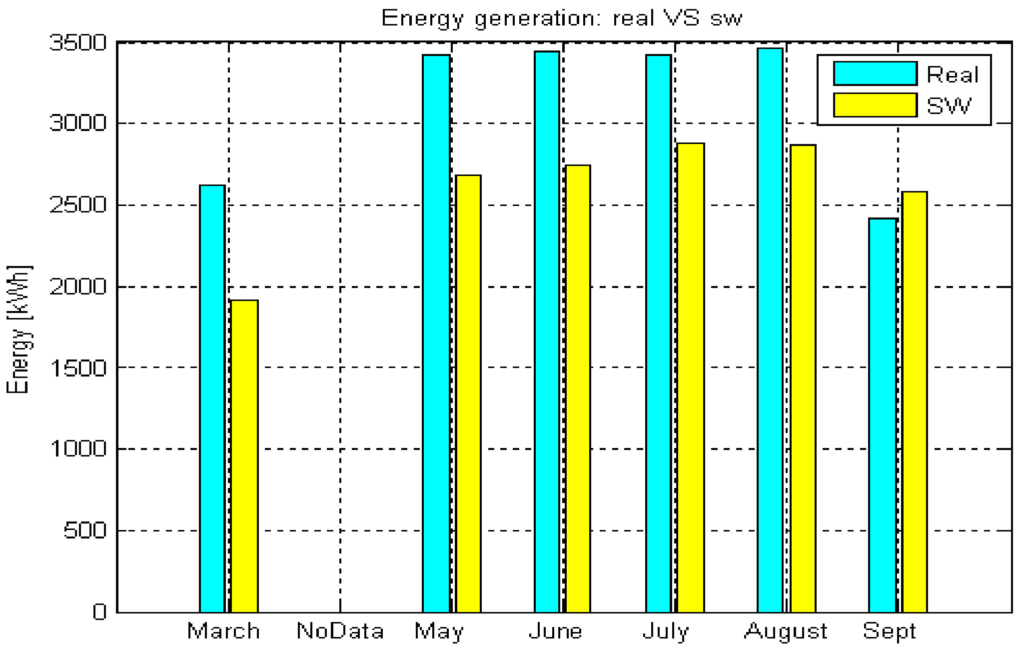


Lo que demuestra que para un voltaje DC de entrada dado, habrá diferentes eficiencias en función del momento del día, o lo que es lo mismo, la temperatura del dispositivo. **Esto refuerza la importancia del control de los ambientes con temperatura creciente.**

0.6 Producción experimental VS teórica

El objetivo de este análisis es triple:

- Asentar las bases del análisis de eficiencia realizado anteriormente.
- Comparar las medidas reales sobre producción energética obtenida en nuestro sistema de 20 kW conectado a red con las medidas simuladas obtenidas a través del software PVSYST, comprobando si simulación y medidas reales están próximas o existe un error significativo.
- Cuantificar el ajuste entre la capacidad de inversión total (15 kW) y la capacidad de producción máxima en el sistema (20 kW).



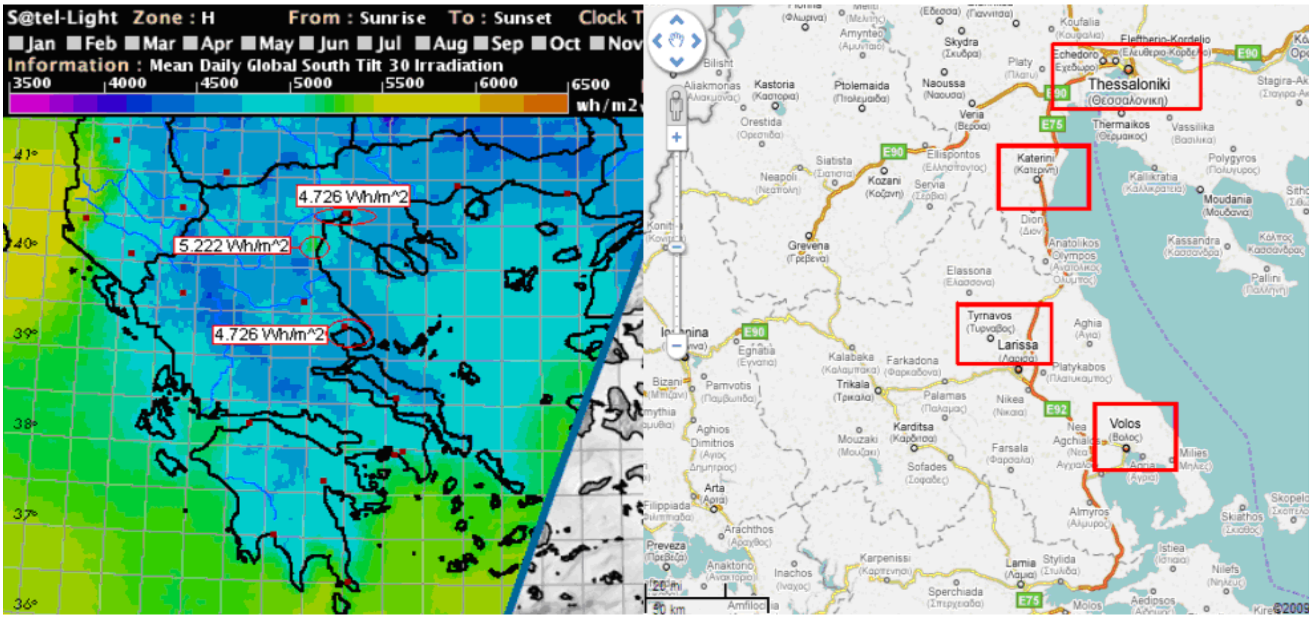
Analizando la producción eléctrica, descubrimos que la producción real es significativamente mayor que la esperada mediante simulación PVSYST. La energía generado para el periodo de datos disponible, fue exactamente de 20,017 MWh. Mientras tanto, para el mismo periodo de tiempo PVSYST estima una generación energética de 17,097 MWh. Esto se traduce en un ratio de energía producida / energía esperada de 1.17.

Posibles explicaciones genéricas a este desajuste podrían ser:

- Las condiciones meteorológicas durante los 7 meses considerados, podrían ser diferentes de las "típicas"
- PVSYST es una herramienta útil en el diseño, ayudando a decidir las mejores configuraciones de entre las posibles. Pero aunque es una aproximación precisa al problema, nunca una herramienta exacta.

Pero... ¿cabe la posibilidad de que exista alguna otra explicación más particular para nuestro caso?. PVSYST se basa en la base de datos METEONORM, que define estaciones concretas para las cuales se conocen los valores de irradiancia. Pero para sitios lejanos de estas "estaciones", como es nuestro caso (Katerini), los valores considerados por PVSYST son valores interpolados entre las 2-3 estaciones más cercanas.

Así que para chequear si la desviación entre producción real y producción esperada se debe a una errónea interpolación de datos, recurrimos al proyecto europeo Satel-Light, que proporciona datos del satélite geo-estacionario METEOSAT obteniendo una cobertura espacial de Europa **sin interpolaciones (a diferencia de METEONORM).**



A primera vista, se puede apreciar en el gráfico Satel-Light (izquierda) que la irradiancia media diaria global sobre Larissa, Volos y Thessaloniki para una inclinación de 30º, es muy similar (en torno a 4.726 Wh/m2). Sin embargo, para la localización de Katerini esta irradiancia llega al valor de 5.222 Wh/m2. Lo cual significa que se produce un incremento de la irradiancia respecto a los anteriores sitios de en torno al 10.5%.

Ahora, puesto que Katerini no cuenta con “estación” METEONORM sobre su superficie, la base de datos PVSYST procederá interpolando los datos de las estaciones más cercanas disponibles (Larissa, Volos y Thessaloniki!!), por o que los datos meteorológicos usados para la simulación tendrán un error de entrada de en torno al 10.5%, lo que justifica en gran medida la desviación detectada entre producción real y producción estimada cuando se usa software PVSYST.

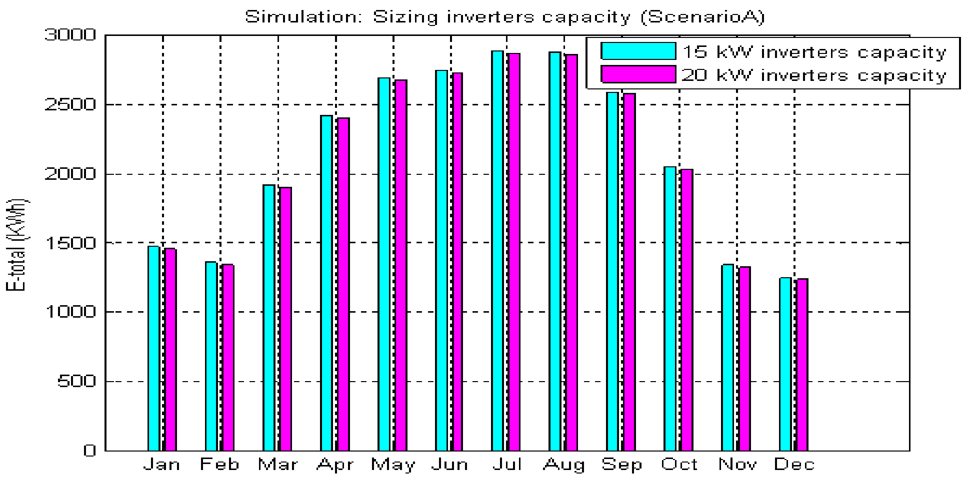
En cuanto a las simulaciones realizadas para concluir si la capacidad de inversión de 15 kW para un sistema de producción máxima de 20 kW está bien dimensionada, los resultados obtenidos son favorables, indicando que este dimensionamiento es el óptimo.

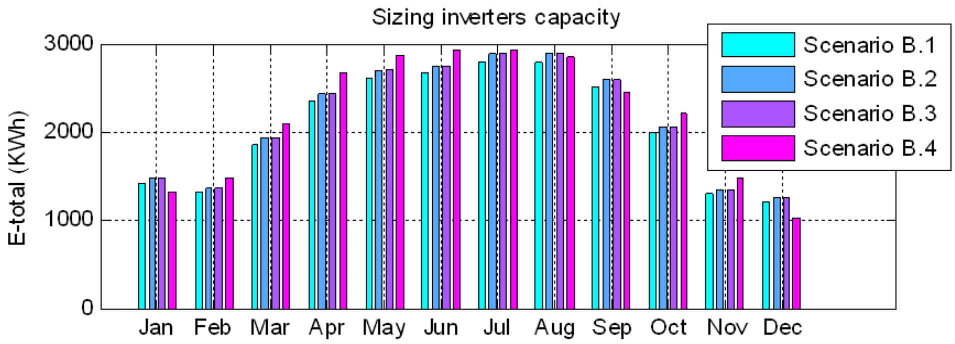
Para comprobarlo, se han comparado mediante simulaciones SW las siguientes capacidades de inversión:

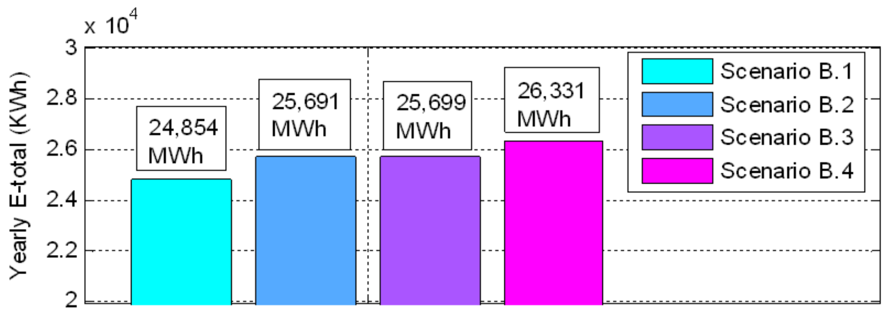
- Escenario A: usando la misma capacidad de inversión (5 kW)
    - A.1: 3 inversores de 5 kW

- A.2: 5 inversores de 5 kW

- Escenario B: usando diferentes tamaños de inversor (5, 6 y 7 kW)
  - B.1: 3 inversores de 5 kW
  - B.2: 3 inversores de 6 kW – última tecnología
  - B.3: 3 inversores de 7 kW – última tecnología
  - B.4: 3 inversores de 5 kW – última tecnología







0.7 Conclusiones

El diseño implementado se ha demostrado como óptimo:

- Las prestaciones globales del sistema se han mejorado gracias de criterios de diseño:
    - Consideración de inclinación óptima (30º)
    - Condiciones especial de irradiancia presentes en el área de Katerini
    - Infra-dimensionamiento de la capacidad total de inversión con respecto a la potencia PV pico instalada.
- Los fabricantes elegidos, SHARP y SMA, han resultado fiables, ofreciendo soluciones de confianza de acuerdo con lo esperado.

Todas las mejoras mencionadas muestran la importancia de una correcta optimización durante la etapa de diseño de la tecnología PV.

Pero más allá de nuestro sistema particular, los resultados obtenidos a través de este estudio son positivos para el futuro de la industria PV en toda Grecia:

- Especialmente ahora que el Parlamento Griego aprobó (15 Enero 2009) el programa de incentivación PV más ambicioso de toda Europa, tras una moratoria de casi 2 años.
- En 2008, los más importantes mercados PV europeos (Alemania, España, Italia, Francia y la recién incorporada Grecia) registraron una nueva capacidad PV instalada superior a 3 GW. Pero el contexto internacional reciente ha cambiado significativamente, haciendo la situación de Grecia incluso más atractiva aún:
    - El número de jugadores en el mercado PV se ha reducido significativamente, de modo que los capitales grandes son los que controlan ahora el crecimiento del mercado especialmente en España.
    - Las tarifas regresivas han sido significativamente elevadas, especialmente en Alemania.

Contra este marco de fondo, Grecia podría resurgir en unos pocos años como el próximo mayor mercado PV de toda Europa.

1. INTRODUCTION

It is a fact that current society tends to the energetic diversification and to the sustainability for the future growth. In this process the knowledge of the different energetic renewable systems and inside them, the photovoltaic solar energy, plays a fundamental role.

The new global conscience in questions of Environment, especially for the need to promote at every level the use of clean or renewable energies, make foresee important technological changes for the first years of the second millennium. The electricity of photovoltaic origin appears, on a worldwide scale, as one of the most important alternatives to satisfy the energetic needs in those cases in which it is needed to have clean, sure and quality energy compatible with sustainable development policies.

The photovoltaic solar energy has met particularly favoured during last years in Greece for the diverse legislations and regulations promulgated recently and for the institutional support given to the development of the sector. Greek government is ambitious when it comes to PV energy, with the goal of having installed at least 700 MWp by 2020. Within this framework, in June 2006 a new feed-in tariff system was launched in Greece, guarantying €0.40 to €0.50 per kWh for the next 20 years. Accompanied by a relaxation of the licensing procedure and the possibility for combination of these benefits with investment grants and subsidies between 30 to 55%, the payback time of PV investment becomes very interesting in this sunny country, getting an even better return on investment than in Spain in certain market segments.

Following this line of work, in the present report we make a complete analysis on the first Greek installation fitting the new regulatory framework, which will be useful to show the viability of solar power at Aristotle's country.

1.1 Preliminary Concepts.

In this paragraph we will try to explain, or to define in a very succinct form, different magnitudes and concepts handled habitually in the photovoltaic framework.

1.1.1 The solar radiation.

To all practical effects, it is valid and it turns out useful to imagine that Sun describes every day an arch on the celestial vault, from the rise up to the west, which length, elevation and duration throughout the time are different every day and in every geographical latitude of the planet.

Sun position in every instant, seen from a certain place of the terrestrial surface, remains perfectly defined just knowing the value of two angular variables: the solar azimuth, Ψ, and the solar height, α. These two angles, which are referred to the straight line that joins the centre of the solar disc with the point in the terrestrial surface from which the observation is carried out, can be known accurately for every instant throughout the year depending on the geographical latitude (parallel of the place), using well-known formulae of Positioning Astronomy, which for major comfort are tabulated and also integrated as data in many computer programs.

The interest of knowing the relative position of the Sun-beam with regard to the horizontal soil is due to the fact that the energetic waves directly from the Sun travel up to the terrestrial surface according to the direction of the above mentioned beam and, therefore, they affect on the soil (or on another flat surface arbitrary positioned as, for example, a solar panel) forming an angle which value will concern the value of the intensity of the solar radiation on the surface in question.

The position of a solar panel remains, likewise, perfectly determined just knowing also two angular values: the azimuth of the panel, γ (angle that forms the projection on the horizontal plane of the normal one to the surface of the panel with the local meridian), and the inclination, β, of the panel with regard to the horizontal plane.

The azimuth of the panel determines its orientation, being zero if it is orientated towards the equator which is the optimum in case of static systems.

The value of the duration of the day is used sometimes as estimation, in a comparative way, of the total irradiation that is necessary to wait to receive in one day with regard to other one of meteorological similar characteristics.

For latitude of 40 °, in the longest day of the year the Sun shines for almost 15 hours, whereas in the shortest day it hardly overcomes 9 hours.

Nowadays there is information available of average irradiation on horizontally of many localities, which allow to establish a few generally enough trustworthy values on the quantity of solar power that it is possible to expect obtaining, as average, in every month of the year.

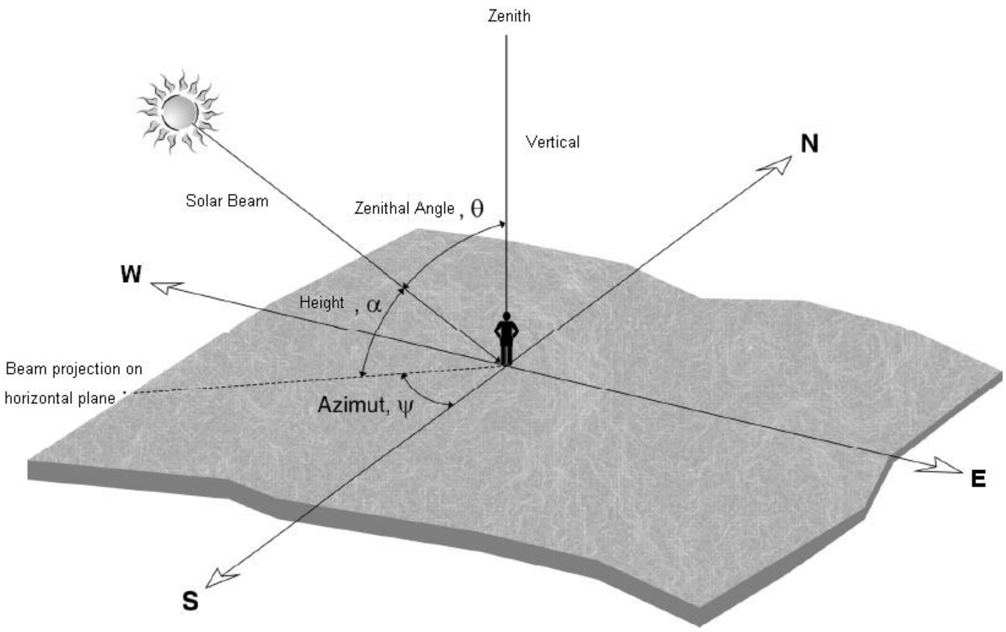


Figure 1: Angles that define Sun position at any moment

From horizontal irradiation values it is possible to calculate the irradiation on a sloping surface using diverse models of temporary and spatial distribution of the solar radiation. Hereby, tables or algorithms easily adaptable to computer-programs can be obtained, showing the quantity of incidental solar power on the photovoltaic panels (generally orientated approximately towards the equator and with an angle of inclination determined). The above mentioned quantity evaluated month by month or for different epochs of the year, constitutes as we will see hereinafter the starting point for trustworthy design of the PV system.

1.1.2 The PV Cell.

Since over one hundred years (Becquerel, in the middle of the 19th century) it is known that under a few certain conditions solar radiation can alter the electrical behaviour of certain materials, originating an electrical current. Since then the efficient ways of generating electric power from the solar radiation have been widely investigated, being called "photovoltaic cell" (or "solar cell") the basic device used to obtain electricity.

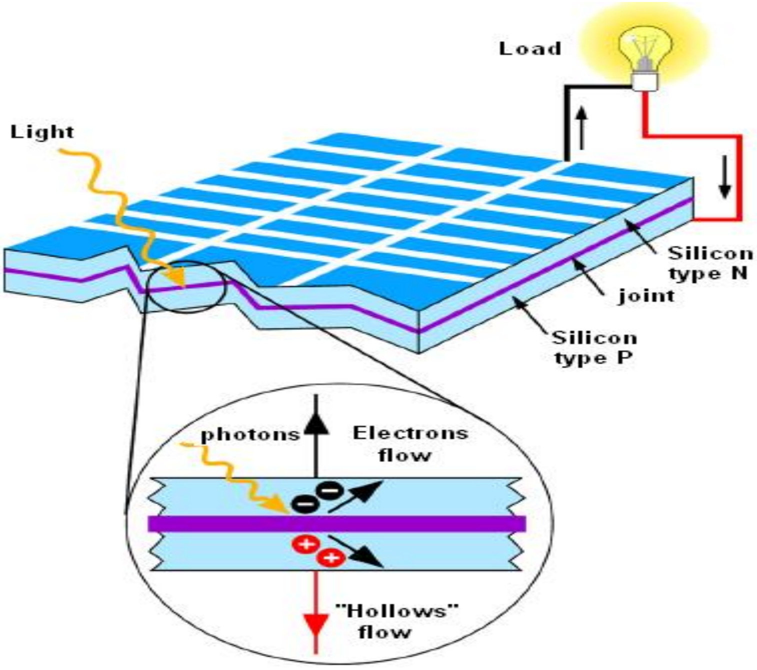


Figure 2: Solar cell performing

The functioning principle of solar cells is the photovoltaic effect:

- The union of two semiconductor materials, one type n and another type p, provokes a potential difference in the proximities of this union.
- Photons transfer the energy of the solar incidental radiation to semiconductor's electrons, liberating them from the crystalline net they were joined to.
- The existing potential difference inside the union provokes an arranged flow of carriers (electrons and hollows) photo generated, originating a clear difference of potential in the cell.
- By means of the existing contacts in the cell, can be assembled an exterior circuit where an electrical current able to provide electrical useful power will circulate (Figure 2).

Before going on, it is worth emphasizing the fact that PV cells are not electrical accumulators. Their electric power generation capacity is subordinated to the presence of solar incidental radiation on them, so the variability, discontinuity and randomness that characterize this radiation will also constitute the signs of identity defining photovoltaic electric power.

1.1.3 The PV Panel.

Solar cells based on crystalline silicon are characterized by their limited capacity to generate electrical power and their fragility and vulnerability to external agents. For their managing and practical utilization several of them are joined together setting up what is called a photovoltaic panel, turning out a compact, manageable and resistant structure.

Silicon-made PV panels are used to become commercialized as devices of 12 or 24 V and up to 100 W, or more, so that in several applications will be necessary the association of various unities to satisfy electrical requirements on voltage, current and power.

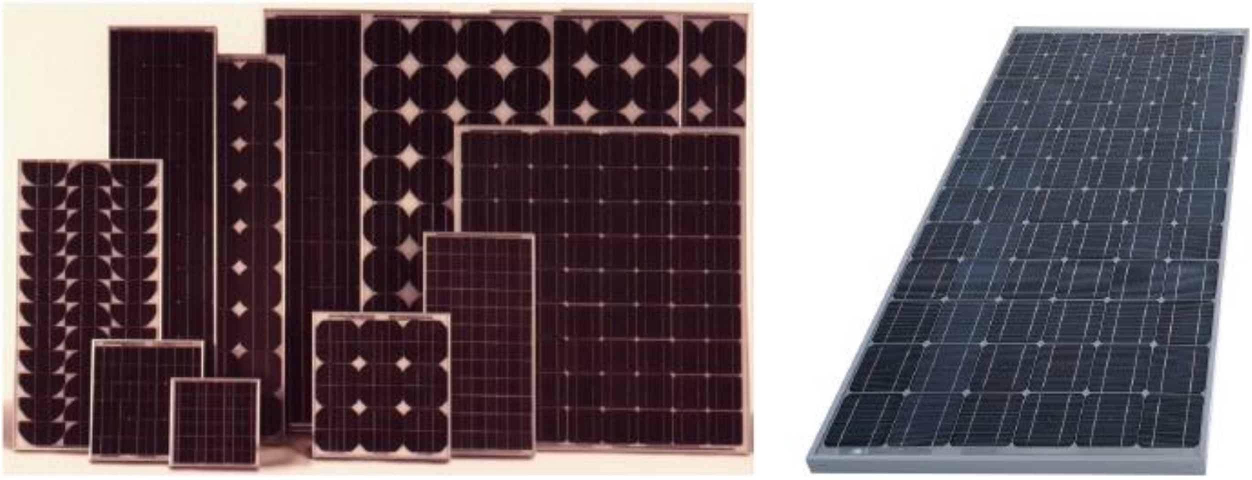


Figure 3: Different kinds of general purpose PV panels (silicon-made)

The modules showed in figure 3 are those who are commercialized usually, with a frame that allows their assembly on most common surfaces and structures (walls, metallic profiles, etc.).

In the same figure can be appreciated different ways of arranging the cells inside the module, obtaining a major or minor surface utilization. In figure 4 it appears the transverse cut of one of these modules, in which it is observed the system of encapsulation and final framing.

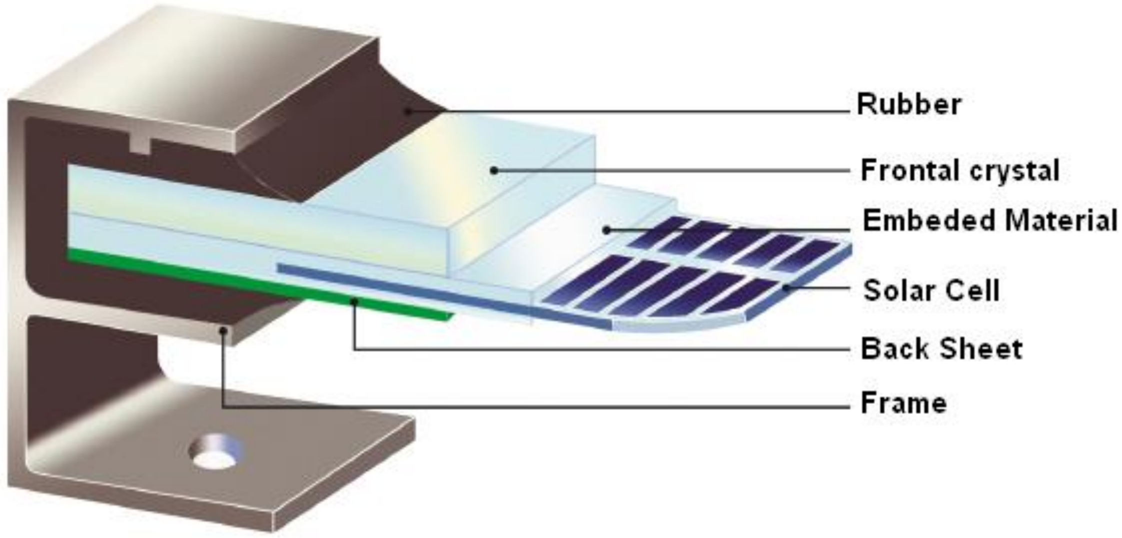


Figure 4: General purpose PV panel cross-section.

Electrical characteristic

We must keep in mind that basic device for PV electricity generation is the solar cell. Nevertheless, in practice we work with consistent modules of a certain number of cells generally connected in series. Because of this, for the study and analysis of the electrical behaviour of the generation subsystem the PV panel will be considered as the unit of electrical generation.

A solar cell can be represented as the electrical equivalent circuit showed in the figure 5. This is just the electrical simplified representation of the functioning described previously: a current of photo-generated carriers, the resultant diode of the union of semiconductors, a tension provoked by the photovoltaic effect and a few resistances that include the existing losses during the functioning (leakage currents, contacts, etc.).

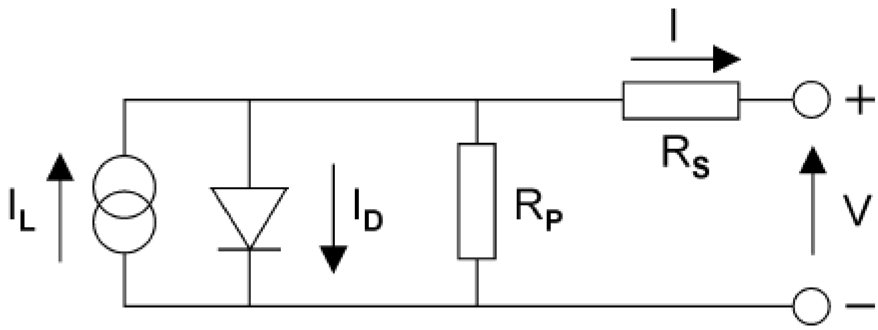


Figure 5: General purpose PV panel cross-section.

This electrical equivalent circuit can be applied to a PV panel formed by N_P rows in parallel and each one with N_S cells in series, turning out to be the relation tension - current that appears following:

$$I = I_{SC}\left[1 - \exp\frac{(V - V_{OC} + I\,R_{SG})}{N_S V_T}\right]$$

, being:

- I: Current provided by PV panel. It is equal to the current provided by one cell, multiplied by the number of cells in parallel.
- Isc: Current provided by PV panel under short-circuit condition. It can be considered equal to the current of photocurrent carriers (I_L in figure 5).
- V: Existing voltage inside PV panel terminals. It is equal to the existing one in a cell multiplied by the number of cells in series.
- Voc: Existing voltage inside PV panel terminals when open-circuit (which means lack of current).
- R_{SG}: Total series resistance of the PV panel, equal to $R_S N_S / N_P$.

The electrical characteristic of the PV cell is generally represented by the current versus voltage (I-V) curve. Next figure shows the I-V characteristic for a PV module. At the same time, it is indicated by means of points the power curve of the module. Both I-V characteristic and power curve must be provided by module manufacturer.

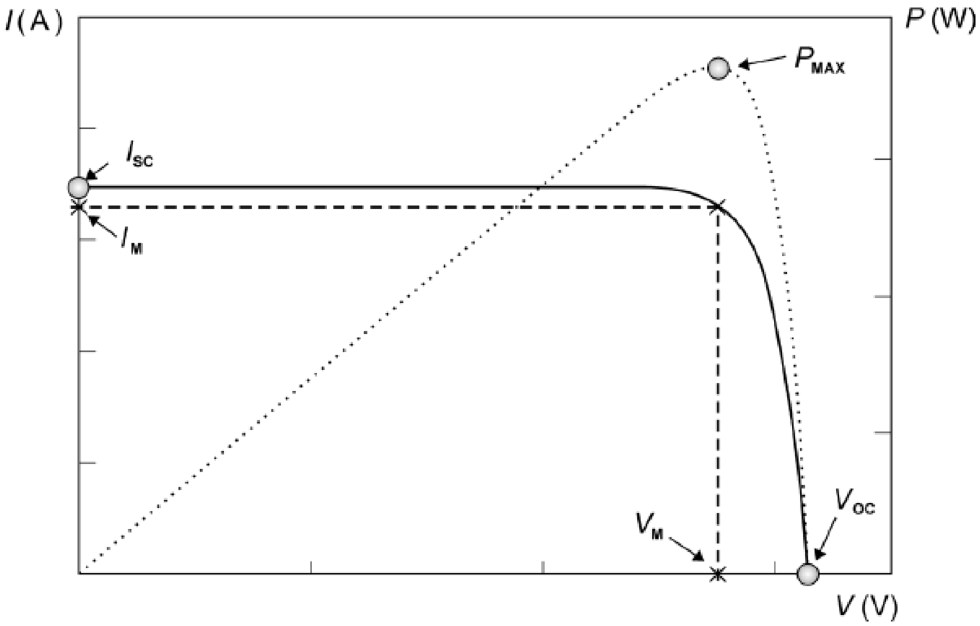


Figure 6: I-V characteristics for a given PV module.

Considering the I-V characteristic, it is necessary to indicate some requirements on how a PV module works:

- Working point of PV panel (pair I-V) can be anyone in the V-I curve, being determined by the intersection of panel's I-V curve and the load to it connected.
- There is only one pair of values V_M, I_M providing maximum power. From now on these values will be called as V_{MP} and I_{MP} (current and voltage at Maximum Power Point). A rough estimation of V_{MP}, valid for most crystalline silicon-made panels is:

$$V_{MP} = 0{,}8\, V_{OC}$$

- The current generated by a module is limited by nature, so that a short-circuit scenario is not a risky situation.

Besides described voltage and current parameters, there exist three more parameters of interest:

- **Shape factor**

  It is defined as:

$$FF = P_{MAX} / I_{SC}\, V_{OC} = I_M\, V_M / I_{SC}\, V_{OC}$$

  , and its name is due to the fact that mentioned factor is a measure on how I-V curve is close to a rectangle with V_{OC} and I_{SC} sides. This factor will be better as nearer it is to the unit.

- **Efficiency**

  The efficiency, as in case of a solar cell, is the quotient of the electrical power generated by the module and the power of the incidental radiation over it.

- **Nominal operating cell temperature**.

  Nominal operating cell temperature (NOCT) indicates the temperature reached by cells when they are under following working conditions:

  - Radiation intensity: 800 W/m^2
  - Spectral distribution: AM 1.5
  - Cell temperature: 25 °C

PV panels association

As it has been said before, individual electrical characteristic of PV panel not always allow satisfying system requirements on voltage and current. To get it, we have to associate the necessary number of panels joining properly their positive and negative terminals.

The junction of two or more panels in series causes a voltage equal to the addition of individual voltages of each module, keeping invariable the current. On the contrary, when connecting in parallel it is current what it is summed, keeping invariable the voltage.

Previously it was stated the effect reached when associating modules in series and in parallel, but such expected effects and real ones only match when every cells in a panel, and every panel, have the same electrical characteristic and work under identical temperature, lighting, etc. conditions, what in practice is not always true.

1.1.4 Stand-alone systems.

The major application of the stand-alone power system is in remote areas where utility lines are uneconomical to install due to terrain, the right-of-way difficulties or the environmental concerns. Even without these constraints, building new transmission lines is expensive. A 230 kV line costs about $1 million per mile. For remote villages farther than two miles from the nearest transmission line, a stand-alone PV system could be more economical.

The solar power outputs can fluctuate on an hourly or daily basis. The stand-alone system must, therefore, have some means of storing energy, which can be used later to supply the load during the periods of low or no power output. Alternatively, PV can also be used in a hybrid configuration with diesel engine generator in remote areas or with fuel cells in urban areas.

According to the World Bank, more than 2 billion people live in villages that are not yet connected to utility lines. These villages are the largest potential market of the hybrid stand-alone systems using diesel generator with PV for meeting their energy needs. Additionally, PV systems create more jobs per dollar invested, which help minimize the migration to already strained cities.

Because power sources having differing performance characteristics must be used in parallel, the stand-alone hybrid system is technically more challenging and expensive to design than the grid-connected system that simply augments the existing utility system.

The typical PV stand-alone system consists of a solar array and a battery connection. The array powers the load and charges the battery during daytime. The battery powers the load after dark. The inverter converts the DC power of the array and the battery into 60 or 50 Hz power. Inverters are available in a wide range of power ratings with efficiency ranging from 85 to 95 percent. The array is segmented with isolation diodes for improving the reliability. In such designs, if one string of the solar array fails, it does not load or short the remaining strings. Multiple inverters, such as three inverters each with 35 percent rating rather than one with 105 percent rating, are preferred. If one such inverter fails, the remaining two can continue supplying essential loads until the failed one is repaired or replaced. The same design approach also extends in using multiple batteries.

Most of the stand-alone PV systems installed in developing countries provide basic necessities, such as lighting and pumping water.

For determining the required capacity of the stand-alone power system, estimating the peak load demand is only one aspect of the design. But there are many other parameters to study:

- Power and energy estimates:

  The system sizing starts with compiling a list of all loads that are to be served. Not all loads are constant. Time-varying loads are expressed in peak watts they consume and the duty ratio. The peak power consumption is used in determining the wire size for making a connection to the source.

- Battery sizing:

  The battery Ah capacity required to support the load energy requirement of Ebat is determined using:

$$Ah = \frac{E_{bat}}{\eta_{disch}\left[N_{cell} \cdot V_{disch}\right] \cdot DoD_{allowed} \cdot N_{bat}}$$

, where:

E_{bat} = energy required from the battery per discharge

η_{disch} = efficiency of discharge path, including inverters, diodes, wires, etc.

N_{cell} = number of series cells in one battery

V_{disch} = average cell voltage during discharge

$DOD_{allowed}$ = maximum DOD allowed for the required cycle life

N_{bat} = number of batteries in parallel

- PV array sizing:

  The basic tenet in sizing the stand-alone “power system” is to remember that it is really the stand-alone “energy system.” It must, therefore, maintain the energy balance over the specified period. The energy drained during lean times must be made up by the positive balance during the remaining time of the period. A simple case of a constant load on the PV system using solar arrays perfectly pointing toward the sun normally for 10 hours of the day is shown in next figure to illustrate the point.

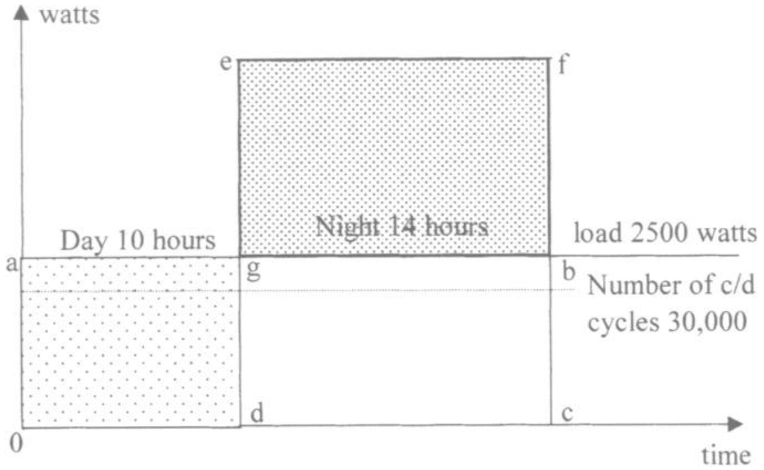


Figure 7: Energy balance analysis over one load cycle

The solar array is sized such that the two shaded areas on two sides of the load line must be equal. That is, the area **oagd** must be equal to the area **gefb**. The system losses in the round trip energy transfers, e.g., from and to the battery, adjust the available load to a lower value as shown by the dotted line.

1.1.5 Grid-connected systems.

PV power systems have made a successful transition from small stand-alone sites to large grid-connected systems. The utility interconnection brings a new dimension in the renewable power economy by pooling the temporal excess or the shortfall in the renewable power economy by pooling the temporal excess or the shortfall in the renewable power with the connecting grid. This improves the overall economy and the load availability of the renewable plant; the two important factors of any power system. The grid supplies power to the site loads when needed, or absorbs the excess power from the site when available. One kWh meter is used to record the power delivered to the grid, and another kWh meter is used to record the power drawn from the grid. The two meters are generally priced differently.

Next figure is a typical circuit diagram of the grid-connected photovoltaic power system:

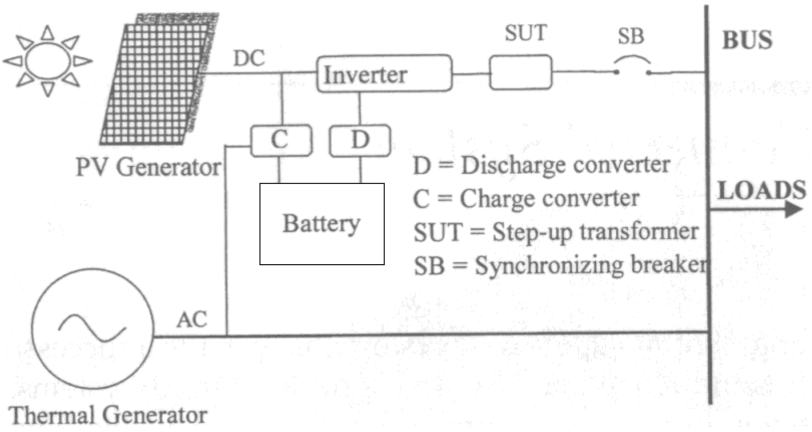


Figure 8: Electrical schematic of a grid-connected photovoltaic system

It interfaces with the local utility lines at the output side of the inverter as shown. A battery is often added to meet short term load peaks.

In recent years, large building-integrated PV installations have made significant advances by adding the grid-interconnection in the system design.

PV systems interface the grid at the output terminals of the synchronizing breaker at the output end of the inverter. The power flows in either direction depending on the site voltage at the breaker terminals. The fundamental requirements on the site voltage for interacting with the grid are as follows:

- The voltage magnitude and phase must equal to that required for the desired magnitude and direction of the power flow. The voltage is controlled by the transformer turn ratio and/or the rectifier/inverter firing angle in a closed-loop control system.
- The frequency must be exactly equal to that of the grid, or else the system will not work. To meet the exacting frequency requirement, the only effective means is to use the utility frequency as a reference for the inverter switching frequency.

The synchronizing breaker has internal voltage and phase angle sensors to monitor the site and grid voltages and signal the correct instant for closing the breaker. As a part of the automatic protection circuit, any attempt to close the breaker at an incorrect instant is rejected by the breaker. Four conditions which must be satisfied before the synchronizing switch will permit the closure are as follows:

- The frequency must be as close as possible with the grid frequency, preferably about one-third of a hertz higher.
- The terminal voltage magnitude must match with that of the grid, preferably a few percent higher.
- The phase sequence of the two three-phase voltages must be the same.

- The phase angle between the two voltages must be within 5 degrees.

In this way, any small mismatch between the site voltage and the grid voltage will circulate an inrush current between the two such that the two systems will come to perfect synchronous operation.

1.1.6 Power fitting-out: the PV inverter.

The component responsible of making the appropriate electrical conversion DC/AC is the inverter. The most common waves generated by inverters are called “pure sine” and “modified sine” (or trapezoidal). In next figure both sort of waves are shown:

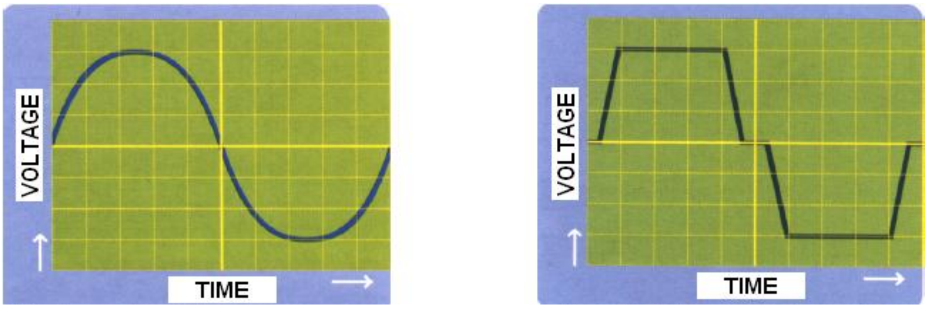


Figure 9: Pure sine wave VS Modified sine wave.

For PV systems grid-connected the energy generated is transferred to conventional electric power network, so mentioned energy must be “pure sine” with the same electrical characteristics (voltage and frequency) than Company provider. In next figure it is shown the typical schema for grid-connected inverters:

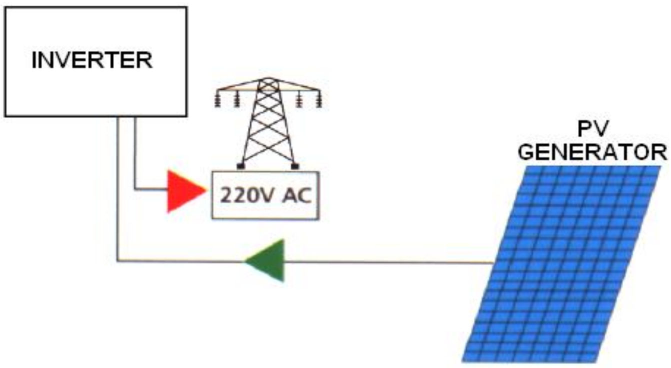


Figure 10: Typical schema for grid-connected PV systems.

The efficiency of the inverter is a parameter of great importance, as long as it shows how the inverter behaves for different power levels (apart from nominal). The efficiency of the inverter varies with the load level. Although this relation is different for each inverter, a conventional model has a load/efficiency curve similar to figure shown down here. Therefore, a key consideration in the design and operation of inverters is how to achieve high efficiency with varying power output.

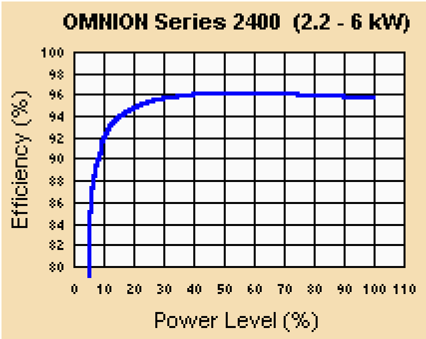


Figure 11: Typical inverter efficiency curve

So when talking about efficiency, the main difference between inverters is its performance at low power (apart from existing losses, inverters need to use some power to execute conversion process).

Another important characteristic for grid-connected inverters is its capacity for tracking Maximum Power Point.

Maximum Power Point Tracker (MPPT)

The electric power supplied by a photovoltaic power generation system depends on the solar radiation and temperature. But designing efficient PV systems heavily emphasizes to track the maximum power operating point.

The amount of power generated by a PV depends on the operating voltage of the array. A PV's maximum power point (MPP) varies with solar insulation and temperature. Its V-I and V-P characteristic curves specify a unique operating point at which maximum possible power is delivered. At the MPP, the PV operates at its highest efficiency so many methods have been developed to determine MPPT.

Inverters/converters must guarantee that the PV module(s) is operated at the MPP, which is the operating condition where the most energy is captured. This is accomplished with an MPP tracker (MPPT).

To understand how MPPT works, following we will explain a simple but efficient method used for this purpose, based on a DC/DC converter as shown in the figure:

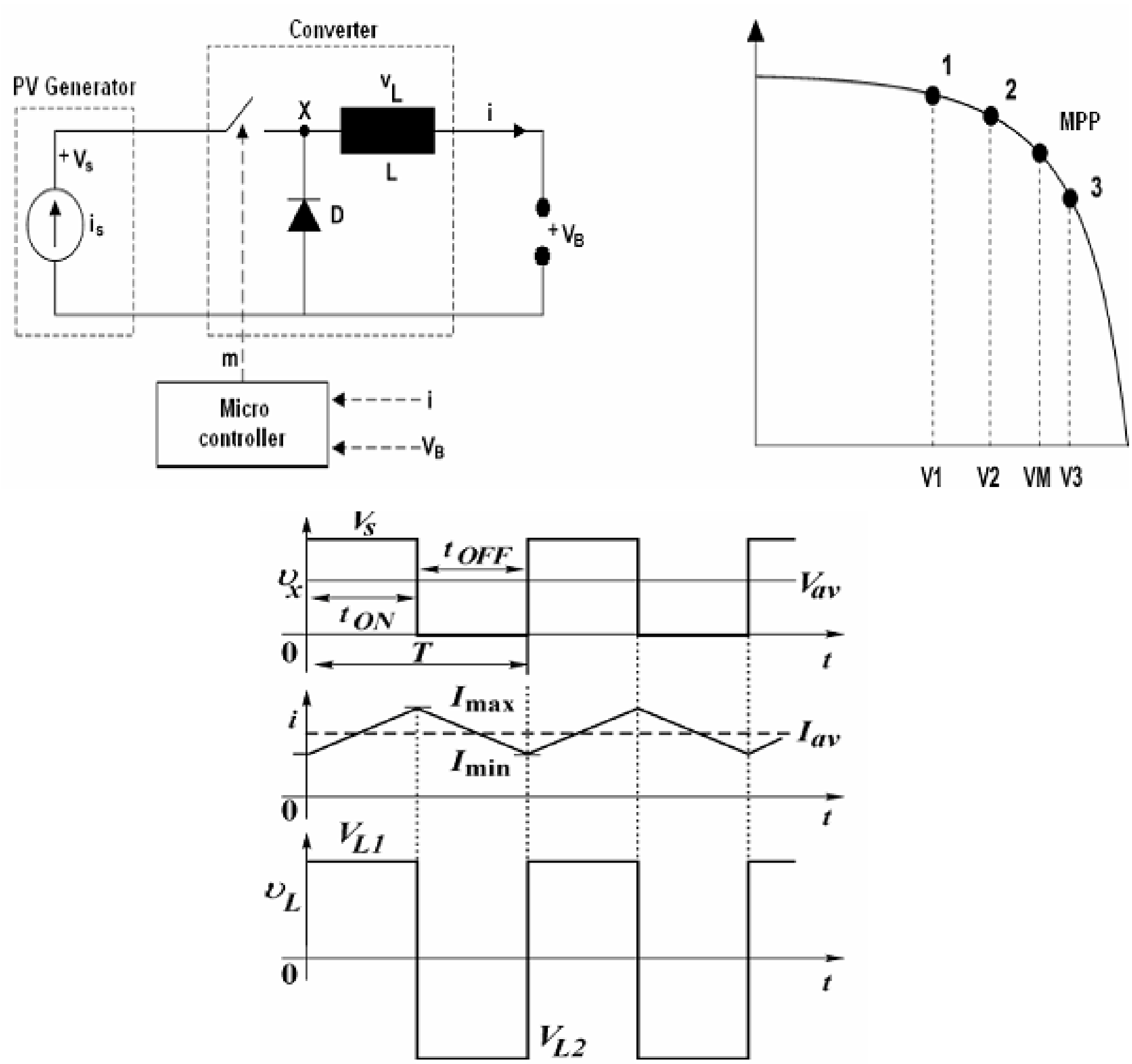


Figure 12: MPPT circuit based on P&O technique

This circuit is based on a P&O technique (Perturb and Observe). The key of this circuit consist of a switcher that can be opened and closed thousand times per second, so the voltage between coil's terminals (V_L) when switcher is closed depends on the voltage V_B and the working cycle (m) of switcher.

$$\text{ON: } v_L = L\,(di/dt) = V_s - V_B = \text{cte.} = V_{L1} \Rightarrow i = t\,(V_{L1}/L)$$

$$\text{OFF: } v_L = L\,(di/dt) = -V_B = \text{cte.} = V_{L2} \Rightarrow i = t\,(V_{L2}/L)$$

$$V_{L1}\,(t_{ON}/T) + V_{L2}\,(t_{OFF}/T) = 0 \Rightarrow mV_{L1} = -V_{L2}\,(1-m) = V_B$$

$$(1-m) \Rightarrow V_{L1} = V_B\,(1-m)/m \Rightarrow V_s - V_B = V_B\,(1-m)/m \Rightarrow V_s = V_B/m$$

This working cycle is defined as the time the switcher is closed and its switching period, this means:

$$m = T_{ON}/T$$

When switch is closed, voltage in PV panel (V_S) is equal to:

$$V_S = V_L + V_B$$

, so with a suitable working cycle we could make this sum was equal to the voltage at the MPP and the problem would be solved.

An easy way of determining the appropriate working cycle could be:

i. Start with m = 1, so V_L (switch closed) is 0, and therefore $Vs = V_B$

ii. With this voltage, PV panel produces a current corresponding with working point "1".

iii. The micro-controller calculates power generated by panel ($P = i \times V_B$), and decreases a little the working cycle of switcher. This decrease means an increase in coil's voltage (V_L) and therefore in panel's voltage (Vs). So the working point moves to "2" (with a new load current).

iv. The micro-controller calculates power generated by panel again, and if it is bigger than before, it decreases once more switcher's working cycle, increasing V_L and passing to a working point between "2" and MPP. This process would keep repeating till the system gets to the point MPP.

v. Once reached the point MPP, the next decrease in working cycle would take us to the point "3" and therefore would cause a decrease in the power calculated by micro-controller, who will react increasing slightly the cycle (and so decreasing Vs and rising again through V-I characteristic).

vi. With this easy procedure, variations in MPP caused by deviations in temperature or irradiance can be followed so the PV panel would be producing always the maximum power available.

The converter just depicted is called "voltage reducer" (or current increaser). It is the most frequent as long as MPP of PV generator is usually bigger than the voltage in the battery. But there exist "voltage increaser" converters too.

Through MPPT control the power provided by PV panels can be increased around 30%. However it is necessary take into consideration that it would not be useful getting 30% additional power if MPPT's efficiency is just 70%. Fortunately, most MPPT nowadays exceed 90% efficiency.

2. SYSTEM DESCRIPTION

Our 20 kW grid-connected system has been placed in Katerini, the capital of Pieria prefecture (Central Macedonia, Greece), between Mt. Olympus and the Thermaikos Gulf, at an altitude of 14 m..

Figure 13: Location of PV System under analysis

2.1 Electrical diagram of the Grid-Connected PV System.

The electrical diagram of Grid-Connected PV System under analysis is shown in next figure.

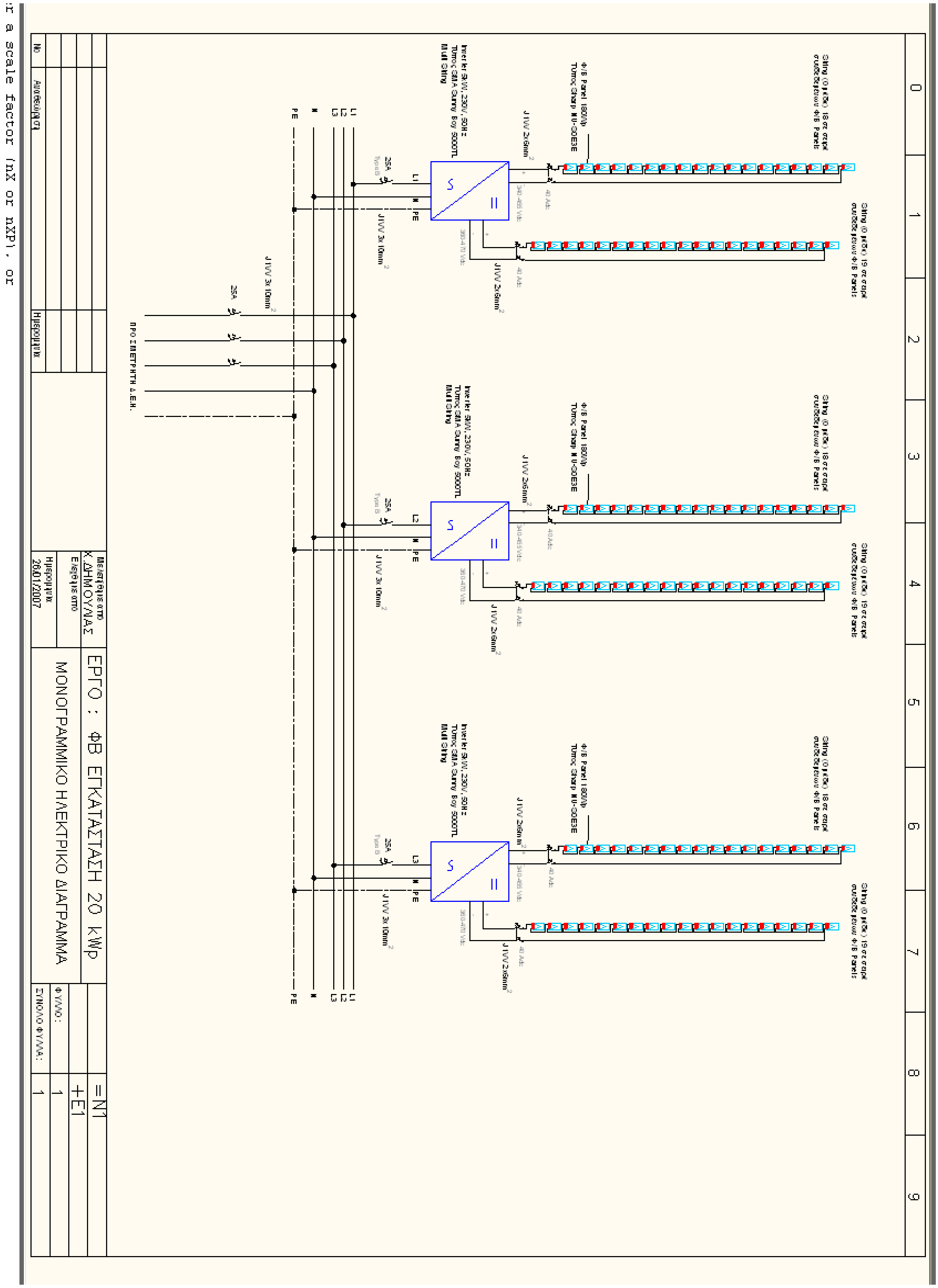


Figure 14: Electrical diagram of the Grid-connected PV System

2.1.1 Solar Array.

The existing PV array is comprised of 111 Sharp NU-S0(E3Z) PV mono-crystalline silicon modules with following electrical characteristics:

Electrical data		
Module production in the EU		
Module production in Japan		**NU-S0 (E3Z)**
Rated power		180 W_p
Open circuit voltage	V_{oc}	30.0
Short circuit current	I_{sc}	8.23
Voltage at maximum power	V_{pm}	23.7
Current at maximum power	I_{pm}	7.6
Module efficiency	η_m	13.7
Temperature coefficient - open circuit voltage	αV_{oc}	-104
Temperature coefficient - short circuit current	αI_{sc}	+0.053
Temperature coefficient – power	αP_m	-0.485

Figure 15: NU-S0 (E3Z) electrical data (under STC).

The 111 panels of 180 Wp each one produce a total power capacity of 19.98 kWp. The solar field is made up of three subarrays of 37 modules with 30º tilt (optimum for Katerini). Each subarray is arranged in two strings:

- String A: 19 modules connected in series
- String B: 18 modules connected in series

Figure 16: Photography of the different strings composing the solar-field.

2.1.2 Grid-connected inverter.

The grid-connected inverters used to convert DC power from PV subarray to AC power on grid have been SMA Sunny Boy 5000TL. Three inverters were employed, each one connected to a subarray (two strings), as shown in next figure:

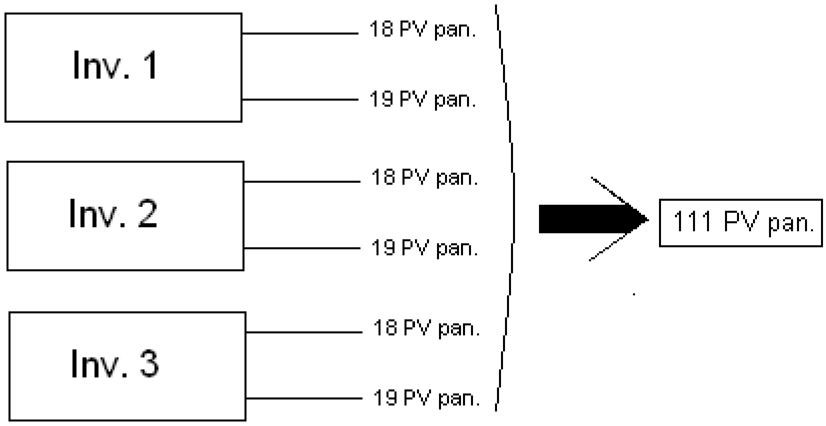


Figure 17: 3 inverters SMA 5000TL connected with 111 PV panels.

Each inverter has two input areas, "String A" and "String B", each with their own MPP tracker. The inverter is designed for operation on 220-240 V grids at a grid frequency of 50 Hz.

Main limits reached by inverter are depicted in next figures:

Limit values for DC input	Input area "String A"	Input area "String B"
Max. voltage	750 V (DC)	750 V (DC)
Max. input current	11 A (DC)	11 A (DC)

Figure 18: DC side limits

	Limit values for AC output
Voltage range (in the area of application of DIN VDE 0126-1-1)	198 V ... 253 / 260 V [a)]
Frequency range (in the area of application of DIN VDE 0126-1-1)	47.55 Hz ... 50.2 Hz
Voltage range (extended operating range)	180 V ... 265 V
Frequency range (extended operating range)	45.5 Hz ... 54.5 Hz

Figure 19: AC side limits

The efficiency of the Sunny Boy inverter used depends mainly on the input voltage of the connected PV strings. The higher the input voltage, the higher the efficiency.

Efficiency		
Max. efficiency	ηmax	96,2 %
European standard efficiency	ηeuro	95,5 %

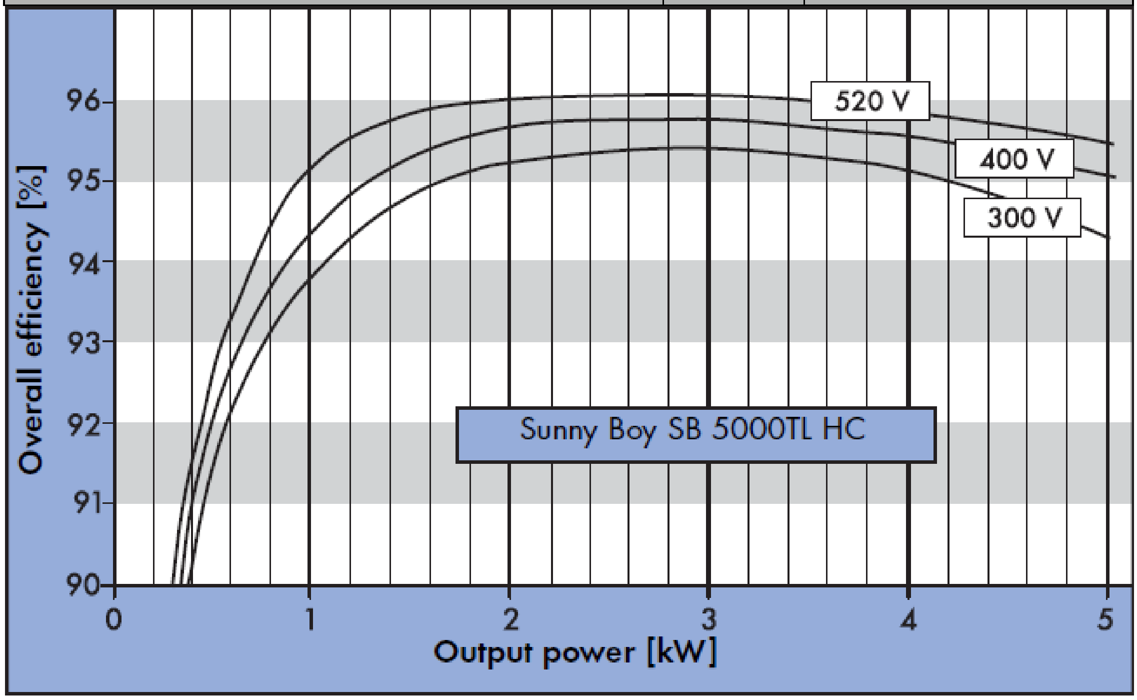


Figure 20: SMA Sunny Boy 5000 TL efficiency curve

2.1.3 Control and Monitoring System.

The control of inverter operating function depends on the inverter itself. This means that the inverter will be turned on in the morning and will automatically synchronize to the electric grid. After being operative all day until the evening, it will just automatically shut down.

For the monitoring of the System, there exists a measurement device inside SMA Sunny Boy 5000 inverter which records all data related to system performance.

Thanks to this system of monitoring, we have compiled info of the PV installation during 6 months, time enough to draw conclusions after a detailed analysis on data available.

So from now on, present report will focus on the analysis of data obtained with the purpose of evaluate whole system operability and performance, as well as other matters of interest.

3. INVERTERS EFFICIENCY

This section is intended to establish the conversion efficiency of the system inverters between the DC source (PV) input and the AC output. The series of analysis described in this section will characterize the unit's performance and efficiency as a function of array power.

3.1 First Approach.

Original .xls data files provided by SMA SunnyBoy 5000 inverters have been converted into a hyper-matrix MATLAB for its handling.

Once loaded in MATLAB all available data, we can start processing them. For such purpose, the first approach to our system consists on the graphical representation of inverters efficiency as a function of output power, for every available day:

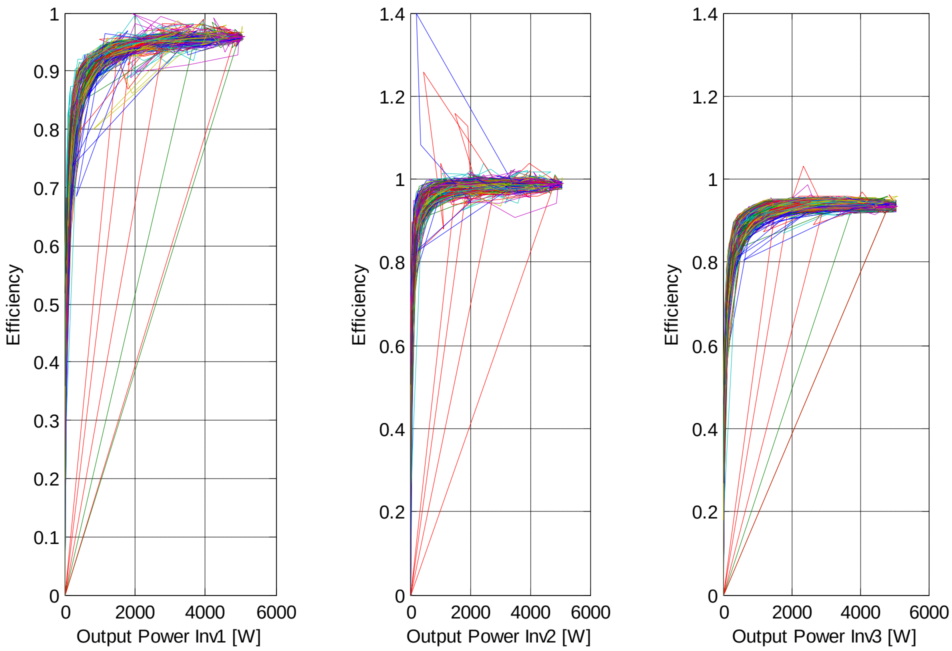


Figure 21: Output Power VS Efficiency, for every available data per day

From previous figure we can note at first sight how efficiency curves are, approximately, for every inverter. In mentioned figure, efficiency curve for every available day have been overprinted. To have a more clear view of the same graphic, let's plot it in a 3-D graphic, including in a new axis indicating the sequence of days:

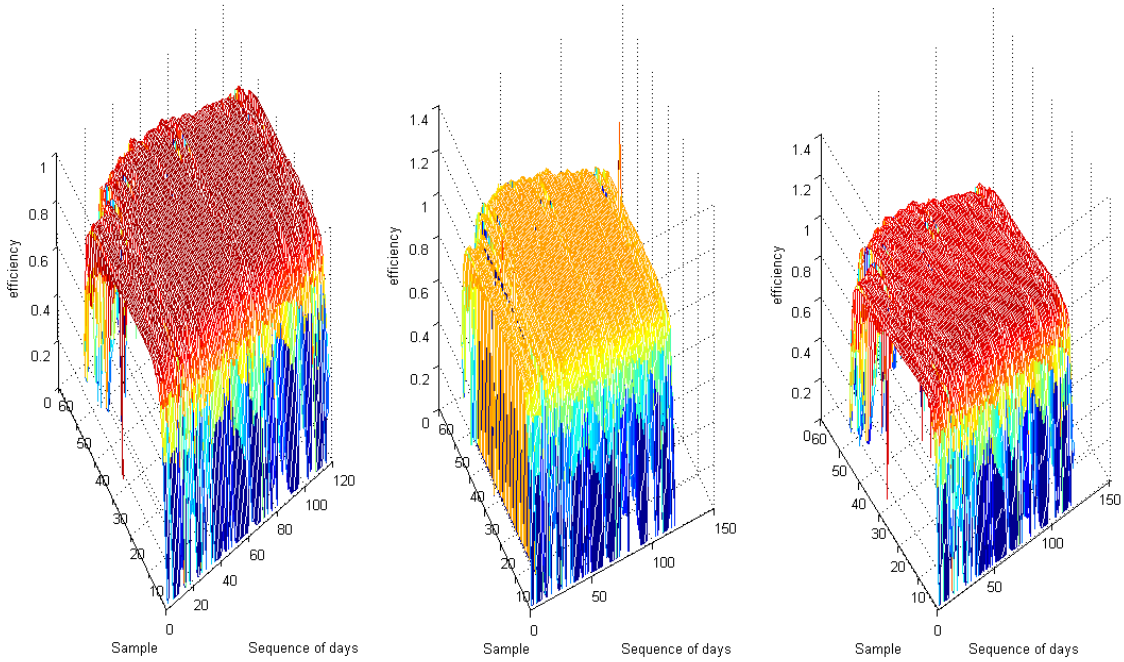


Figure 22: 3-D Output Power VS Efficiency, for every available data per day

In this point we can check that there are some punctual "erroneous data" due to operating failures of the system (inverter shutdown, grid disturbances, etc.)

After erasing erroneous samples (for example, those who have efficiency value higher than 1), we can plot the same figures as before:

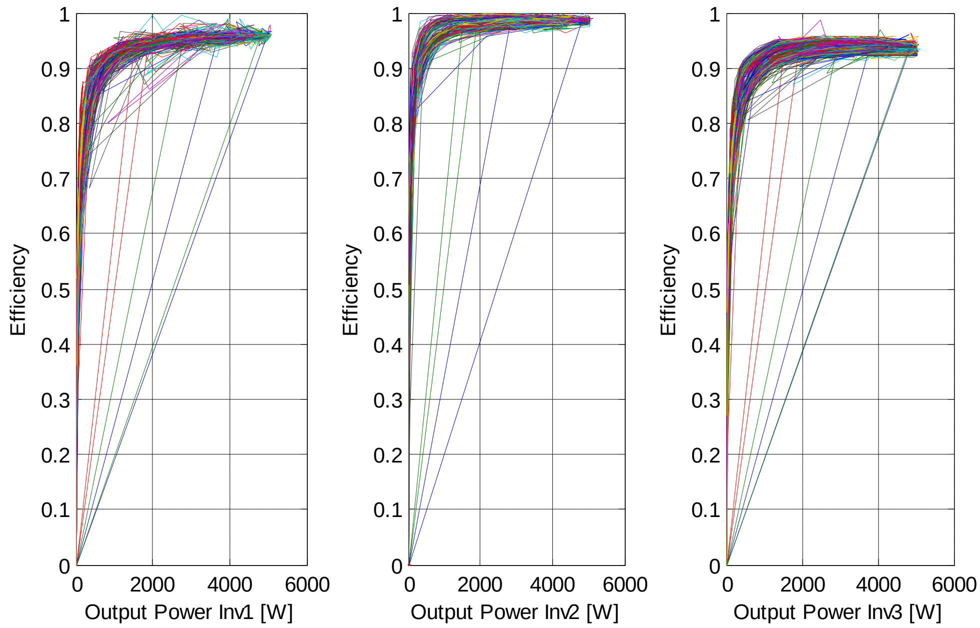


Figure 23: Output Power VS Efficiency, for every available data per day [no error data]

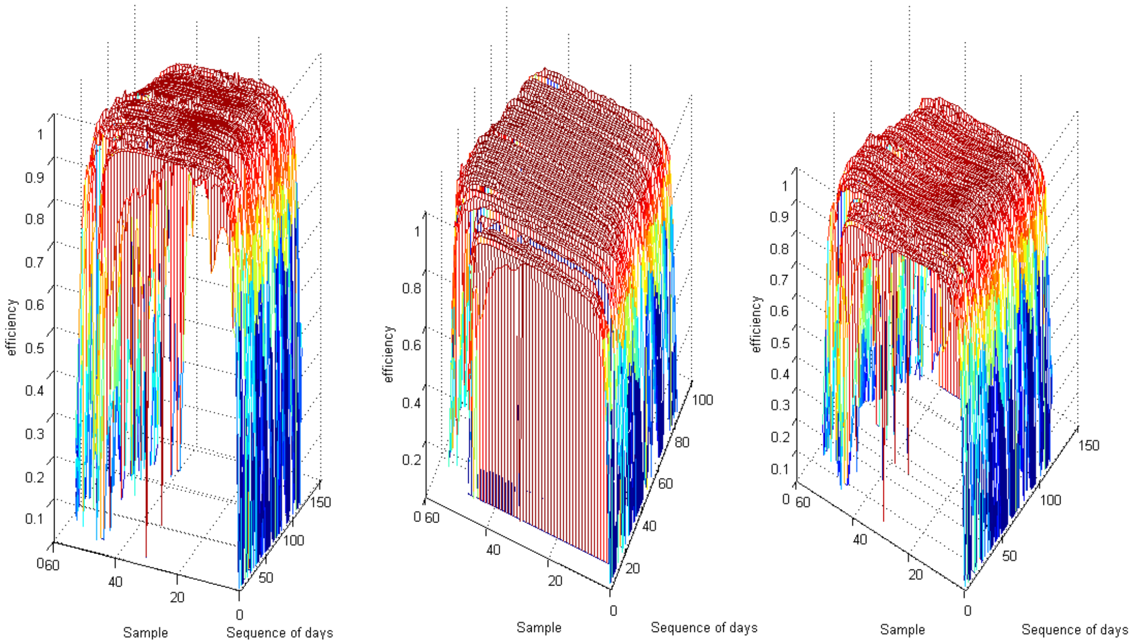


Figure 24: 3-D Output Power VS Efficiency, for every available data per day [no error data]

From this first approach it seems that PV system is working quite properly. But for assuring this assertion, we will make further analysis on it.

3.2 Inverter efficiency variation.

Inside this section we will focus on the analysis of inverter 1, being the results and conclusions here obtained extensive to the other inverters of our PV system.

Let's plot now the graphic of Efficiency VS Output Power, attending to different input voltage. Firstly, we have chosen as input voltage the same as indicated by the manufacturer in the efficiency curve provided:

- 300 V (green coloured, allowing range of voltage between 280 and 320 V)
- 400 V (blue coloured, allowing range of voltage between 380 and 420 V)
- 520 V (red coloured, allowing range of voltage between 500 and 540 V)

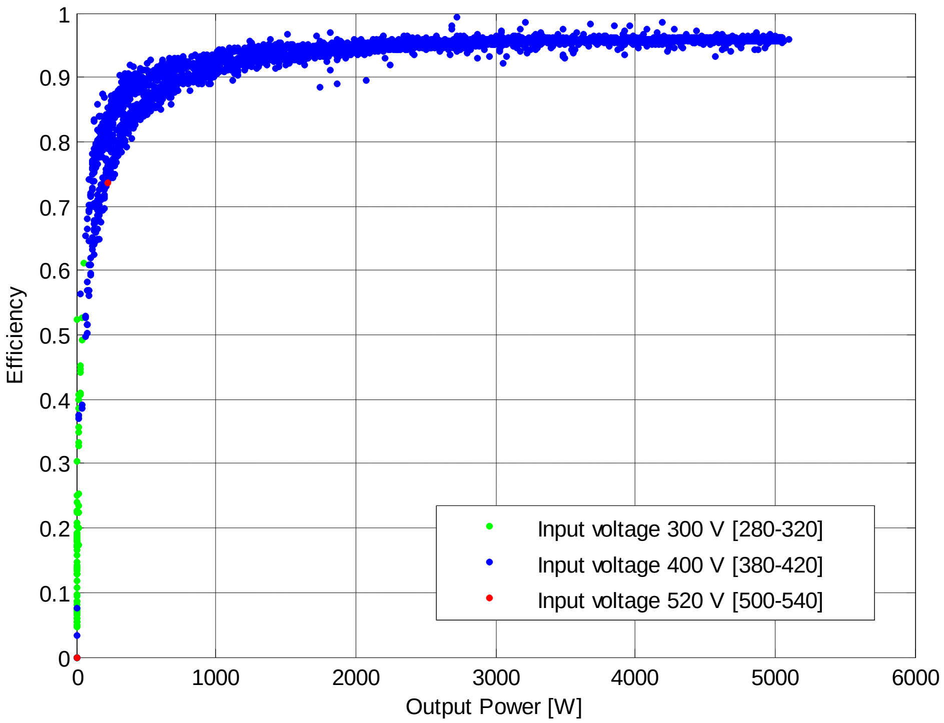


Figure 25: Output Power VS Efficiency, for input voltage indicated by manufacturer

However, choosing the voltages indicated by manufacturer as just done, we loose a lot of samples as long as our PV device is working to different input voltages. We can see it in the following histogram:

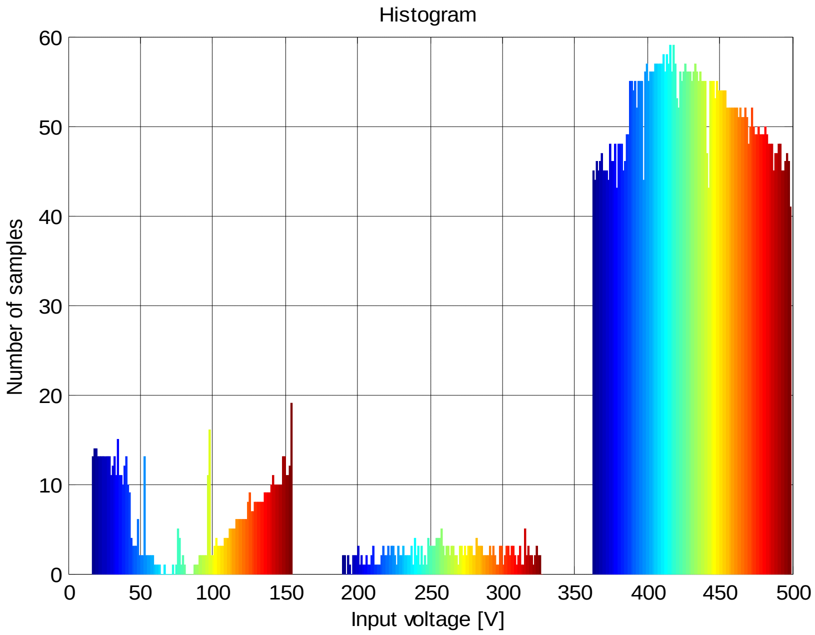


Figure 26: Distribution of input voltage among three bins

The three bins shown are centred in the points 86.167, 258.5 and 430.83, so for checking the whole efficiency shape we will consider now the following 3 main ranks:

- Green coloured: [30-160] V
- Blue coloured: [200-330] V
- Red coloured: [360-500] V

Considering these wide ranks, we are covering most input voltage possibilities, obtaining the following figure:

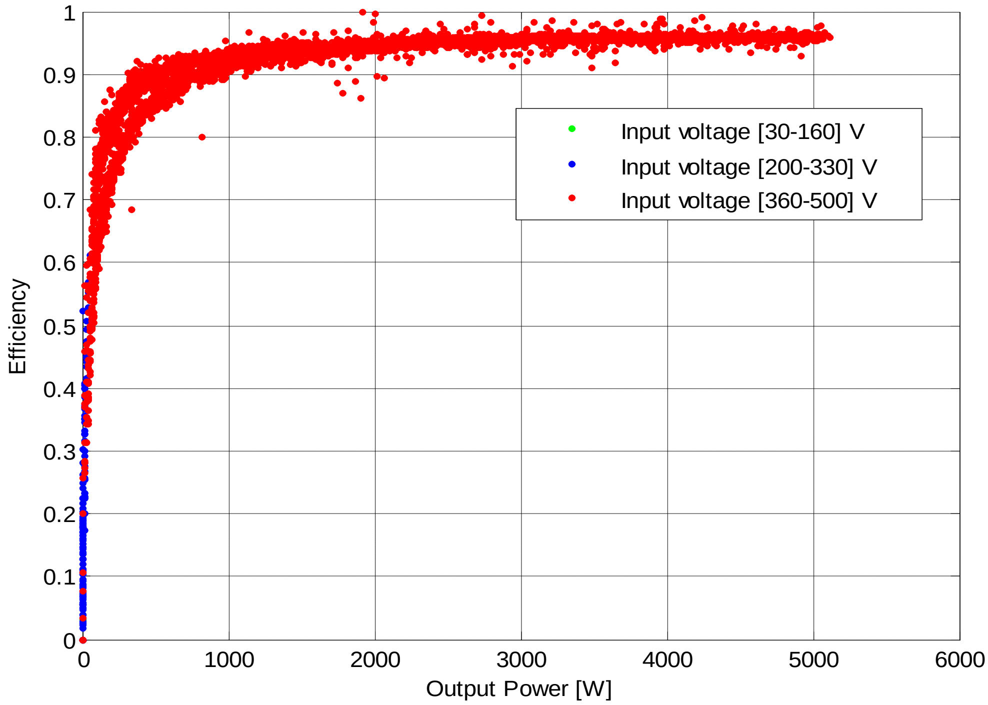


Figure 27: Output Power VS Efficiency, for different ranges of input voltage

Manufacturer indicated that “the higher the input voltage, the higher the efficiency”, which agrees with picture just shown. But in this point we can’t explain yet the reason of the efficiency width observed: is it just due to wide input voltage considered? Or ther is any other parameter affecting efficiency curve?

To solve this question, in the following figure we show Efficiency VS Output Power for every available sample (making no distinction on input voltage). However, now we make following distinction:

- Green coloured: first half of the day (starting with the sun-rise)
- Red coloured: second half of the day (ending with the sun-set)

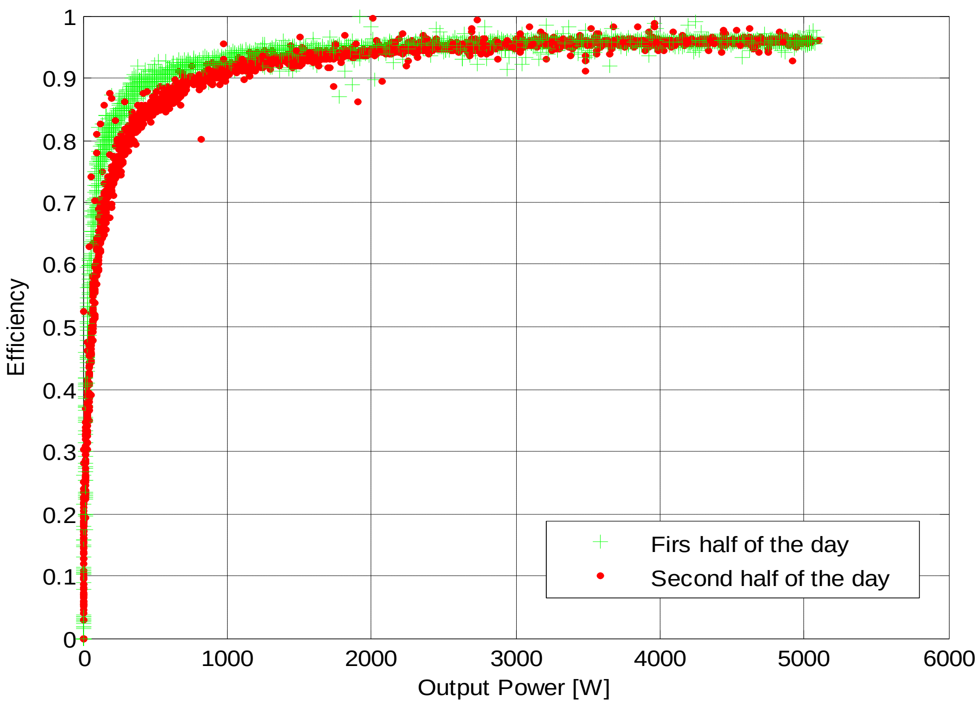


Figure 28: Output Power VS Efficiency attending to the moment of the day

Analysing this figure isolated, we could deduce that the inverter behaves as if it had an hysteresis-cycle which causes a better efficiency during the switch-on (input voltage increasing) than during the switch-off (input voltage decreasing). This effect very probably could be attributed to the temperature increase of the inverter over the course of the day.

However, as long as the efficiency of the Sunny Boy depends mainly on the input voltage of the connected PV strings (the higher the input voltage, the higher the efficiency) we can try to make a more precise delimitation on the input DC voltage. So let's consider now a very particular input voltage case that matches with the info provided by the inverter manufacturer. For such purpose we select the value V = 400 V (actually we will allow a small voltage rank, [398 - 402], in order to take into account a significant number of samples). The new figure obtained is shown next:

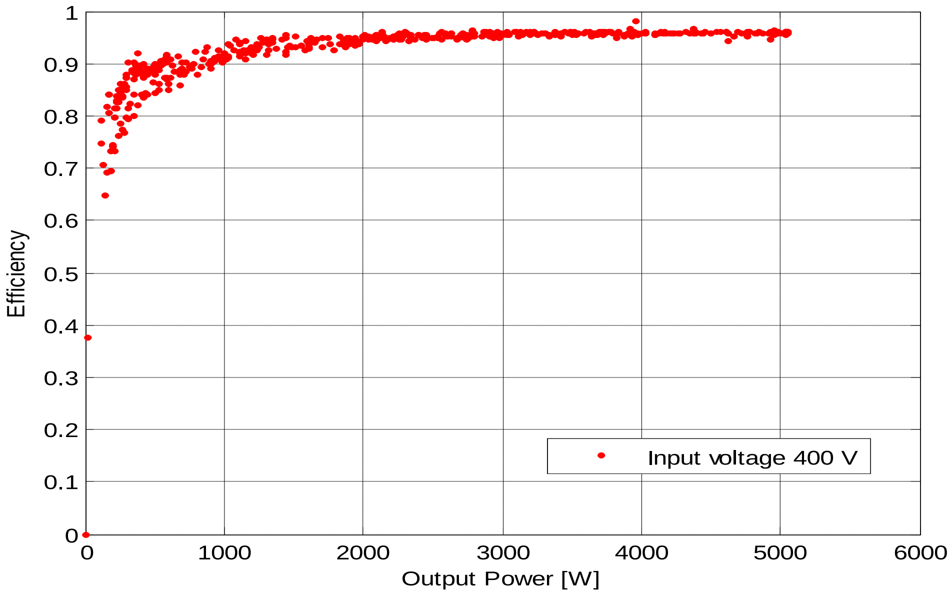


Figure 29: Output Power VS Efficiency when input voltage is 400 V

Even if we have fixed a very specific input voltage, we can check that there exists still some kind of "hysteresis" or margin within the efficiency. So in order to know if this behaviour can be assigned to the moment of the day, we will plot the same figure as before but making a distinction: in green colour we will show the first half of the day (sun-rise), and in red colour we will show the second half of the day (sun-set).

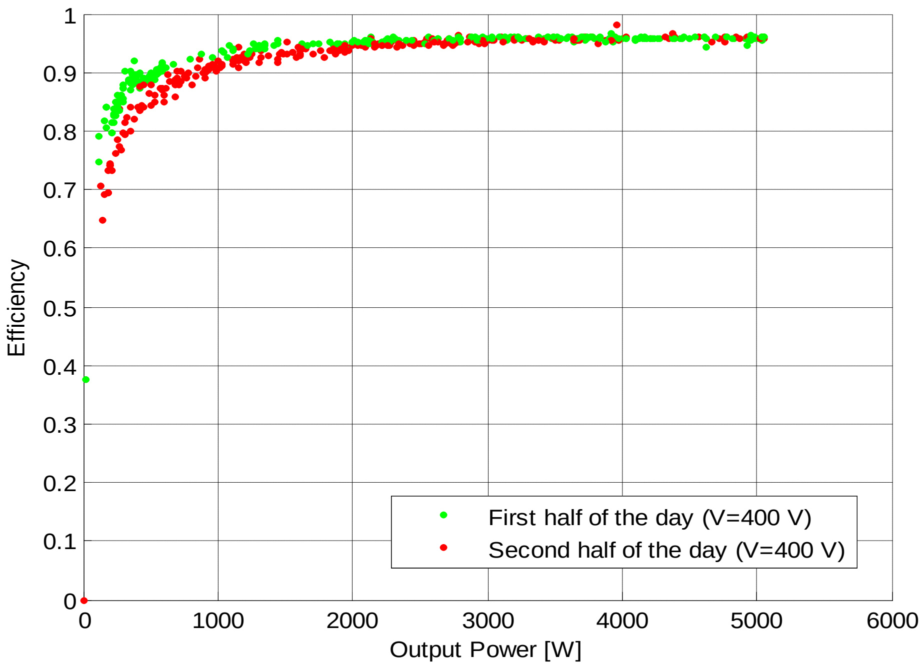


Figure 30: Output Power VS Efficiency when input voltage is 400 V [sunset/sunrise]

We can assert that for a given input DC voltage there will be different efficiency depending on the moment of the day, which stresses the importance of the increasing ambient temperature.

Now we are going to plot the same figure as before (Vdc = 400V) but including the average efficiency value for every output power, so that we can make a comparison with the data provided by manufacturer.

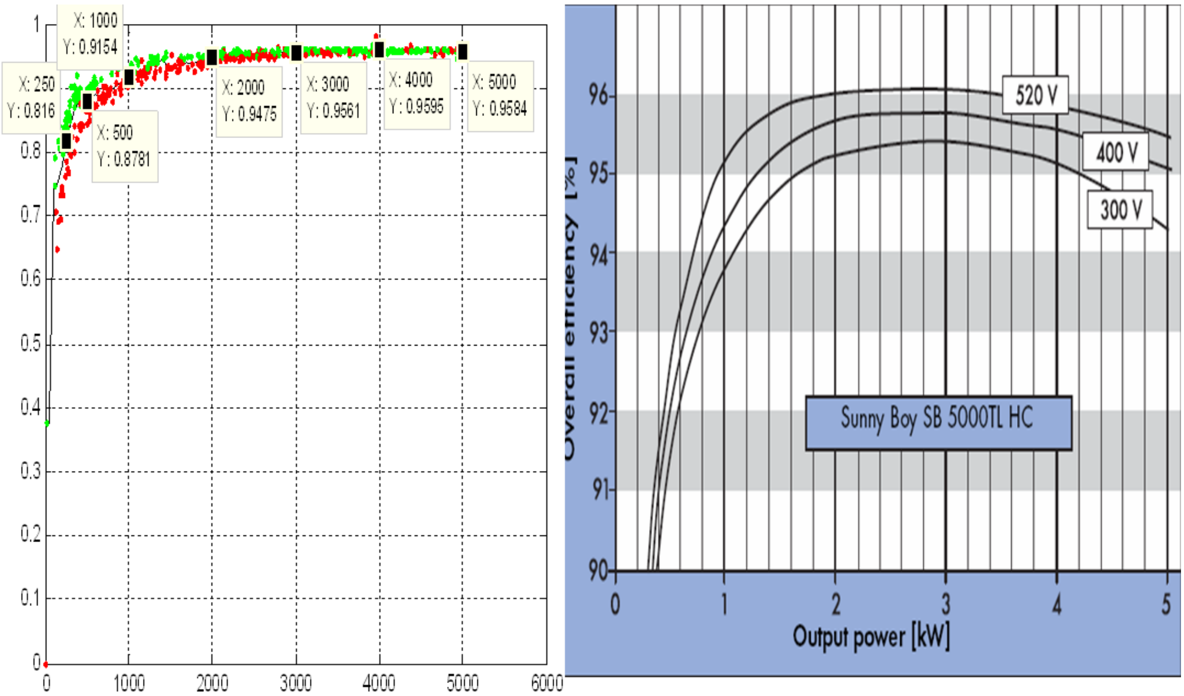


Figure 31: Real VS Manufacturer efficiency curve

To make a fair comparison of the inverters under partial load conditions, we can calculate the "European Standard Efficiency". According to its definition, the efficiency for each inverter must be computed at six different operating points, based on "average" components from the component survey as indicated in the next formula:

$$\eta_{EU} = 0.03\times\eta_{5\%} + 0.06\times\eta_{10\%} + 0.13\times\eta_{20\%} + 0.10\times\eta_{30\%} + 0.48\times\eta_{50\%} + 0.20\times\eta_{100\%}$$

In this formula the individual efficiencies are weighted and summed up, while the index value is equal to percent of rated power.

Using this definition we can calculate the real average efficiency of our inverter (regarding real measurements taken). For such purpose we will implement two different methods:

1. Let´s consider power ranges of 50 W: [0-50; 50-100; 100-150; ....; 4900-4950; 4950-5000].

For each range we calculate the average efficiency, ascribing it to the maximum value of the range, i.e. the efficiency obtained for 2500 W of power will match the average efficiency between 2450 W and 2500W.

Operating this way, we obtain the following results:

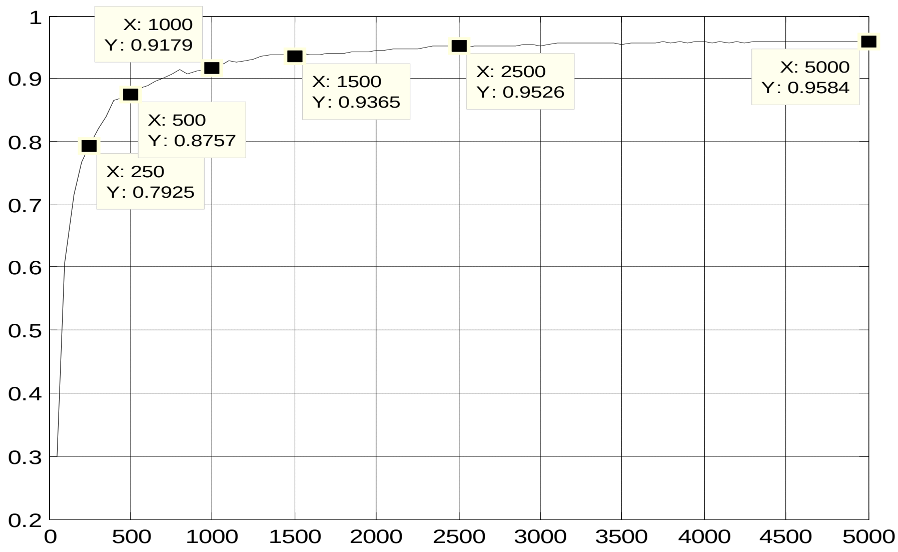


Figure 32: European standard efficiency [Method 1]

$$\eta_{EU} = 0.03\times\eta_{5\%} + 0.06\times\eta_{10\%} + 0.13\times\eta_{20\%} + 0.10\times\eta_{30\%} + 0.48\times\eta_{50\%} + 0.20\times\eta_{100\%} = 0.03\times\eta_{250W} + 0.06\times\eta_{500W} + 0.13\times\eta_{1000W} + 0.10\times\eta_{1500W} + 0.48\times\eta_{2500W} + 0.20\times\eta_{5000W} = 0.03\times0.7925 + 0.06\times0.8757 + 0.13\times0.9179 + 0.10\times0.9365 + 0.48\times0.9526 + 0.20\times0.9584 = \mathbf{0.9382}$$

2. The second method is more precise. We consider now power gaps of 25 W: [0-25; 25-50;...; 4950-4975; 4975-5000].

For calculating the average efficiency at a power point X, we will use the average efficiency in the interval [X-25, X+25] W.

Proceeding in this way, we get the next results:

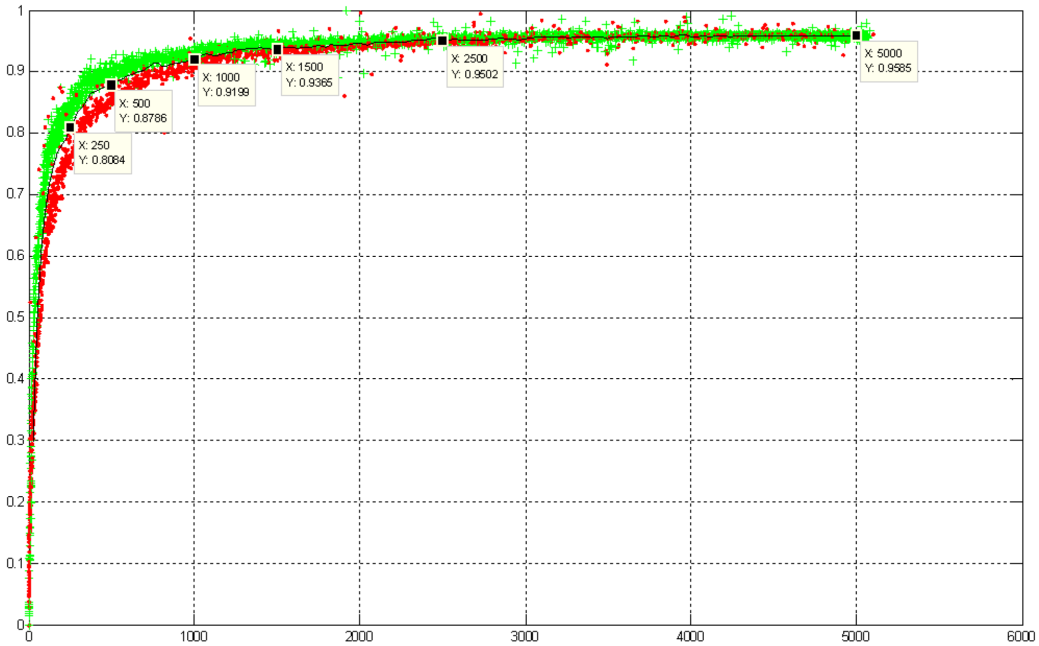


Figure 33: European standard efficiency [Method 2]

$$\eta_{EU} = 0.03\times\eta_{5\%} + 0.06\times\eta_{10\%} + 0.13\times\eta_{20\%} + 0.10\times\eta_{30\%} + 0.48\times\eta_{50\%} + 0.20\times\eta_{100\%} = 0.03\times\eta_{250W} + 0.06\times\eta_{500W} + 0.13\times\eta_{1000W} + 0.10\times\eta_{1500W} + 0.48\times\eta_{2500W} + 0.20\times\eta_{5000W} = 0.03\times0.8084 + 0.06\times0.8786 + 0.13\times0.9199 + 0.10\times0.9365 + 0.48\times0.9502 + 0.20\times0.9585 = \mathbf{0.9380}$$

Considering all the measurements taken, **we can finally determine that the European standard efficiency of the inverter SMA 5000 in our system is 93.8 %, being slightly smaller (1.7%) than the one indicated by the manufacturer**.

Efficiency of Sunny Boy SB 5000TL HC Multi-String

Efficiency		
Max. efficiency	ηmax	96,2 %
European standard efficiency	ηeuro	95,5 %

Figure 34: European standard efficiency [Manufacturer]

However, the efficiency we have calculated ourselves can not be immediately compared with the efficiency specified in the data sheet (95.5%) because of multiple reasons:

- *Inverter measuring devices*:

Measuring devices integrated into the inverter ensure the proper system management of the inverter. The inverter's task is to determine the operating point along with the maximum yield. Therefore, to achieve maximum energy conversion it is crucial for the inverter to precisely detect changes in parameters, such as grid current of PV voltage. In this case, high reproducibility is more important than absolute accuracy.

The SMA 5000 measuring device does not meet the high standards of calibrated measurement equipment. The inverter's measuring channels may have a tolerance of up to ± 4 % for DC measurements and up to ± 3 % for AC measurements (based on the respective final value of the measurement range under nominal conditions). As a result, the relative deviation may also be correspondingly larger if the feed-in power is low. These deviations have a proportional effect on the derived measurements.

- *The efficiency of the inverter:*

  The efficiency specified for the inverter is determined using a high-precision measuring process and represents the ratio of the output power to the input power during nominal conditions. Inverters not operated under nominal conditions, but rather under other conditions, such as with deviating input voltages, under partial load or at an increased ambient temperature produce deviating efficiency values.

- *Determining the Efficiency by Producing a Ratio:*

  An efficiency calculation that produces a ratio of the input and output values displayed or measured on the inverter also yields invalid results. The reasons for this include the tolerances stated above (see "Inverter measuring devices") involved in the acquisition of measured values as well as a slight time offset in the internal communication of the inverter or during the transmission to a data logger. As a result of these reasons, the current, voltage and power values for the display and the communication do not match exactly. During inconsistent weather conditions, i.e. if the radiation intensity suddenly changes, this result is also affected by the calculation of a mean value.

3.3 *Efficiency comparative between Inverters.*

3.3.1 Efficiency at "*Inverter Level*".

In order to provide a general overview of the behaviour of the 3 inverters, we will now represent the average efficiency of each one of them for every output power:

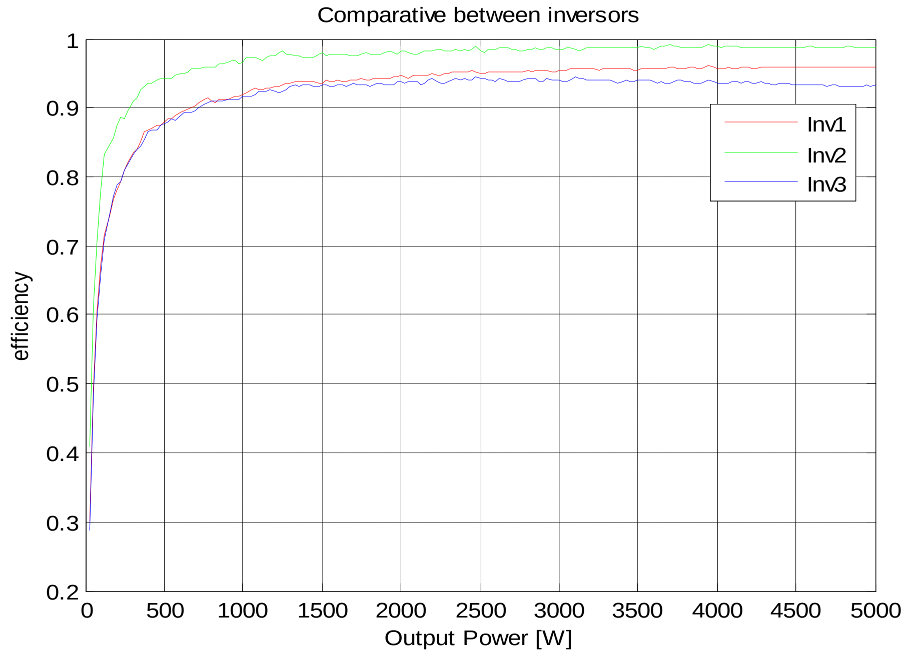


Figure 35: Inverters' efficiency

In figure 35 we can check that the Inverter number 2 has significantly better efficiency behaviour than inverters 1 and 3. Now we will explain the reason for this efficiency difference between inverters.

3.3.2 Efficiency at "*String Level*".

The way we calculated the efficiency for each one of the inverters is as follows:

$$\eta = \text{Output AC Power}/ (\text{DCPowerStringA} + \text{DCPowerStringB}) = P_{AC} / (P_{DCA} + P_{DCB})$$

[EQ.2.2.1]

But in order to discover why inverter 2 has a significantly better efficiency than inverters 1 and 3, we must get a higher level of detail. So now we will analyze the efficiency of each one of the strings (A and B) separately, in order to find out an answer to our question.

First of all, let's see which is the relation between the global efficiency of each inverter (calculated as indicated above) and the efficiency of each string. For such purpose we define two new variables:

$$\eta_A = P_{AC} / P_{DCA}$$
[EQ.2.2.2]

$$\eta_B = P_{AC} / P_{DCB}$$
[EQ.2.2.3]

Using these new efficiency variables separately, we can now plot the efficiency of each string for every inverter:

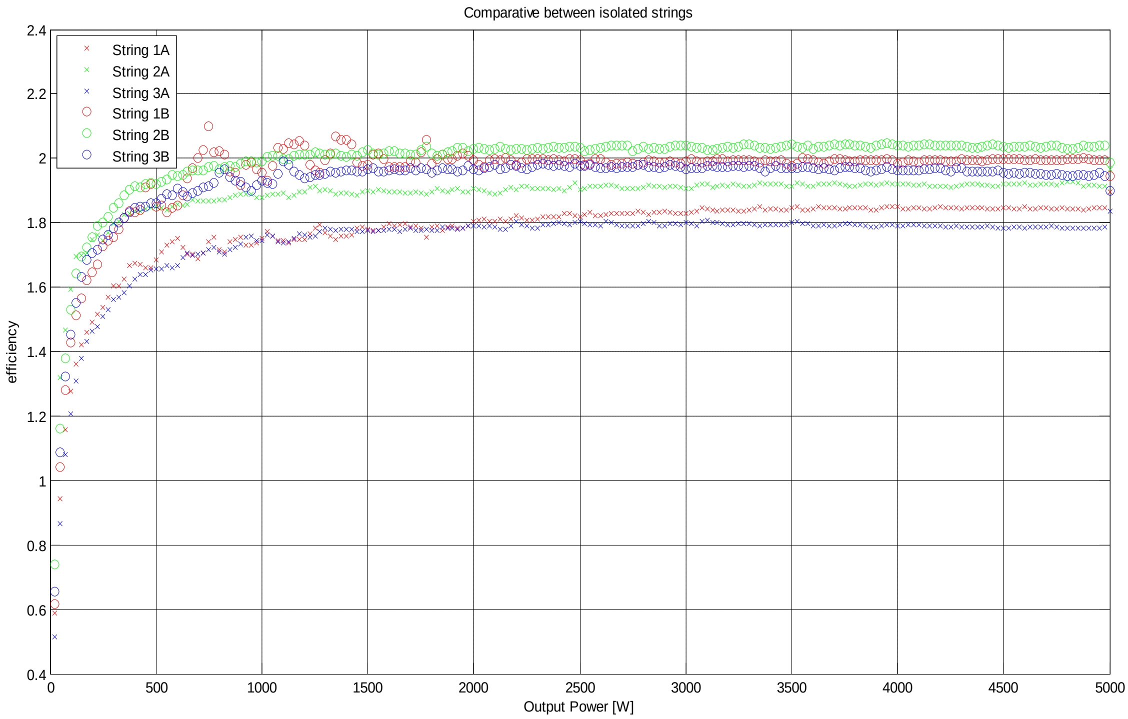


Figure 36: Strings efficiency

From figure 36 we could conclude:

1. Strings "A" with 19 panels (plotted with 'x') have always less efficiency than strings "B" with 18 panels (plotted with 'o').
2. The efficiency is near to the value 2 (with no physical but mathematical meaning).

These conclusions are wrong because do not take consideration on the way we have calculated the efficiency for each one of the strings [EQ.2.2.2] and [EQ.2.2.3], so:

1. As long as DC power of strings with 19 panels is slightly bigger than DC power of strings with 18 panels, meanwhile the output AC Power considered is the same for both strings (it is obtained with the sum up of both contributions), the efficiency will behave as shown in the previous figure.

2. Due to this way of calculating the efficiency for every string, which considers as numerator the output power obtained by both strings of each inverter, meanwhile considers as denominator the DC power obtained by only one of the strings, we get to efficiency values over 1.

Anyway, we could have corrected the behaviour depicted by applying corrector factors (18/37 for the 18 panel string and 19/37 for the 19 panel string), but we did not because that was not the main point of the question we are trying to ask.

So once clarified the real meaning of the last figure shown, we will focus again in the problem we are trying to solve: *why there is a significant difference in efficiency between inverters 1 and 3, and inverter 2?*

Let's now remember the expressions [EQ.2.2.1], [EQ.2.2.2] and [EQ.2.2.3], trying to find out which is the link between them so we can analyze what happens to the global inverter efficiency (EQ. 2.2.1) in relation to the behaviour of each one of its strings (EQ. 2.2.2 and 2.2.3):

$$\eta = P_{AC} / (P_{DCA} + P_{DCB}) \qquad \textbf{[EQ.2.2.1]}$$

$$\eta_A = P_{AC} / P_{DCA} \qquad \textbf{[EQ.2.2.2]}$$

$$\eta_B = P_{AC} / P_{DCB} \qquad \textbf{[EQ.2.2.3]}$$

$$\eta^{-1} = (P_{DCA} + P_{DCB}) / P_{AC} = (P_{DCA} / P_{AC}) + (P_{DCB} / P_{AC}) = \eta_A^{-1} + \eta_B^{-1} \qquad \textbf{[EQ.2.2.4]}$$

$$\eta = (\eta^{-1})^{-1} = (\eta_A^{-1} + \eta_B^{-1})^{-1} = ((1/\eta_A)+(1/\eta_B))^{-1} = ((\eta_A + \eta_B)/(\eta_A\eta_B))^{-1} =$$

$$\eta_A\eta_B/(\eta_A+\eta_B) \qquad \textbf{[EQ.2.2.5]}$$

The last equation shows us the relationship between inverter's global efficiency and the efficiency of each one of its strings. Paying attention, we can find out a logical parallelism: the equivalent efficiency of two strings associated "in parallel" behaves in the same way as the equivalent resistance of two parallel resistances. So going on with this parallelism, we can assert that:

- It is important to note that the equivalent resistance of two resistors in parallel is always smaller than either of the two resistors, so the efficiency of the inverter will be lower than the lowest efficient string.
- To maximize the efficiency of the inverter, the efficiency of each one of the strings should be as similar as possible to the efficiency of the other string.

These assertions can be checked out easily through a graphic, so in the next figure we show how the global efficiency of the inverter varies in function of the efficiency of each string.

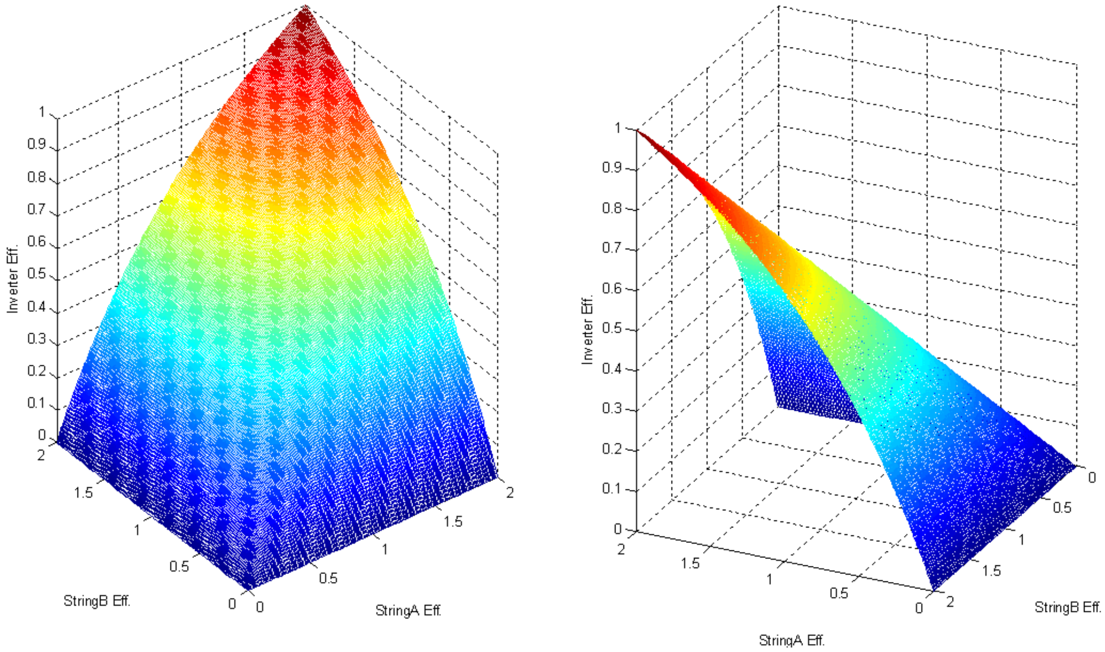


Figure 37: Inverter efficiency as a function of strings efficiency

As shown in figure 37, the best inverter efficiency will be provided when both strings have similar efficiency values (ideally equals) and this value is maximum.

Keeping in mind all these considerations, if we check again figure 36 we will extract now a new valuable information: **inverter 2 is the best inverter** (in efficiency terms) **not only because each one of its strings (A and B) has the highest value in their group, but also because they are the pair of strings with the most similar behaviour in relation with each other amongst the available**.

3.3.3 Efficiency at "PV Panel Level".

Now that we have solved out that inverter 2 is the most efficient for the reasons explained, let's try to go one step beyond getting the core of the matter by discovering what is the underlying reason that makes one inverter being more (or less) efficient than another one.

Stepping now into a higher level of detail than before, in the next figure we can see the power distribution of panels and the strings they were assigned to:

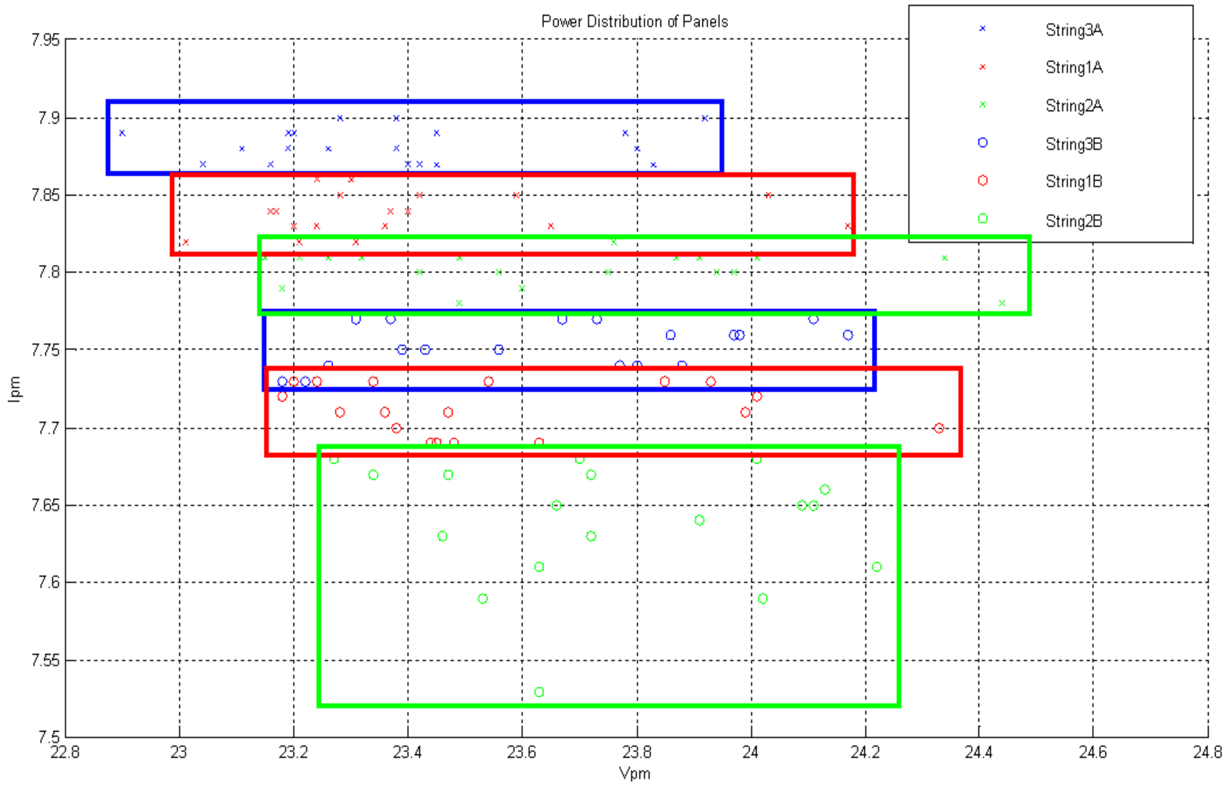


Figure 38: Panels assigned to each inverter

All the panels in every string are connected in series, so the total DC voltage of the string will be calculated as the addition of each element while the total DC current of the string will be limited by the lowest Ipm of the string. According with the power distribution of panels stated before, we have:

	Vpm String A (Vdc)	Ipm String A (Adc)	Vpm String B (Vdc)	Ipm String B (Adc)	Max. Power (Wdc)
Inverter1	444,39	7,82	424,1	7,69	6736,46
Inverter2	449,67	7,78	427,62	7,53	6718,41
Inverter3	444,14	7,87	425,66	7,73	6785,73

Figure 39: Maximum power generation per inverter

From figure above we conclude that strings connected to inverter 2 are the ones with least maximum power generation capacity.

In the next graphs, we plot the behaviour of all the strings in terms of Vdc and Idc for two output power (Pac): 0.5 kW and 4.5 kW.

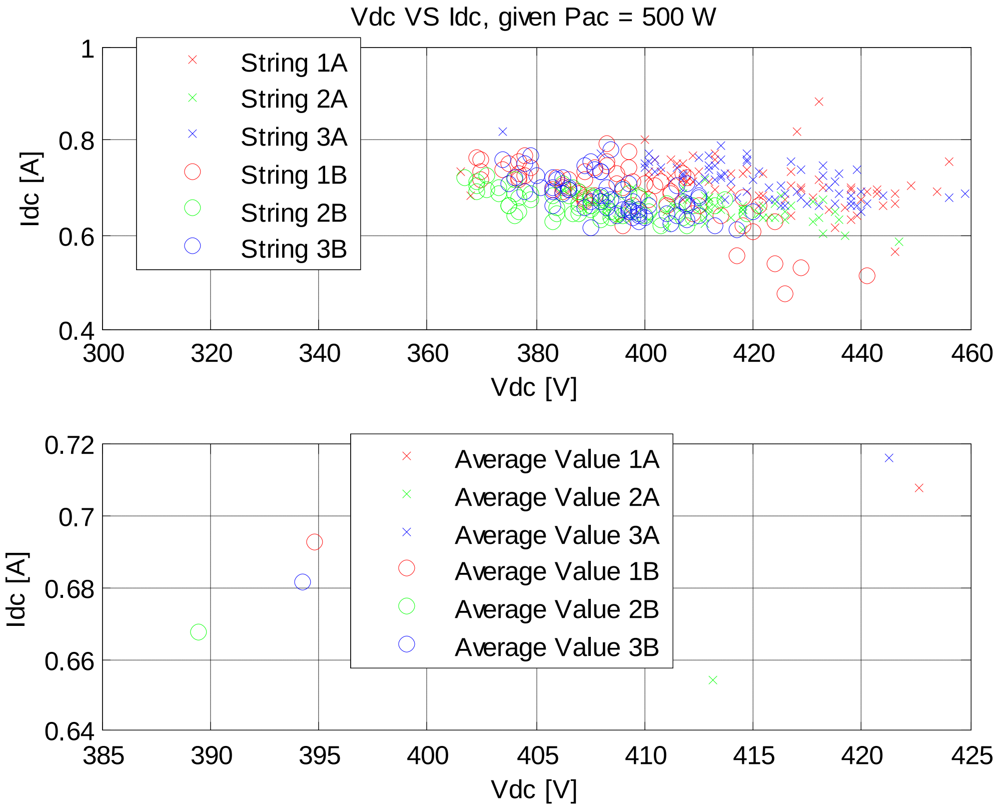


Figure 40: a) Vdc vs Idc when Pac=500 W; b) Average Vdc vs Idc when Pac=500 W

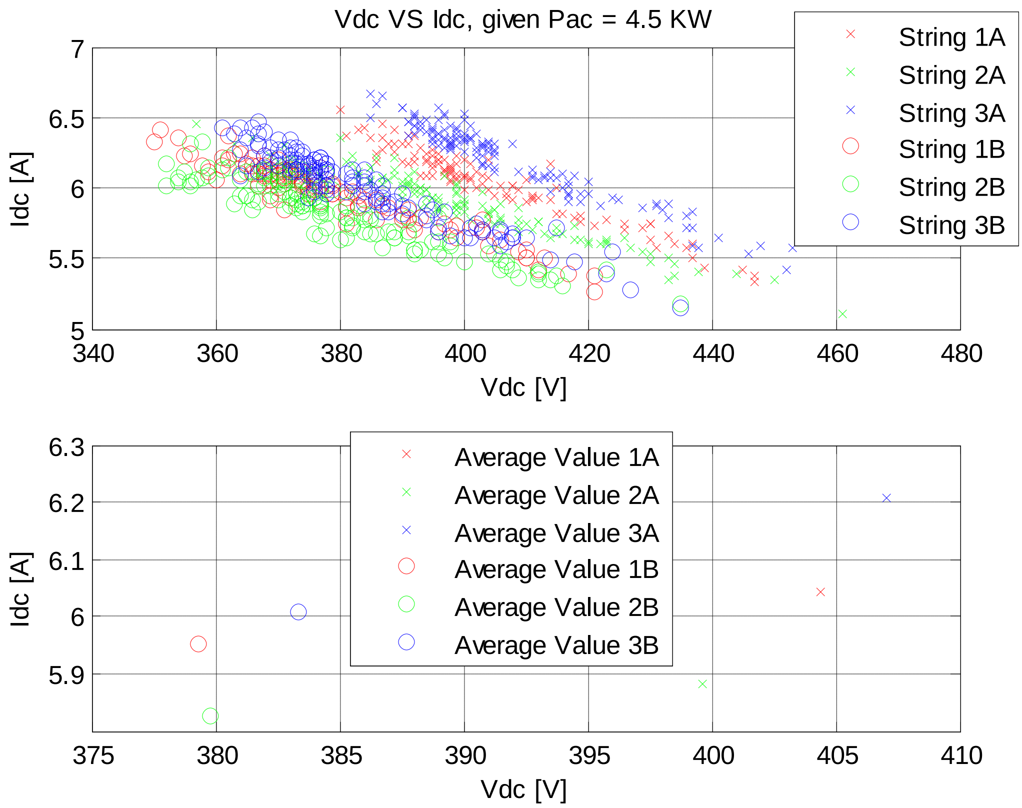


Figure 41: a) Vdc vs Idc when Pac=4.5 kW; b) Average Vdc vs Idc when Pac=4.5 kW

Figures 40 and 41 confirm the expected results: inverter 2 is the one working under lowest load condition (lowest Idc and Vdc) meanwhile inverter 3 is the one working under highest load condition (highest Idc and Vdc), with inverter 1 being in the middle of both. The behaviour just depicted is responsible of making inverter 2 (coloured in green) the most efficient in the group meanwhile inverter 3 (coloured in blue) is the least efficient.

From the study executed till now, we can conclude that inverter 2 is significantly the most efficient of the three inverters, even if paradoxically it is the inverter with lowest maximum capacity of generating DC Power (check figure 39).

So the lower generation of energy from Inverter 2 seems could be compensated thanks to a better efficiency performance. To verify if this *compensation* between efficiency and generation capacity becomes true, we will now make a comparison between all inverter performances.

3.4 Inverters performance comparison.

To make comparison between the 3 inverters, we will take as reference the inverter number 1.

We will consider a complete set of cases in which inverter 1 provides next fixed output power: 0.5 kW, 1 kW, 2 kW, 3 kW, 4 kW and 5 kW.

Immediately after we will represent the behaviour provided by inverter 2 and inverter 3 for such situation (which means that we will check the power the other inverters are providing, meanwhile inverter 1 is providing a given particular power).

In next figure we can compare Inverter 1 against Inverter 2. Apart from “real” comparison, we include a “theoretical” expected result. As long as the 3 inverters are supposed to be the same and working in similar load conditions, we have assumed that the “theoretical” expected result should be a straight line with slope equal to 1 and offset equal to 0:

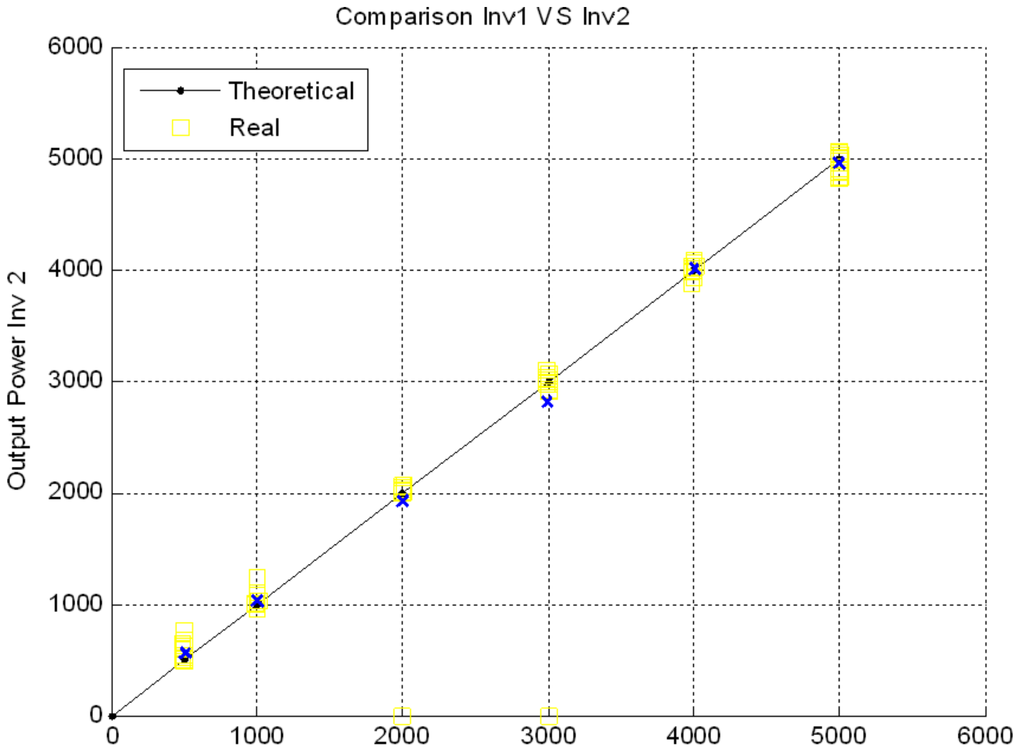


Figure 42: Inverter 2 performance, for a set of given output power from Inverter 1

Now, let's check inverter 1 and inverter 3 by means of the next figure:

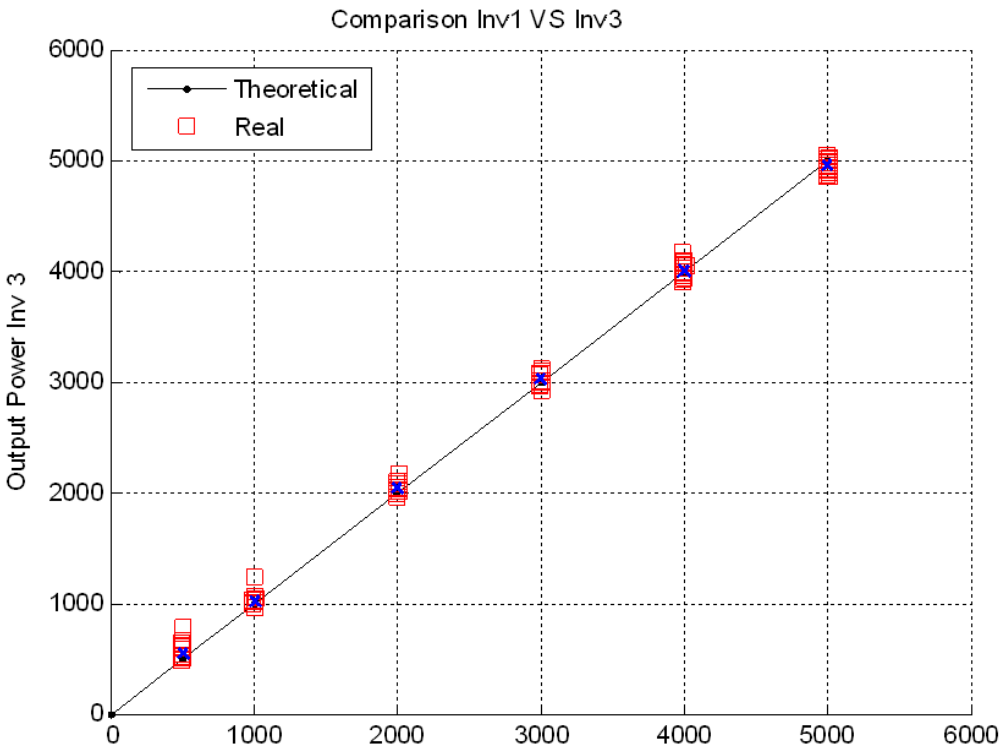


Figure 43: Inverter 3 performance, for a set of given output power from Inverter 1

As it was expected, we can check in figures 42 and 43 that inverters 1, 2 and 3, have a close behaviour for all the possible output power values. So when one of the inverter is providing a given output power “X”, all the other inverters will be providing a similar output power “X”, with a very little range of variation. Moreover, if talking in average terms, we can check from figures 42 and 43 that this assertion takes meaningful sense as long as the average “real” value (**indicated with a blue cross in the figures**) matches with a significant precision with the “theoretical” expected result.

From all the investigation performed until this moment, we can check that the whole system is working properly, meaning that the power generation of the 3 inverters with equally distributed strings of panels, is being approximately the same for all of them (as it was expected to be).

So as a general conclusion we can state that:

- **When the whole system is appropriately designed, the inverters capacity MPPT (Maximum Power Point Tracker) will take care of compensating little disturbances, such as:**
    - **Non-ideal panels, causing efficiency performance deviations due to:**
        - **Different power distribution**
        - **Different Ipm and Vpm**

, and finally leading us to a balanced system.

In the following section, we will make considerations about power generation of all the inverters during the period with available data [10/03/08 – 25/09/08], so finally we will be able to confirm the assertion previously stated.

4. Real "production" measurements VS SW Simulation

The aim of this section is triple:

- To lay the foundations of the previously executed analysis.
- To compare the real measurements on energy production obtained in our 20 kW grid-connected PV system with the output of simulation software (PVSYST), checking out if simulation and measurements are close or there was any significant error.
- Quantify the adjustment of inverter sizing in the PV system developed, and compare them with the results we would have got considering different inverter values.

4.1 Real Measurements.

In order to have a global vision of the energy generated per day and per inverter, let's have a look at the next figure:

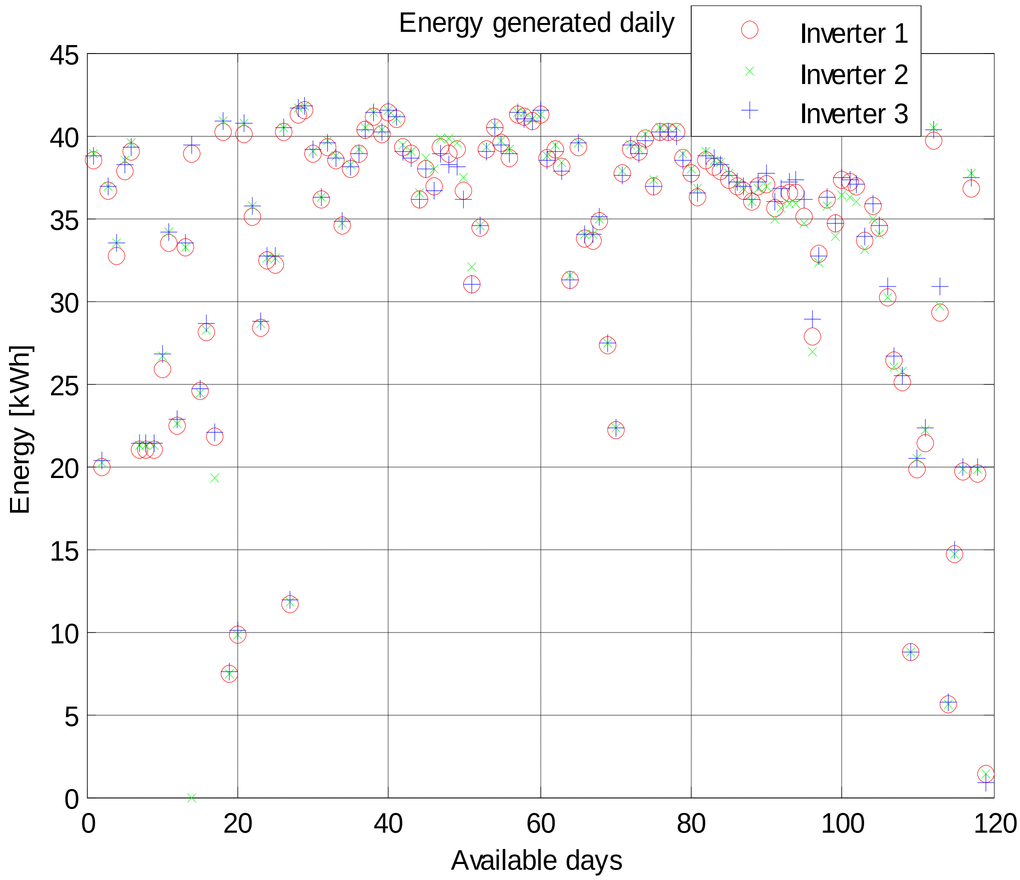


Figure 44: Sequence of energy generated per available data day per inverter

In figure 44 we can check that the energy generated per inverter is normally the same for the three inverters for a given day, even if this generation varies significantly depending on the period of the year (irradiance, temperature, sky clearness, etc.). So as it was predictable during March (first days of the graph) the production is lower than during summer months (about the range of days [30-80]).

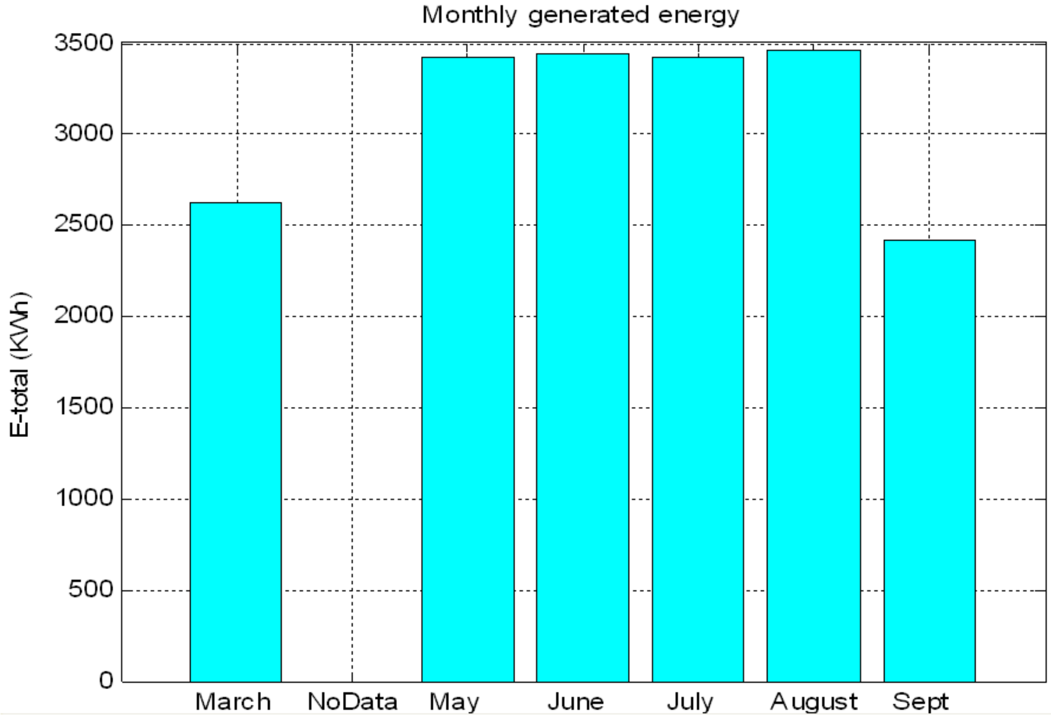


Figure 45: Total energy generated per month

In previous figure we can check how the global energy production of our system gets to its maximum during sunny and sky-cleared months (May, June, July and August), meanwhile decreases significantly during the beginning of spring and beginning of autumn (March and September). During the month of April, measurements could not be collected.

Considering individually the production of energy generated by each inverter, we can verify that the contribution of each inverter is similar every month, getting to maximum values during the mentioned sunny and sky-cleared months, as can be checked in next figure:

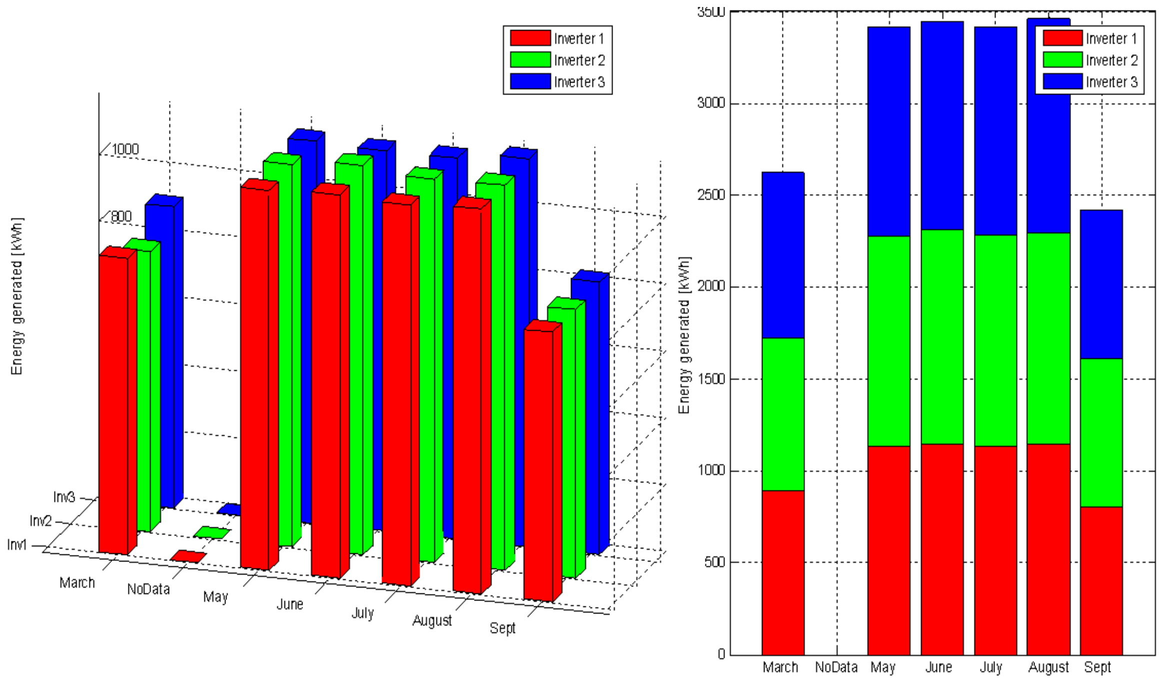


Figure 46: a) Energy generated per month per inverter b) Total energy generated by global system

From figures shown above and according with all the results obtained till now, we can say that, even if the panels associated to each inverter string and their efficiencies vary from one to another, when talking about energy generation every inverter behaves in a very similar way.

To be more precise about how this energy distribution is as symmetrical as desired, we show in next pie diagram the percentage of global energy generation produced by each one of the inverters monthly, illustrating how energy generation is equally distributed amongst inverters.

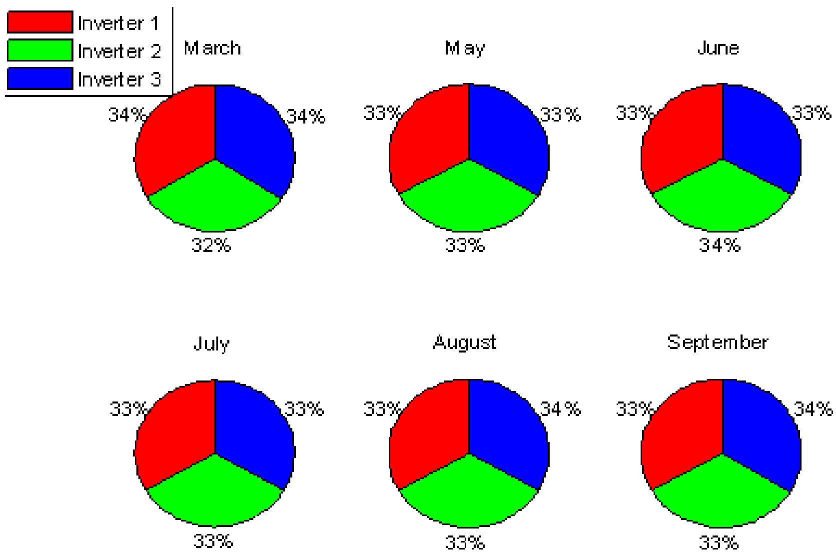


Figure 47: % of energy generated per month per inverter (regarding the whole system)

4.2 SW Simulation.

The chosen software for making the comparison has been PVSYST 4.1, a PC SW package for the study, sizing, simulation and data analysis of complete PV systems, including grid-connected, stand-alone, pumping and DC-grid systems.

In addition to this, PVSYST will offer us an extensive meteorological and PV-components database which can be modified and customized according with the results obtained in the previous study on inverter efficiency.

Following we show the way the simulation was performed. Firstly, we select “Project design” for a “Grid-connected” System, as indicated in the figure:

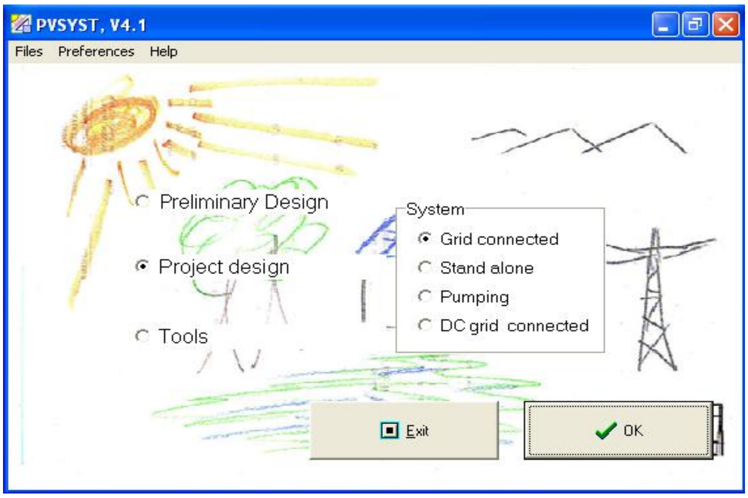


Figure 48: Grid-connected design

Once selected the type of system, we complete all the variables related to our 20 kW grid-connected PV system.

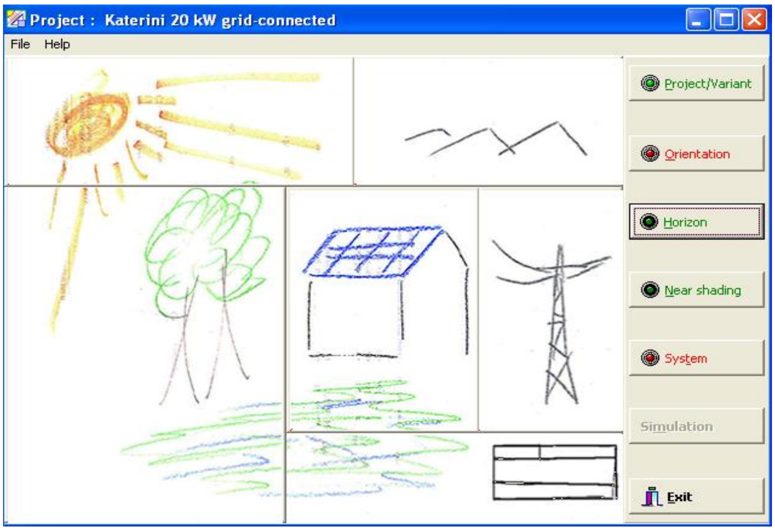


Figure 49: Set of variables defining PV system considered

This engineer-oriented part is aiming to perform a thorough system simulation using detailed hourly data, including:

- A large database of PV components, location and meteorological sites.
- Definition of the plane orientation, near shading and horizon.
- An expert system to facilitate the PV system layout definition.

As our system was designed with optimal tilt planes for annual yield, the collector field orientation considered is as shown next:

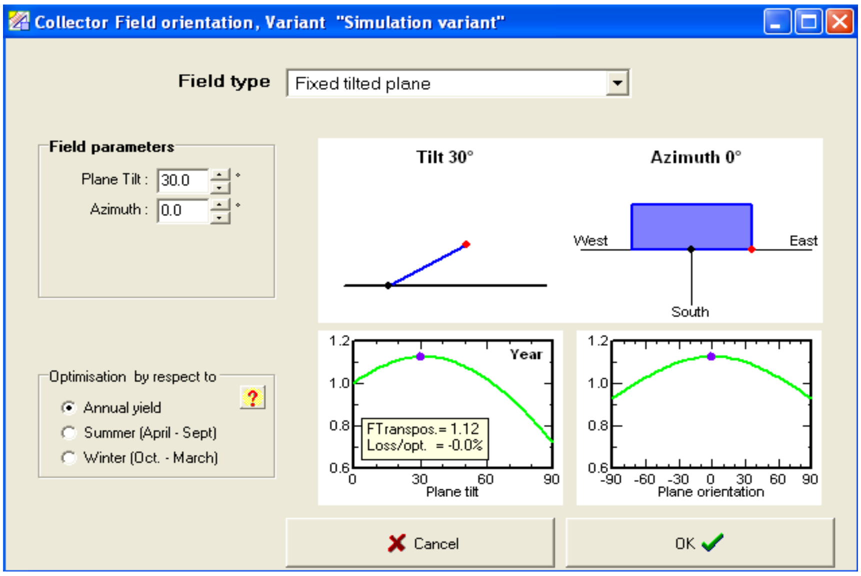


Figure 50: Collector field orientation

Considering the optimum tilt (30º) and given that our PV system is located in open field ("no shading" scenario), we obtain the following horizon line drawing:

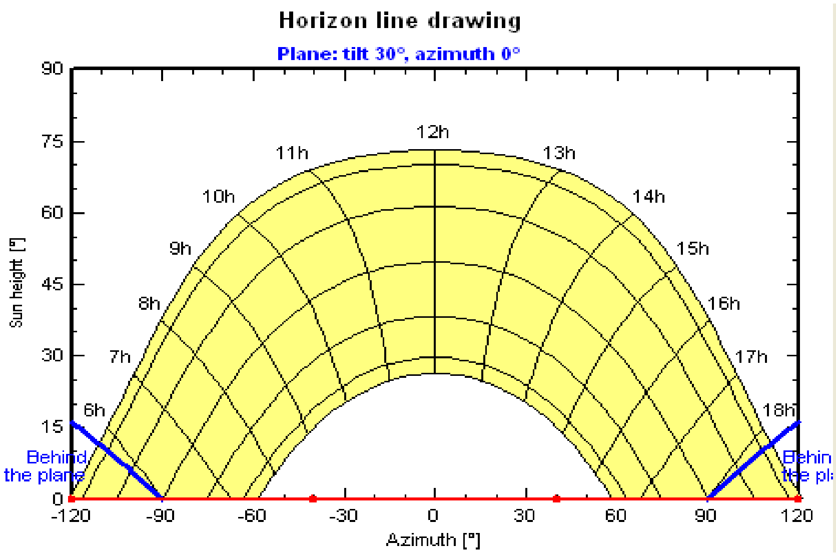


Figure 51: Horizon line drawing (open field PV system)

Once we have defined all the previous variables we only have to indicate the system characteristics:

- Inverters
- Modules
- Array design

The inverter and modules used in our system located in Katerini are not available in the PVSYST database. However as long as we know their characteristic we can "create" these new elements adding them into the database mentioned.

Referring to the inverter definition for the simulation, we have considered both manufacturer specifications and experimental conclusions obtained in previous sections of the present report. Besides, we have just verified that every inverter was performing similar energy production values. So for efficiency curve, we have considered as pattern model the experimental curve obtained for inverter 1.

In next figures we indicate all the parameters that were included during the definition phase of the inverters for the simulation phase.

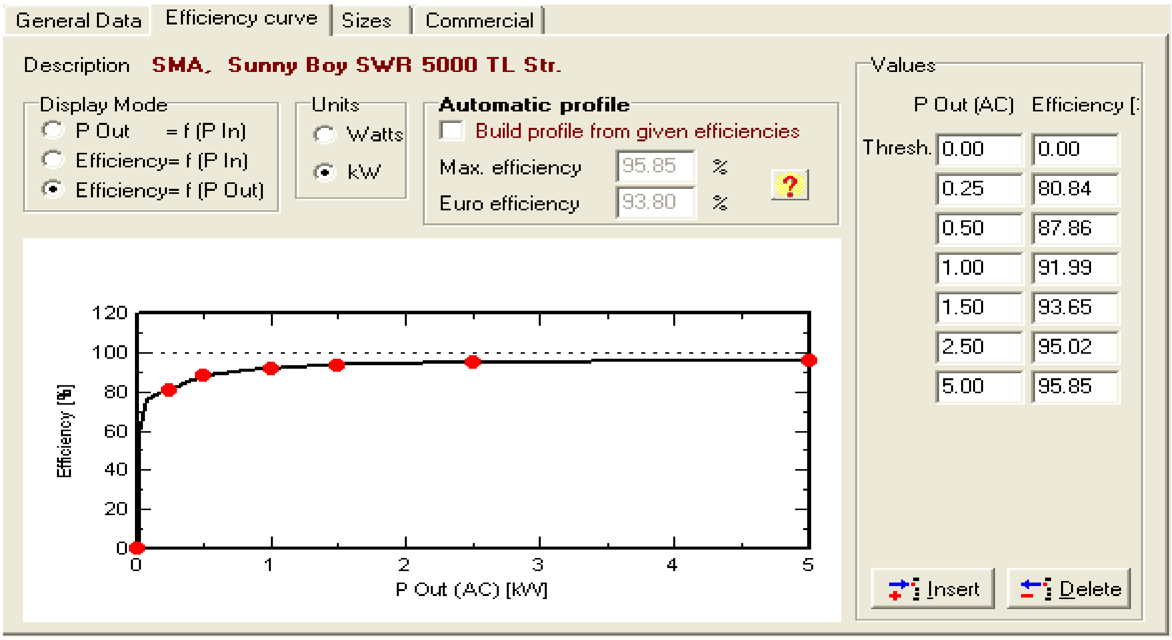


Figure 52: Inverter efficiency curve

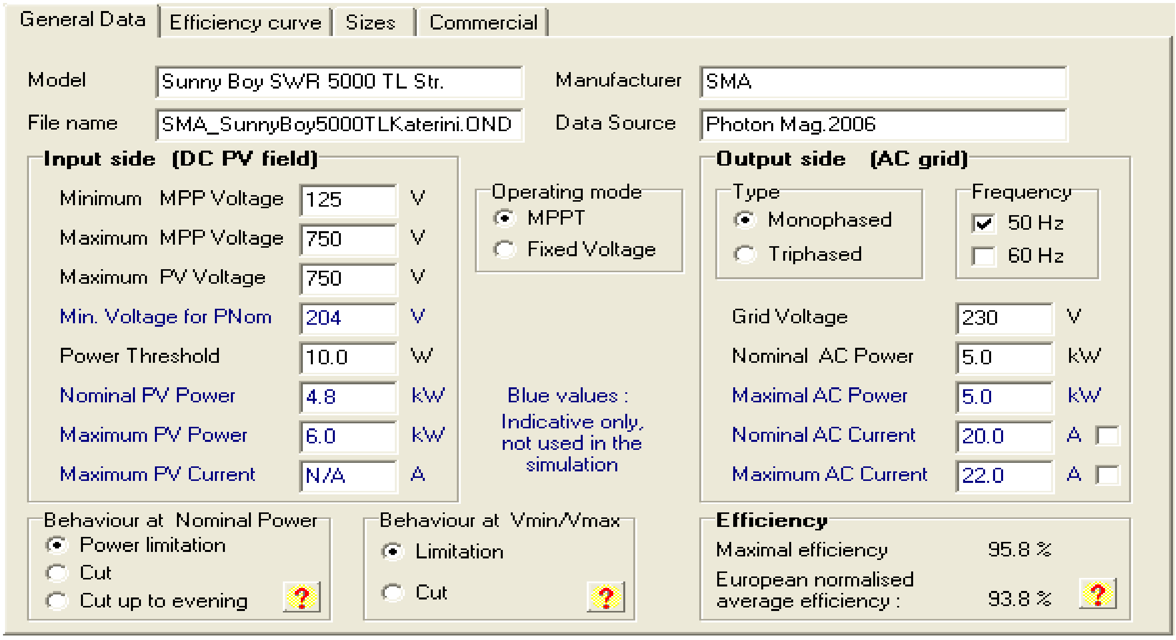


Figure 53: Inverter general data

The power distribution amongst PV panels, as we saw in figure 38, is not ideal. But for their simulation, the same as for inverters case, the problem can be simplified considering the 111 panels identical to each other and with technical specifications indicated by manufacturer (introduced in PVSYST as indicated in figure 54). So, referring to the PV module simulation, the criteria considered are:

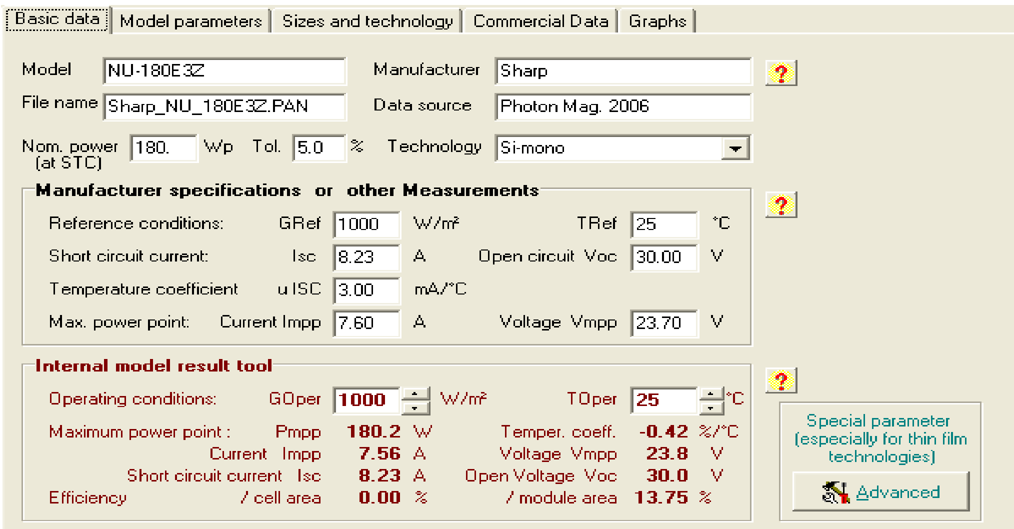


Figure 54: % of energy generated per month per inverter, regarding whole system

Both simplifications (considering 3 inverters and 111 PV panels identical to each other) can be done without fear of making any mistake since in the previous study of our system, measurements and behaviour, we have checked this as a reasonable approximation.

Once defined the inverter and modules used in our PV system, we just have to indicate to the PVSYST SW the array designed. But in this point we find a problem with the simulation due to the design implemented.

As we are using a 180 Wp PV module, to get to the desired total power of 20 kW we needed 111 modules (which provide us 19.98 kW). As the inverter selected is a multi-string one, 19 modules have been allocated in the String A and 18 modules in the String B for each one of the 3 SMA inverters available, dividing up in such way the 111 available modules.

So even if it did not have physical logic, for the simulation we could consider a total amount of 6 Strings (two per inverter) with “18.5” (average value between 18 and 19) PV modules each String. The problem is that PVSYST does not accept this mathematical abstraction with no physical sense, as indicated in the following figure:

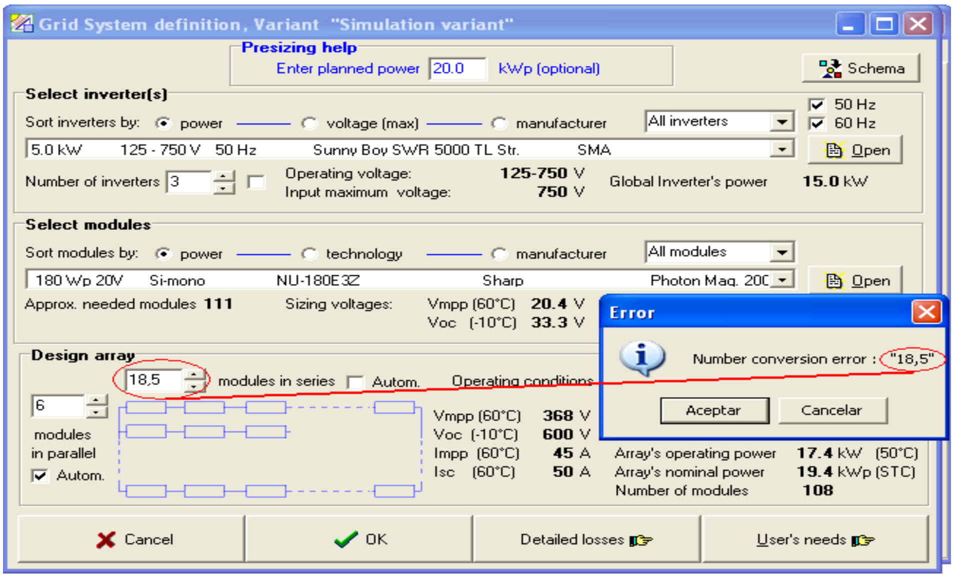


Figure 55: “Number conversion error” screen

So in the present state PVSYST is only able to treat homogeneous fields and systems (same module and number of modules, same inverter).

The development of this opportunity of multistring inverters is planned for future versions, even if this is really not easy to realize in full generality. In the meantime, when two different inverters or numbers of modules in series are present, we have to perform two different simulations with homogeneous systems, and add the results.

With multistrings inverters as SMA there is no direct possibility of different strings. But we can approach the result by performing a simulation with each configuration and take the average.

So we have divided the original problem into two new problems. On the one hand we will have two strings of 18 panels each one connected to one inverter, and on the other hand we will have two strings of 19 panels each one connected to another inverter.

So, averaging both results, we will find out the simulation of a system with one inverter and two strings of 19 and 18 PV panels. If we multiply these results by a factor 3, we will get an approximate simulation of our system (3 inverters, each one with two unbalanced strings of 19 and 18 PV panels).

To obtain a whole description of our system in terms of balances and main results, we will collect next data:

- Horizontal global irradiation
- Ambient temperature
- Global incident in collector plane (considering optimum angle used)
- Effective global, corrected for shadings and IAM (Incidence Angle Modifier, corresponding with he weakening of the irradiation really reaching the PV cells' surface, with respect to irradiation under normal incidence. In principle, this loss obeys Fresnel's Laws concerning transmission and reflections on the protective layer, the glass).
- Effective energy at the output of the array
- Available energy at Inverter Output
- Efficiency of the array (Energy at the output of the array / rough area)
- Efficiency of the whole system (Energy at inverter output / rough area)

Operating in this way, we got following simulation results:

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	EOutInv kWh	EffArrR %	EffSysR %
January	63	10,8	91,8	88,9	533	503	11,68	11,01
February	68	10,8	85,9	83,2	491	462,5	11,49	10,82
March	105	12	121	117,2	696	657,4	11,55	10,91
April	146	14,7	153,9	149	875	829,1	11,42	10,82
May	180	18,8	175,7	169,9	969	917,9	11,07	10,49
June	195	23	182,8	176,3	991	939,6	10,89	10,33
July	201	25,6	192,9	186,7	1041	987,2	10,84	10,28
August	186	25,4	192	186,1	1035	982,9	10,82	10,28
September	146	22,9	170	165	931	884,9	11,01	10,46
October	100	18,9	131,7	127,8	741	702,2	11,31	10,71
November	60,9	15,8	86,4	83,7	486	457,3	11,3	10,64
December	51	12,7	79	76,4	452	425,3	11,5	10,81
Year	**1501,9**	**17,66**	**1663**	**1610,4**	**9241**	**8749,3**	**11,16**	**10,57**

Figure 56: Balances and main results for inverter with (2x19) strings

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	EOutInv kWh	EffArrR %	EffSysR %
January	63	10,8	91,8	88,9	505,3	475,7	11,68	10,99
February	68	10,8	85,9	83,2	466,4	438,6	11,51	10,83
March	105	12	121	117,2	659,1	621,9	11,55	10,9
April	146	14,7	153,9	149	828,2	784,3	11,41	10,81
May	180	18,8	175,7	169,9	920,8	871,6	11,11	10,52
June	195	23	182,8	176,3	939	889,3	10,89	10,32
July	201	25,6	192,9	186,7	985,7	933,8	10,83	10,26
August	186	25,4	192	186,1	981,9	931,8	10,84	10,29
September	146	22,9	170	165	883,3	838,6	11,02	10,46
October	100	18,9	131,7	127,8	702	664,3	11,31	10,7
November	60,9	15,8	86,4	83,7	460,5	432,8	11,31	10,63
December	51	12,7	79	76,4	428,4	402,1	11,49	10,79
Year	**1501,9**	**17,66**	**1663**	**1610,4**	**8760,7**	**8284,8**	**11,17**	**10,56**

Figure 57: Balances and main results for inverter with (2x18) strings

With the data shown above we can now calculate the average main results for one inverter with strings 1x19+1x18:

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	EOutInv kWh	EffArrR %	EffSysR %
January	63	10,8	91,8	88,9	519,15	489,35	11,68	11
February	68	10,8	85,9	83,2	478,7	450,55	11,5	10,825
March	105	12	121	117,2	677,55	639,65	11,55	10,905
April	146	14,7	153,9	149	851,6	806,7	11,415	10,815
May	180	18,8	175,7	169,9	944,9	894,75	11,09	10,505
June	195	23	182,8	176,3	965	914,45	10,89	10,325
July	201	25,6	192,9	186,7	1013,4	960,5	10,835	10,27
August	186	25,4	192	186,1	1008,5	957,35	10,83	10,285
September	146	22,9	170	165	907,15	861,75	11,015	10,46
October	100	18,9	131,7	127,8	721,5	683,25	11,31	10,705
November	60,9	15,8	86,4	83,7	473,25	445,05	11,305	10,635
December	51	12,7	79	76,4	440,2	413,7	11,495	10,8
Year	**1501,9**	**17,66**	**1663**	**1610,4**	**9000,9**	**8517,05**	**11,165**	**10,565**

Figure 58: Balances and main results for one inverter with (1x19 + 1x18) strings

And multiplying these results by 3, we obtain the global simulation results for the PV system finally implemented:

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	EOutInv kWh	EffArrR %	EffSysR %
January	63	10,8	91,8	88,9	1557,45	1468,05	11,68	11
February	68	10,8	85,9	83,2	1436,1	1351,65	11,5	10,825
March	105	12	121	117,2	2032,65	1918,95	11,55	10,905
April	146	14,7	153,9	149	2554,8	2420,1	11,415	10,815
May	180	18,8	175,7	169,9	2834,7	2684,25	11,09	10,505
June	195	23	182,8	176,3	2895	2743,35	10,89	10,325
July	201	25,6	192,9	186,7	3040,05	2881,5	10,835	10,27
August	186	25,4	192	186,1	3025,35	2872,05	10,83	10,285
September	146	22,9	170	165	2721,45	2585,25	11,015	10,46
October	100	18,9	131,7	127,8	2164,5	2049,75	11,31	10,705
November	60,9	15,8	86,4	83,7	1419,75	1335,15	11,305	10,635
December	51	12,7	79	76,4	1320,6	1241,1	11,495	10,8
Year	**1501,9**	**17,66**	**1663**	**1610,4**	**27002,55**	**25551,15**	**11,165**	**10,565**

Figure 59: Balances and main results for three inverters with (1x19 + 1x18) strings

And the corresponding loss diagram for this scenario is:

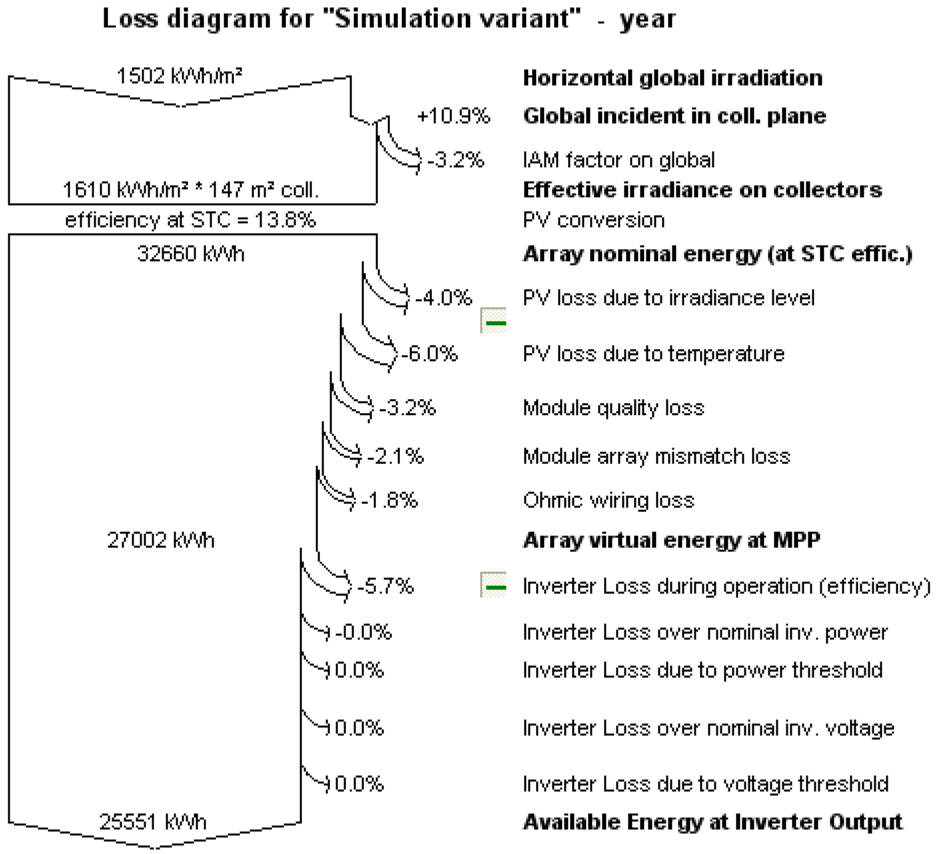


Figure 60: Loss diagram for three inverters with (1x19 + 1x18) strings

In next figure we show these simulation results in a graphical way:

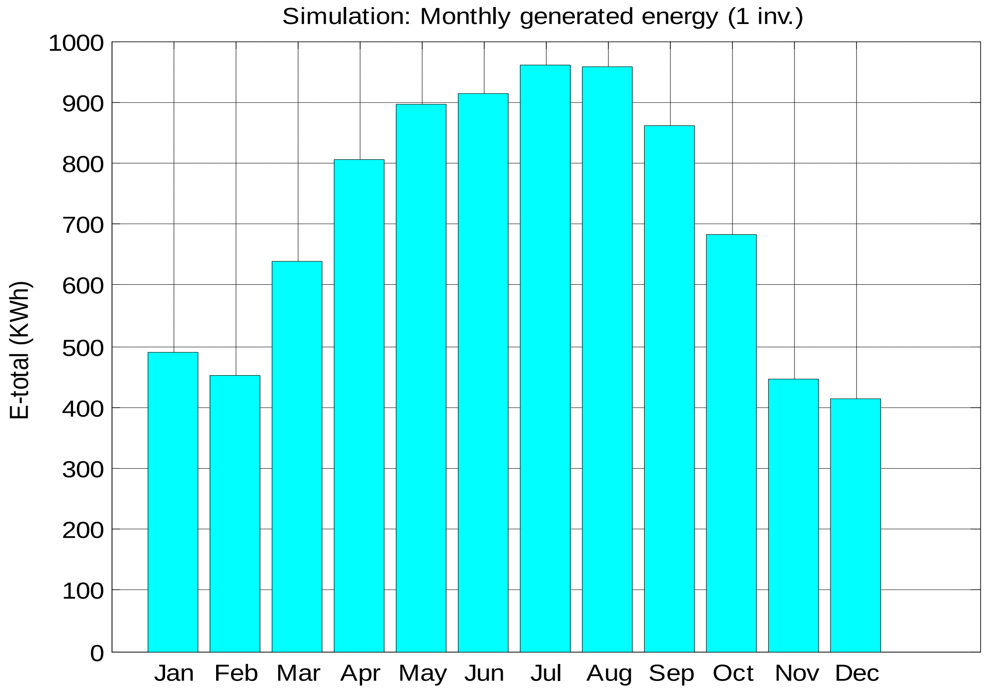


Figure 61: Simulation of monthly generated energy for one inverter with (1x19 + 1x18) strings

And considering three identical inverters (as stated and justified previously), we can obtain the simulation of the total amount of energy generated monthly by our 20 kW photovoltaic grid-connected system during a period of one year:

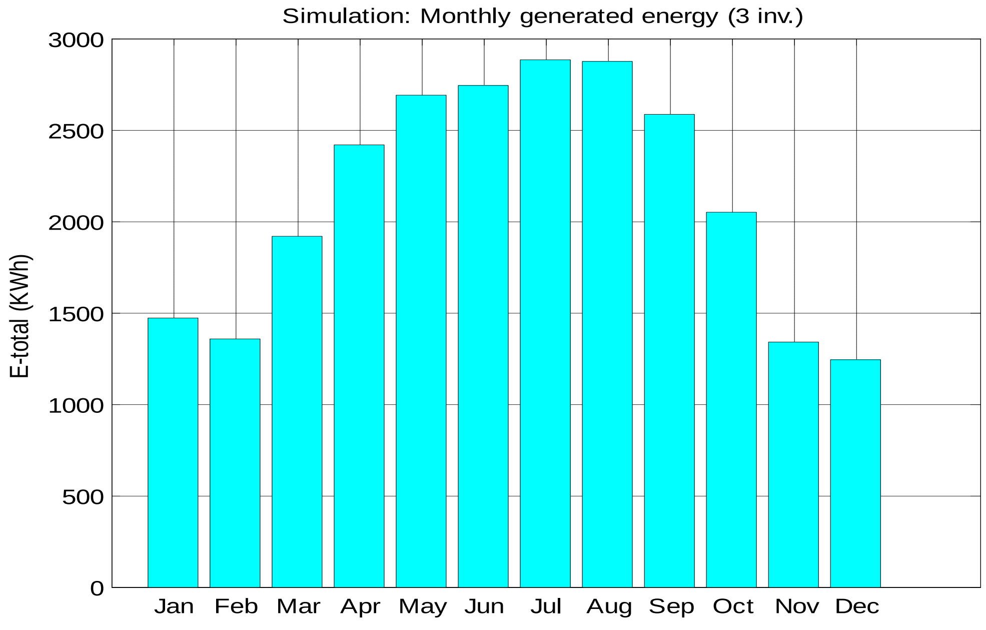


Figure 62: Simulation of monthly generated energy for our 20 kW grid-connected system.

4.2.1 Inverter sizing.

During the design phase of our 20 kW photovoltaic system, it was decided to allocate three inverters of 5 kW. It could seem that the system is under-sized from inverters point of view, because the sum of inverters capacity just provides 15 kW while the maximum generation capacity could reach to about 20 kW.

However, both general system design recommendations for grid-connected PV installations as well as particular previous studies focused on the north of Greece, lead to install inverters with a nominal capacity power considerably smaller than the PV array’s nominal power, due to:

1) PV systems almost never have a Direct Current output equal to their nominal power, so inverters are usually sized with a nominal power some 25% below the PV array nominal power.
2) For partial loads under 20% of nominal power, state-of-the-art inverters operate at reduced peak efficiencies, needing loads over 30% of their nominal power to obtain acceptable efficiencies (as we have checked before in the present report). This means that oversized inverters (or excessively tighted to the array nominal power) might operate at low capacity levels for long periods of the day and therefore accumulate long intervals with performance levels below maximum.
3) Inverter sizing strategy followed during the design phase took into account site-dependent peculiarities previously analyzed, such as inverter operating temperature or solar irradiation distribution characteristics.

To confirm all these assertions verifying that the system was well designed from the point of view of inverters sizing, we will compare SW results for different inverters capacities subject to study, considering two scenarios:

A) Using the same inverter size (5 kW):

A.1) Inverter sizing of 15 kW (3x5)

A.2) Inverter sizing of 20 kW (4x5)

B) Using different inverters size:

B.1) Inverter sizing of 15 kW (3x5)

B.2) Inverter sizing of 18 kW (3x6)

B.3) Inverter sizing of 21 kW (3x7)

SCENARIO A

This scenario is the most significant as long as we will compare different size configurations considering the same inverter (SMA 5000), so deviations between the cases compared can not be attributed to the different inverters characteristic curves.

Moreover, to make the comparison as significant as possible, in this scenario we are going to consider 111 PV panels (to coincide with the number of panels used in the PV system under analysis).

Let's note that the efficiency curve employed for these simulations is again the same to the efficiency curve obtained for inverter 1 based on the real measurements taken (see previous section in the present report):

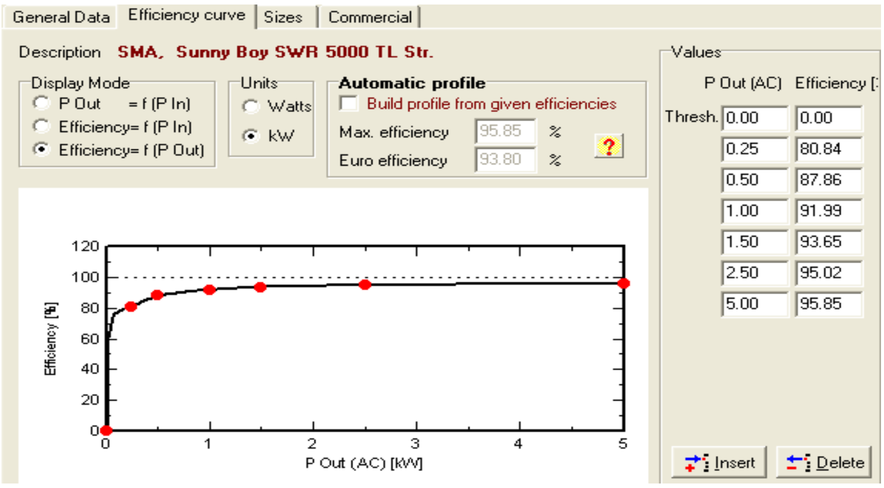


Figure 63: Efficiency curve considered for simulation of inverter SMA 5000

A.1) Total inverters capacity of 15 kW.

The inverter capacity has been distributed in 3 inverters of 5 kW each one, **according with the configuration** chosen during design-phase and **finally implemented in our PV system.**

The distribution chosen amongst inverters for the 111 PV panels providing 20 kW is shown in figure 64.

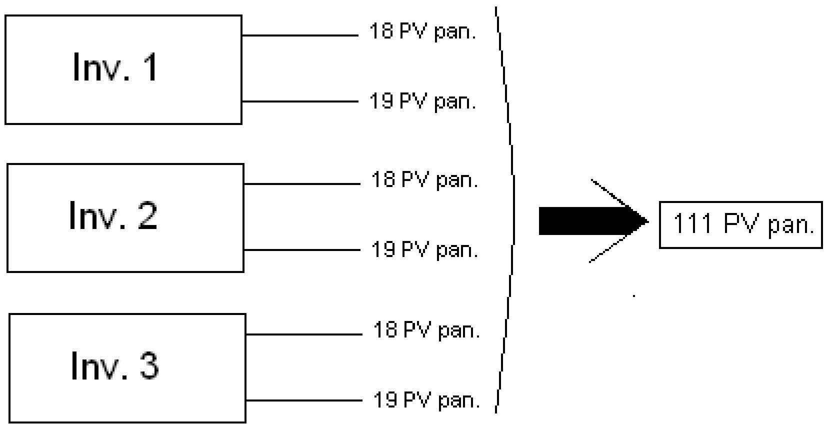


Figure 64: 3 inverters SMA 5000TL connected with 111 PV panels.

A.2) Total inverters capacity of 20 kW.

The inverter capacity has been distributed into 4 inverters of 5 kW each one. The distribution chosen amongst inverters for the 111 PV panels providing 20 kW is shown in figure 65.

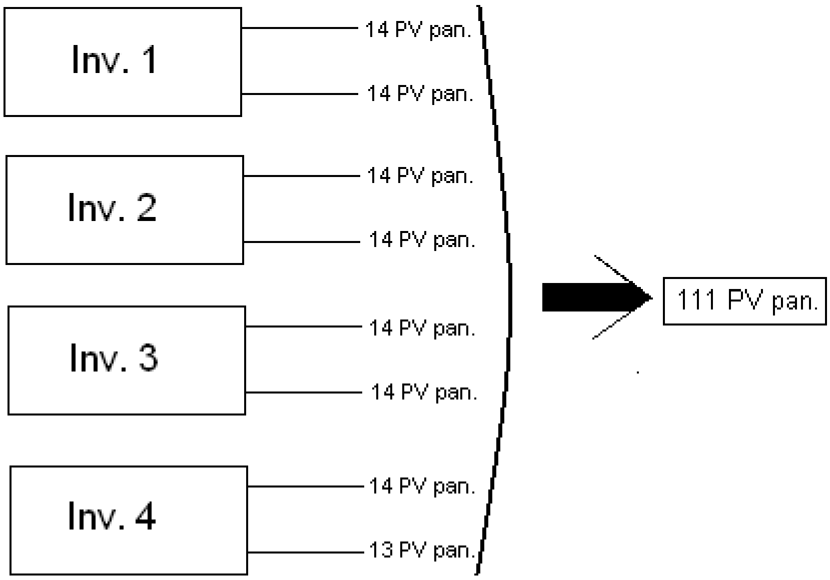


Figure 65: 4 inverters SMA 5000TL connected with 111 PV panels.

The simulation of the first case (total inverters capacity of 15 kW) was shown in the previous chapter, so now we are not stressing on it again. With respect to the second case (total inverters capacity of 20 kW), just as we did before, the original problem has been divided into two new simulation cases:

- One inverter with 2 strings of 14 strings.
- One inverter with 2 strings of 13 strings.

So averaging in the one hand both simulation cases and on the other hand adding three times the balances of the first simulation case, we can find out an approximate simulation of the system desired, obtaining following simulation results:

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	EOutInv kWh	EffArrR %	EffSysR %
January	63	10,8	91,8	88,9	1557,55	1454,45	11,67	10,89625
February	68	10,8	85,9	83,2	1438,2	1341,5	11,51875	10,74625
March	105	12	121	117,2	2031,7	1902,7	11,54875	10,81625
April	146	14,7	153,9	149	2553,35	2402,95	11,41	10,7375
May	180	18,8	175,7	169,9	2840,75	2672,05	11,11875	10,4575
June	195	23	182,8	176,3	2894,7	2724,75	10,89	10,2475
July	201	25,6	192,9	186,7	3038,55	2861,5	10,83	10,1975
August	186	25,4	192	186,1	3027,9	2857,6	10,84	10,2375
September	146	22,9	170	165	2723,45	2571	11,02	10,3975
October	100	18,9	131,7	127,8	2164,05	2034,35	11,3	10,6275
November	60,9	15,8	86,4	83,7	1419,2	1323,2	11,3	10,53625
December	51	12,7	79	76,4	1320,5	1228,9	11,49	10,695
Year	**1501,9**	**17,66**	**1663**	**1610,4**	**27010,65**	**25375,25**	**11,17**	**10,49625**

Figure 66: Balances and main results for 111 PV panels distributed amongst 4 inverters

And the corresponding loss diagram for this scenario is:

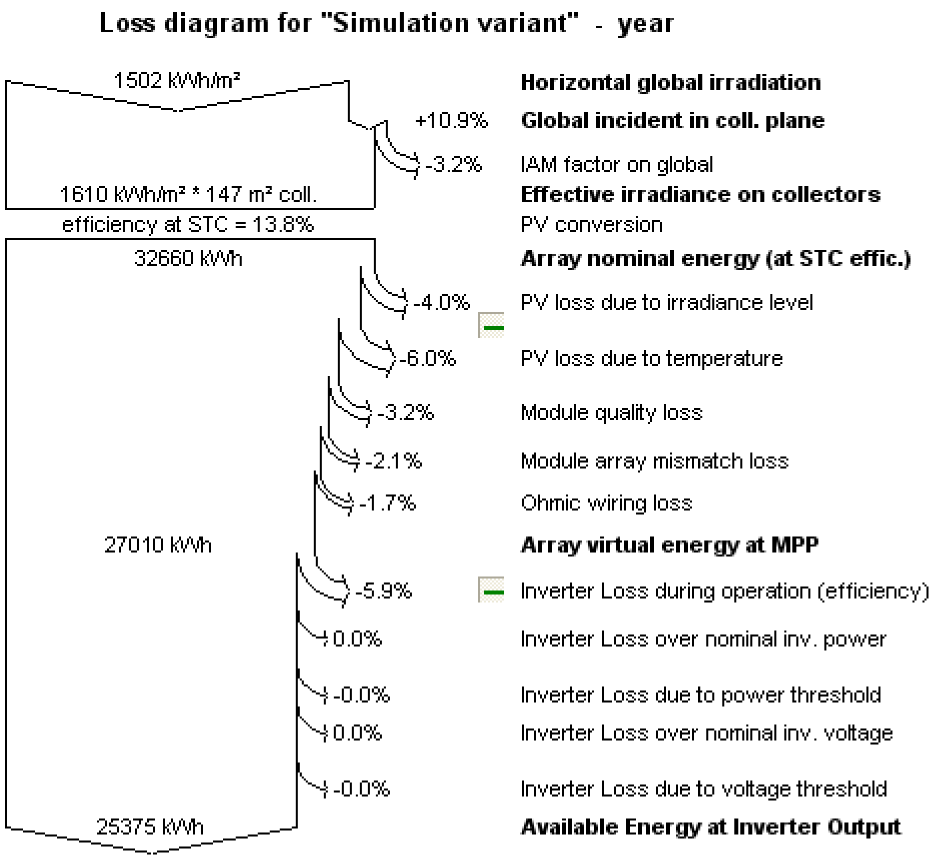


Figure 67: Loss diagram for 111 PV panels distributed amongst 4 inverters

As can be checked easily, when there are 3 inverters installed each one of 5 kW, the amount of energy generated yearly will be of 25.551,15 kWh, meanwhile when 4 inverters installed, the yearly amount would be reduced in 175,9 kWh, till 25.375,25 kWh.

The reason for this difference can be explained directly when comparing loss diagram for both scenarios:

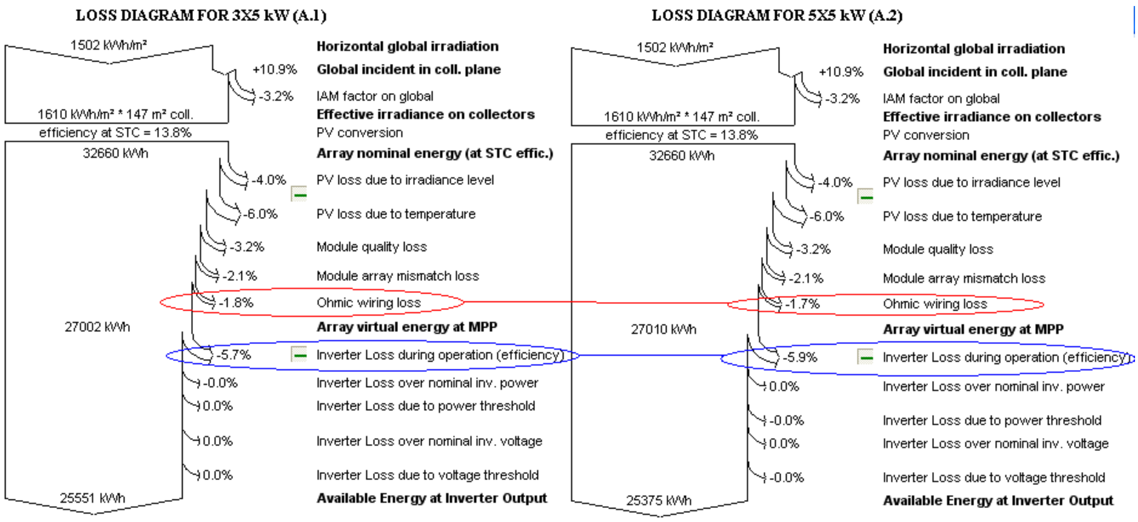


Figure 68: Loss diagrams comparison (A.1 VS A.2)

From previous figure we can conclude:

- As it was predictable, Horizontal global irradiation, Effective irradiance on collectors and Array nominal energy are the same for both scenarios, as long as simulation conditions were the same.
- However, there are some parameters which make the difference between both scenarios:
    - Ohmic wiring loss: Scenario A.1 has bigger loss than scenario A.2 (1.8% VS 1.7%). The reason explaining this difference is simple; meanwhile in scenario A.1 we are using strings of "18.5" panels, in scenario A.2 we are using strings of "13.875" panels, so the length of wire needed in the second case is smaller and in consequence "ohmic wiring loss" is smaller too.
    - Inverter loss during operation: now it is Scenario A.2 the one which presents bigger loss (5.9% VS 5.7%) under this concept. The reason that explain this behaviour is simple too; for scenario A.2 the total inverter capacity is oversized (actually, excessively tighted to the array nominal power), and for this reason inverters are operating at low capacity levels

for long periods of the day and therefore accumulating long intervals with performance levels below maximum.

So we have just verified that the decision of installing a global inverter capacity of 15 kW instead of 20 kW was the right one, as long as according to the simulation in this way we will obtain a bigger amount of energy not only yearly, but month too, at the same time that we are saving the investment cost of buying the fourth inverter.

In next figure we can check in a visual way the results obtained for both cases, 15 kW and 20 kW inverter's total capacity:

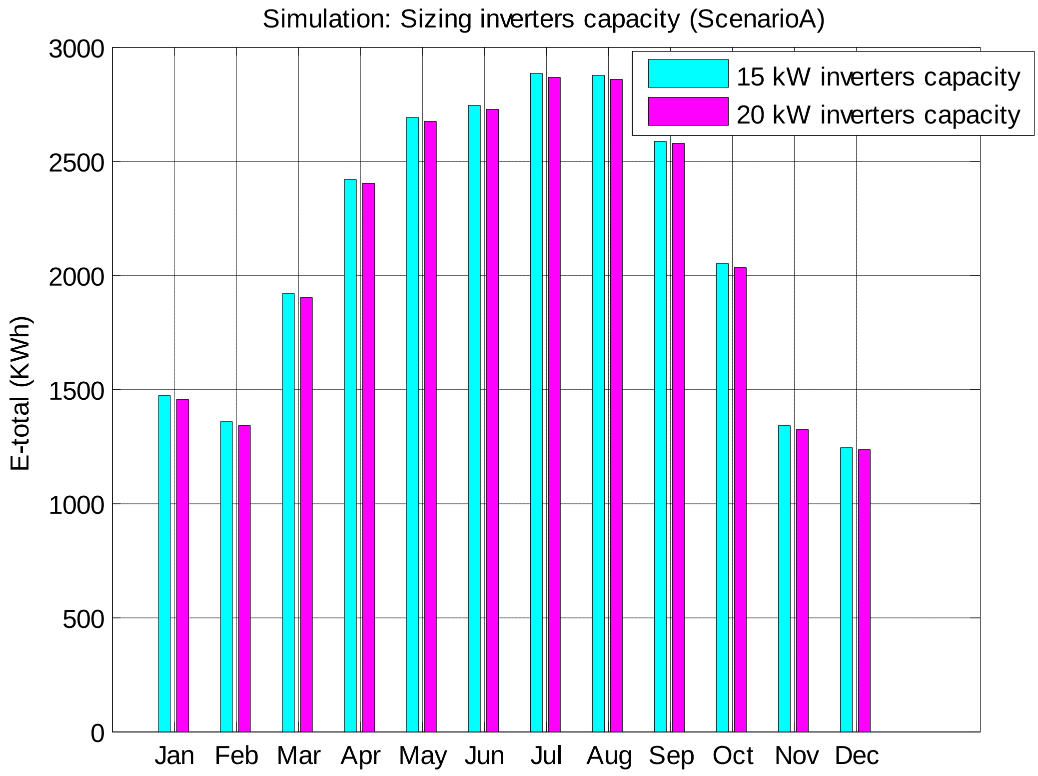


Figure 69: Monthly energy generated when 3 and 4 SMA 5000 inverters are installed

SCENARIO B

This scenario is not as significant as the one considered previously as long as now we are considering different inverters (5 kW, 6 kW and 7 kW), and consequently, different characteristic curves.

However it is interesting to make this analysis too in order to evaluate if there would be a better configuration (in terms of energy production) than the one installed for our system. Moreover, to reduce complexity keeping the aim of the analysis, we will consider now 108 PV panels so the inverter distribution for this scenario will be as follows:

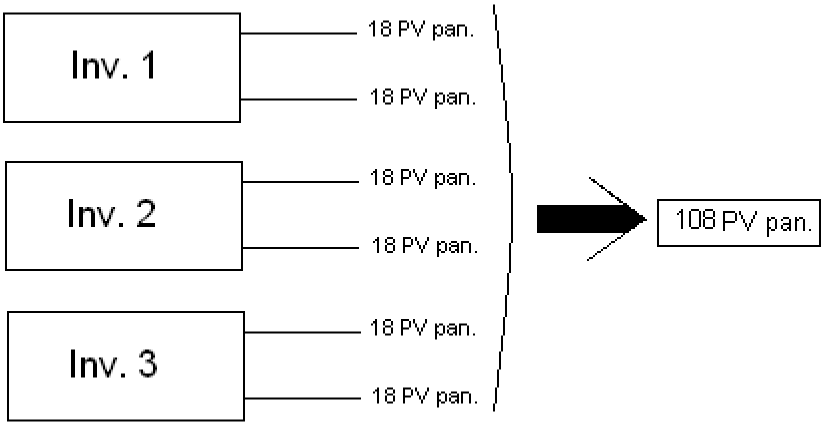


Figure 70: Inverters distribution for Scenario B (considering inverters of 5, 6 and 7 kW).

On the other hand, the three inverters considered now will belong to the same manufacturer (SMA), being:

- 5 kW inverter: SMA Sunny Boy 5000 TL
- 6 kW inverter: SMA Sunny Mini Central 6000 TL
- 7 kW inverter: SMA Sunny Mini Central 7000 TL

As for inverter of 5 kW we can obtain the “real” efficiency curve (according with measurements and analysis done in the present report previously), but we can not make the same with inverters of 6 and 7 kW, in the present analysis we will consider the original characteristic curves provided by manufacturer without any correction. So efficiency curves considered for Scenario B are shown in next figures:

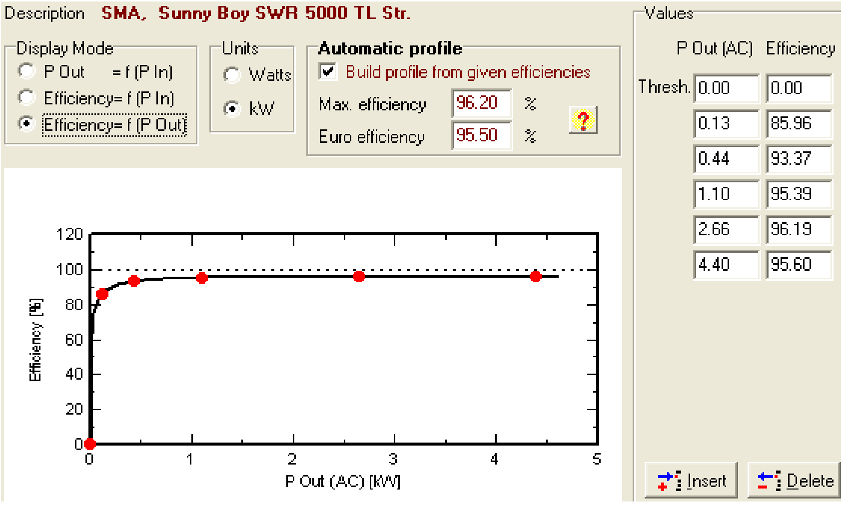


Figure 71: Efficiency curve indicated by manufacturer for Sunny Boy 5000 TL

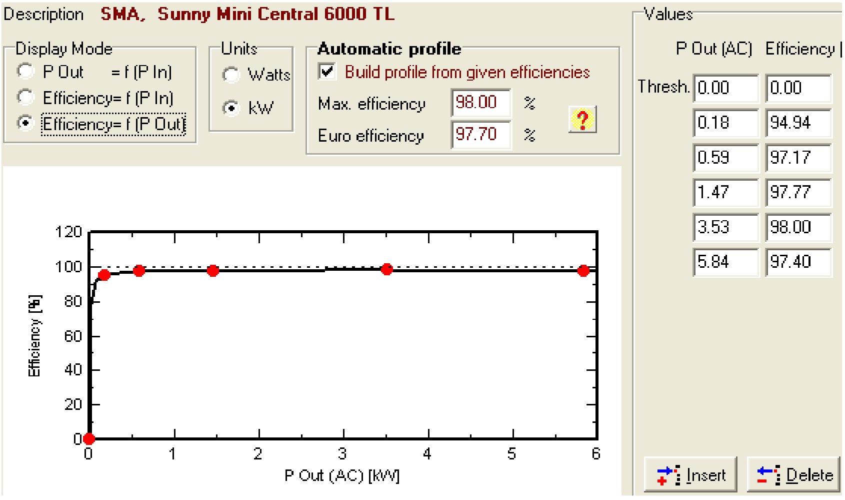


Figure 72: Efficiency curve indicated by manufacturer for Sunny Mini Central 6000 TL

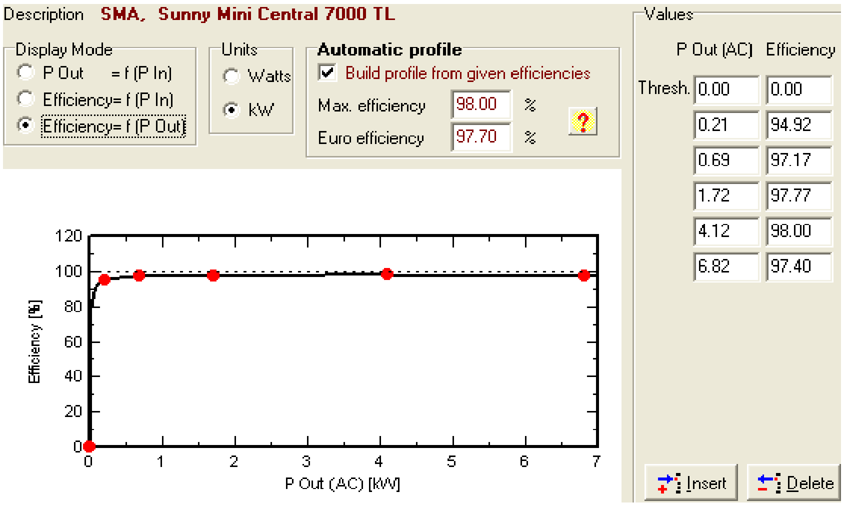


Figure 73: Efficiency curve indicated by manufacturer for Sunny Mini Central 7000 TL

From figures above we can realize that the recently appeared line of inverters "SMA Sunny Mini Central" (available since second semester of 2008), offer the **highest efficiencies available nowadays**, what means a great step forward in PV industry. This fact has been reached **through an optimized MPP Tracker system and an innovative active cooling system**.

As a result of this advances, we can observe that **SMA Sunny Mini Centra**l not just **offers a better maximum efficiency value** when compared with SMA SunnyBoy but also **improves efficiency for <u>every output power threshold</u>**. As an immediate consequence of this fact, we can assume from this moment that very probably the energy production will be significantly improved when using this new line of inverters than when using previous state of the art inverters (like SunnyBoy).

Following we will check if this supposition was right.

B.1) <u>Total inverter capacity of 15 kW.</u>

In this case the total amount of inverter capacity is of 15 kW, distributed into three identical Sunny Boy inverters of 5 kW each one.

The main results obtained for this simulation are depicted following:

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	EOutInv kWh	EffArrR %	EffSysR %
January	63	10,8	91,8	88,9	1516	1427	11,68	10,99
February	68	10,8	85,9	83,2	1399	1316	11,51	10,83
March	105	12	121	117,2	1977	1866	11,55	10,9
April	146	14,7	153,9	149	2485	2353	11,41	10,81
May	180	18,8	175,7	169,9	2763	2615	11,11	10,52
June	195	23	182,8	176,3	2817	2668	10,89	10,32
July	201	25,6	192,9	186,7	2957	2801	10,83	10,26
August	186	25,4	192	186,1	2946	2795	10,84	10,29
September	146	22,9	170	165	2650	2516	11,02	10,46
October	100	18,9	131,7	127,8	2106	1993	11,31	10,7
November	60,9	15,8	86,4	83,7	1381	1298	11,31	10,63
December	51	12,7	79	76,4	1285	1206	11,49	10,79
Year	**1501,9**	**17,66**	**1663**	**1610,4**	**26282**	**24854**	**11,17**	**10,56**

Figure 74: Balances and main results for 108 PV panels distributed amongst 3x5kW inverters

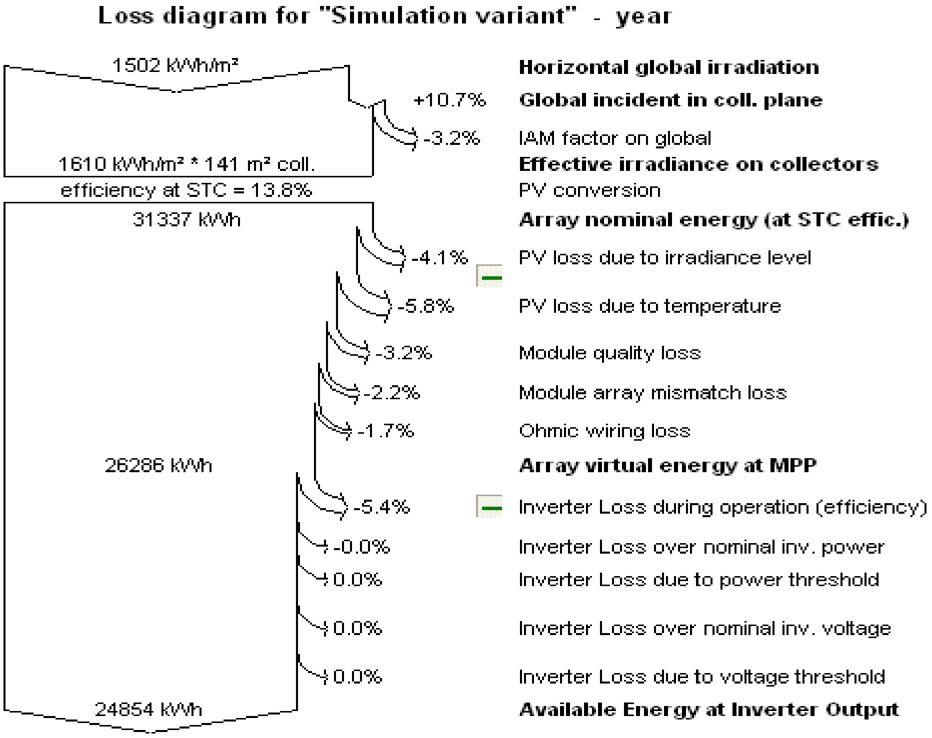


Figure 75: Loss diagram for 108 PV panels distributed amongst 3x5kW inverters

B.2) Total inverter capacity of 18 kW.

In this case the total amount of inverter capacity is of 18 kW, distributed into three identical Sunny Mini Central inverters of 6 kW each one.

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	EOutInv kWh	EffArrR %	EffSysR %
January	63	10,8	91,8	88,9	1516	1482	11,67	11,42
February	68	10,8	85,9	83,2	1399	1367	11,52	11,25
March	105	12	121	117,2	1977	1933	11,55	11,29
April	146	14,7	153,9	149	2484	2429	11,41	11,16
May	180	18,8	175,7	169,9	2763	2701	11,11	10,86
June	195	23	182,8	176,3	2816	2753	10,89	10,64
July	201	25,6	192,9	186,7	2955	2890	10,83	10,59
August	186	25,4	192	186,1	2946	2881	10,84	10,6
September	146	22,9	170	165	2649	2590	11,02	10,77
October	100	18,9	131,7	127,8	2106	2059	11,3	11,05
November	60,9	15,8	86,4	83,7	1381	1350	11,3	11,04
December	51	12,7	79	76,4	1285	1256	11,49	11,23
Year	**1501,9**	**17,66**	**1663**	**1610,4**	**26278**	**25691**	**11,17**	**10,92**

Figure 76: Balances and main results for 108 PV panels distributed amongst 3x6kW inverters

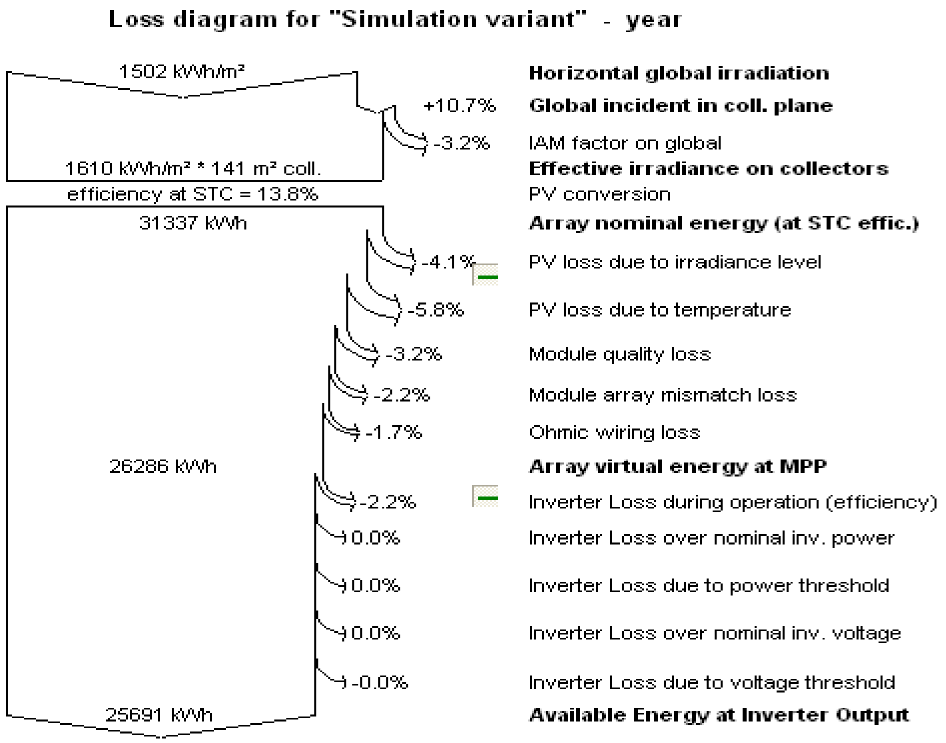


Figure 77: Loss diagram for 108 PV panels distributed amongst 3x6kW inverters

B.3) Total inverter capacity of 21 kW.

In this case the total amount of inverter capacity is of 21 kW, distributed into three identical Sunny Mini Central inverters of 7 kW each one.

	GlobHor kWh/m²	T Amb °C	GlobInc kWh/m²	GlobEff kWh/m²	EArray kWh	EOutInv kWh	EffArrR %	EffSysR %
January	63	10,8	91,8	88,9	1516	1482	11,67	11,41
February	68	10,8	85,9	83,2	1399	1367	11,52	11,25
March	105	12	121	117,2	1977	1933	11,55	11,29
April	146	14,7	153,9	149	2484	2430	11,41	11,16
May	180	18,8	175,7	169,9	2763	2702	11,11	10,87
June	195	23	182,8	176,3	2816	2754	10,89	10,65
July	201	25,6	192,9	186,7	2955	2891	10,83	10,59
August	186	25,4	192	186,1	2946	2882	10,84	10,61
September	146	22,9	170	165	2649	2592	11,02	10,78
October	100	18,9	131,7	127,8	2106	2060	11,3	11,06
November	60,9	15,8	86,4	83,7	1381	1349	11,3	11,04
December	51	12,7	79	76,4	1285	1256	11,49	11,23
Year	1501,9	17,66	1663	1610,4	26278	25699	11,17	10,92

Figure 78: Balances and main results for 108 PV panels distributed amongst 3x7kW inverters

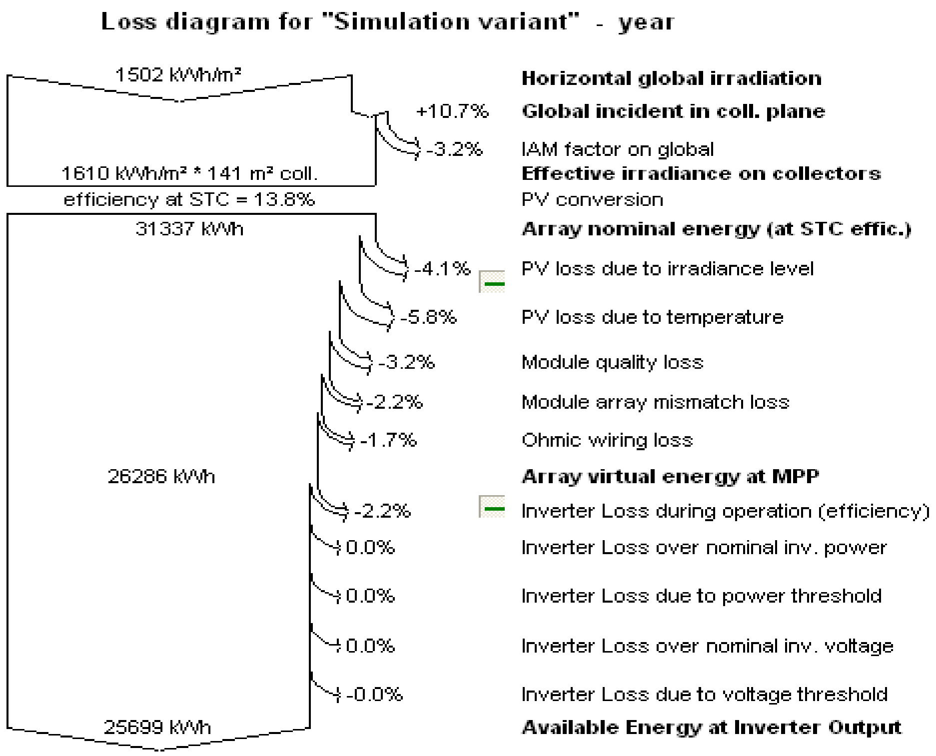


Figure 79: Loss diagram for 108 PV panels distributed amongst 3x7kW inverters

As can be checked quickly for the cases considered **in scenario B, as bigger is the installed inverter capacity bigger is the amount of energy produced**. This increase in energy production is not significant when comparing energy produced in scenarios B.3 -inverter capacity of 21 kW producing 25,699 MWh/year- and B.2 -inverter capacity of 18 kW producing 25,691 MWh/year-, existing a difference of just 0.03%. But comparing scenarios B.3 and B.2 with B.1 (inverter capacity of 15 kW producing 24,854 MWh/year), the difference in energy production is much bigger reaching to the value of 3.39%.

The reason for this difference can be explained directly when comparing loss diagram for both scenarios:

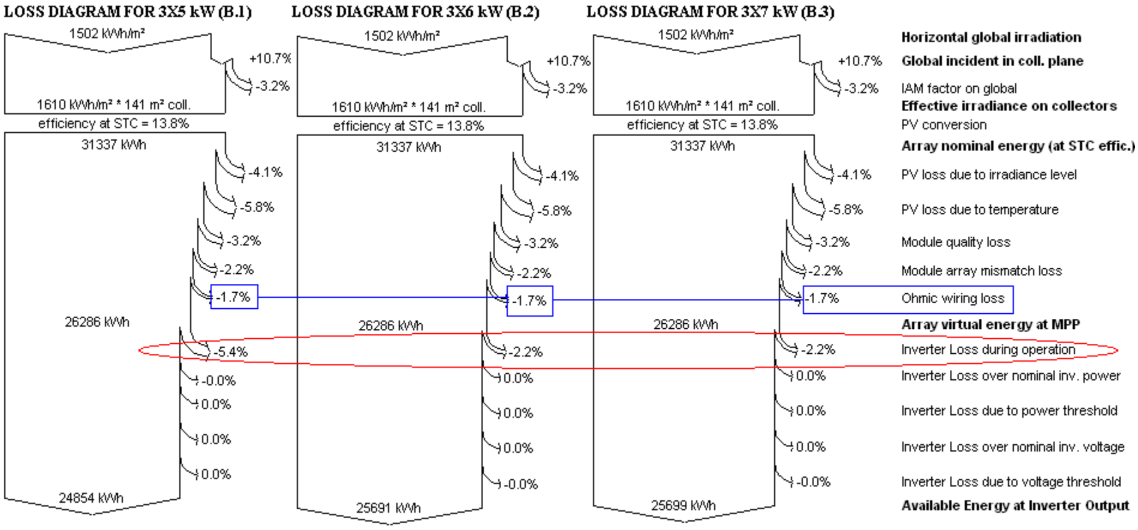


Figure 80: Loss diagrams comparison (B.1 VS B.2 VS B.3)

From previous figure we can conclude:

- As it was predictable, Horizontal global irradiation, Effective irradiance on collectors and Array nominal energy are the same for both scenarios, as long as simulation conditions were the same.
    - Moreover, now ohmic wiring loss keeps the same for every case under analysis because we are always working with the same panel configuration (and so, the same wire length).
- However, there is a fundamental parameter which makes the difference between both scenarios:
    - Inverter loss during operation: the inverter models used for this simulation have significant different efficiency curves: “euro efficiency” for case B.1 (Sunny Boy) is 3.9 points lower than for cases B.2 and B.3 (Sunny Mini Central). This important difference is the one responsible of making energy production bigger for cases B.2 and B.3.

All these results obtained for scenario B are shown in a graphical way in next figure:

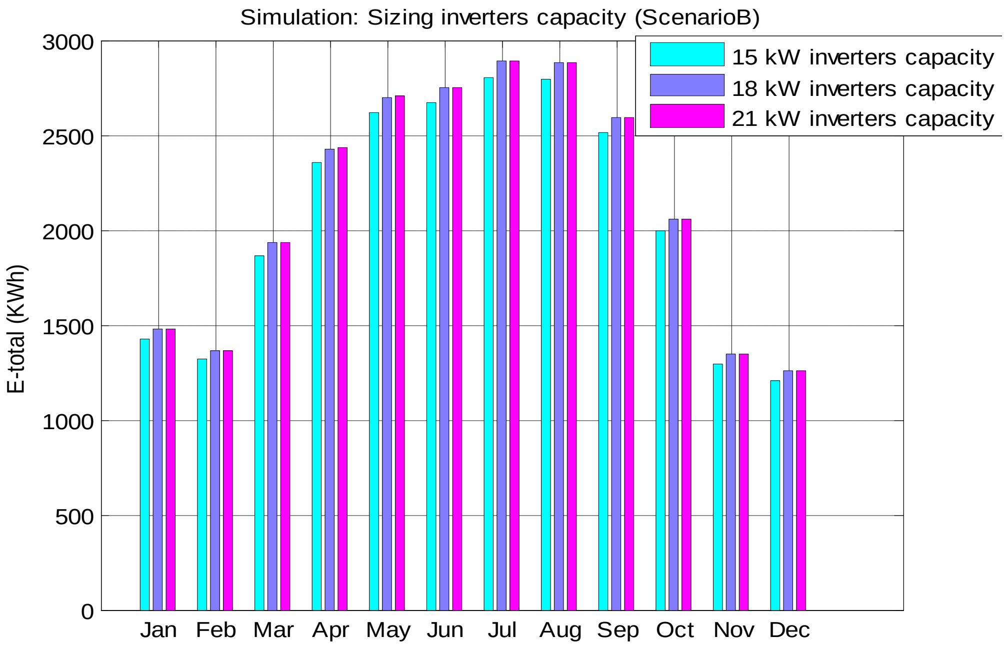


Figure 81: Monthly energy generated when installing 15 SB kW, 18 SMC kW and 21 SMC kW of inverting capacity

Anyway, **these results could seem incoherent with conclusions obtained for scenario A, which established that we could improve our energy production if under-sizing properly our global inverter capacity**. But the real truth is that both conclusions are right, being useful this apparent contradiction to stress on the importance of inverters efficiency curve.

So **the reason that makes energy production bigger when global inverter capacity is of 21 kW** (or 18) **than when it is of 15 kW**, **is not a better dimensioning condition but the use of more efficient inverters.**

**** And not only more efficient from the point of view of maximum efficiency value, but mainly for every output power threshold!!! ****

To prove previous assertion is truth we will make a final simulation repeating the analysis made previously for Scenario B, but now considering all our inverters (5, 6 and 7 kW) behave in the same way from the perspective of efficiency (“Maximum efficiency” and “Euro efficiency” values). So the new efficiency values we will consider - for every inverter! - during this simulation will be the shown immediately following (matching with values for SMA Sunny Mini Central):

- Max. efficiency: 98.00%
- Euro efficiency: 97.70%

The new imposed condition will be considered as a new scenario, called B.4. This new scenario will be the same as B.1 (three 5 kW inverters) but considering the previously stated "rule". It is convenient to emphasize that scenarios B.2 and B.3 will not be affected, as long as their efficiency curves are not modified by the new fixed efficiency values.

Considering such conditions and operating properly, in next figure we show the amount of energy produced monthly and yearly for every case under study:

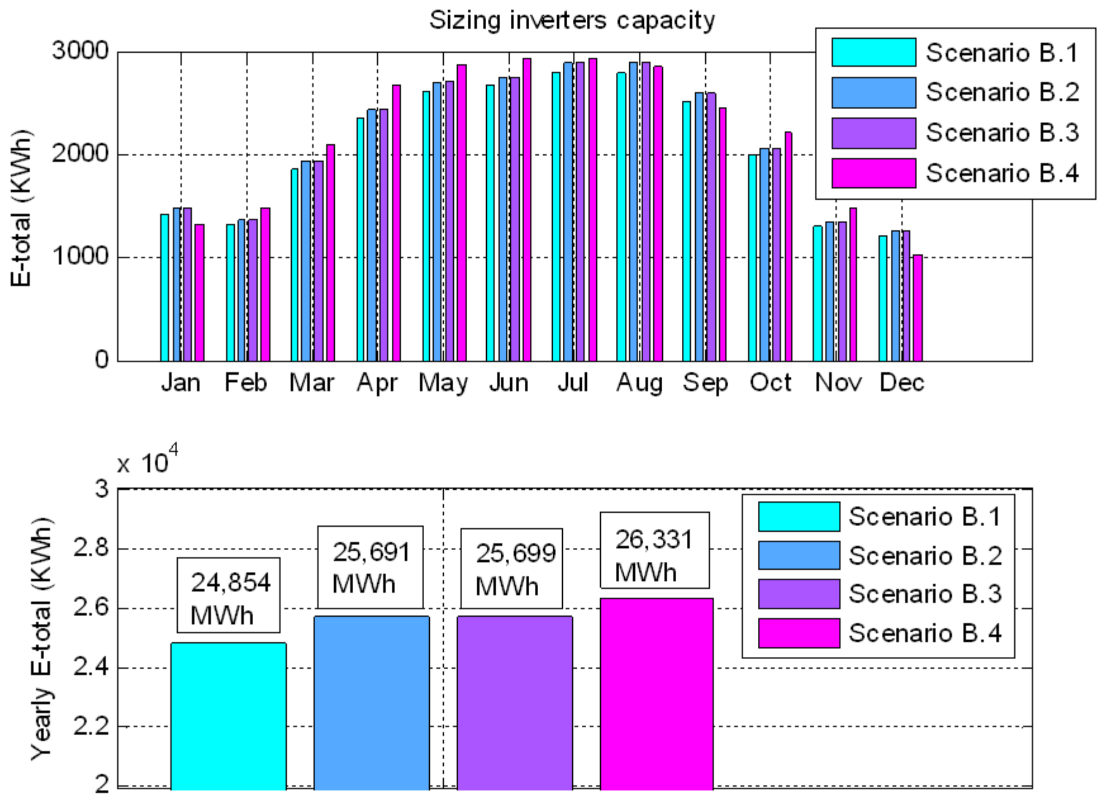


Figure 82: Monthly and yearly energy generated for scenarios B.1, B.2, B.3 and B.4

In previous figure we can check how scenario B.4 is the most productive in the great majority of months. In fact, even if there are some particular months were scenarios B.2 and B.3 produce more energy than B.4, this keeps being the most productive scenario considering the whole year energy production.

So as a general conclusion for our system, when assuming identical efficiency characteristic for inverters, the best inverter sizing configuration is 15 kW.

4.3 Comparing SW results and real measurements.

In this section we will compare software-expected results with the real results obtained during the first months of our installation's operation.

Analyzing the electricity production, we find that the real production is significantly higher than expected from PVSYST simulation. The energy generated for the available period of time, from 10/03/08 to 25/09/2008, was exactly 20,017 MWh. Meanwhile, for the same period of time PVSYST estimates energy generation should be 17,097 MWh. **This means a ratio of produced/expected energy of 1.17.**

If we compare energy generated with energy expected month by month, as shown in next figure, we can check out easily this 17% of energy overproduction:

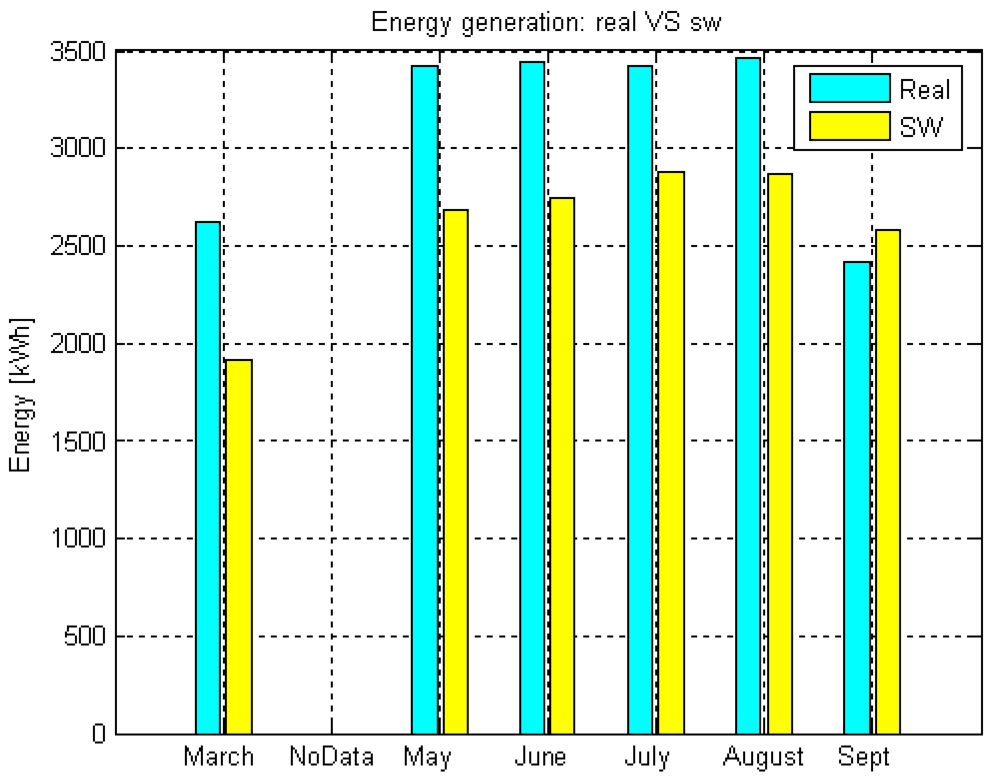


Figure 83: Monthly energy generated (real VS simulated)

We can observe how the real production exceeds the expected production in every month except September, month where both amounts keep quite similar. During March the *overproduction* gets to its maximum value, with a ratio of 1.37, getting values about 1.2 for summer months.

Apparently the deviation between real and expected energy generation is excessive. However, we will try to find some **generic explanation** to the results obtained.

- First of all, it should be taken into account that weather conditions during a short period of time as considered can not match with the typical expected conditions.

As weather conditions during only 7 months can be different from the "typical" ones (unusual heavy rainfalls, storms, floods, or in the opposite, especially dry months with abundance of clear sky, etc.), several years of operation are necessary in order that real performance can be calculated and compared. So, just like sadistic matters, the smaller the number of samples considered, the bigger the margin of error. Anyway, the first measured monthly values of system parameters indicate that the extended efforts in the first stage of PV system design, orientation and final construction execution lead to optimal system performance.

- Secondly, every simulation programmes work properly when designing the systems, helping us to decide about which configuration is best when comparing with another. So these programmes are more focused on relative comparison between different possible configurations (orientation, inverters and modules sizing, comparative between manufacturer, etc.) than in obtaining absolute parameters values (such as total energy generation). So PVSYST and other design/simulation software must be considered as it is: an accurate approximation to the problem but never a exact tool.

However, apart from these generic explanations, the differences between real and expected energy generation are so significant that there must exist other **particular reasons affecting our specific system**:

- PVSYST meteo-database (monthly values) used is based on the METEONORM database. METEONORM software defines "stations" for which the measured irradiances values are available (in our case, average values belonging to year 1990). For sites far away from these "stations", like our location in Katerini, the values considered by PVSYST are values interpolated between the 2-3 nearest stations.
- For many regions of the world, measured data may only be applied within a radius of 50 Km from weather stations. This makes it necessary to interpolate parameters between stations. Interpolation models for solar radiation, temperature and additional parameters, allowing application at any site in the world, have been considered for our simulation. This interpolation is really effective in the great majority of cases, but is subject to significant errors in some particular environments.

So in order to check if a wrong interpolation could be the responsible of deviation between real and expected energy generation, we have turned to the Satel-Light European project, which provides data from the geostationary satellite Meteosat obtaining a continuous (**with no interpolations !!**) spatial coverage of Europe at a high frequency (every 30 minutes).

CONTRAST BETWEEN SATEL-LIGHT AND METEONORM.

The Satel-Light project was funded by the European Union (Directorate General XII) from 1996 to 1998. **Images produced by the Meteosat satellite every half hour were chosen as the one and only source of climatic information.** The major difficulty stood in producing precise ground level data from the images using various models.

The main Satel-Light aim was to improve/develop and validate such models, making later a database from satellite images widely available via any Internet web server.

Before Satel-Light, the only way to obtain trusty meteorological data was either to contact a measurement station or to buy a climatic atlas, both solutions being less than ideal. There are very few measurement stations continuously recording this kind of data in Europe. Climatic atlases such as METEONORM database are available on CD-ROMs and gather useful climatic information.

However, these products have weaknesses:

1. There is no continuity of information over Europe: the information is based on a limited number of ground stations, around 600.
2. There are no hourly/half hourly values except for a few sites. High frequency values are essential to provide information on the dynamics of daylight and solar radiation. The data from the geostationary satellite Meteosat seemed to be the only way to obtain a continuous spatial coverage of Europe at a high frequency (30 minutes).

So with all the information provided by Satel-Light, and available all over Internet, we decided to consult their database for a further verification of climatic parameters in our location, Katerini. The results obtained were surprising and explained by themselves why there was such an important difference between PVSYST estimations and real measurements.

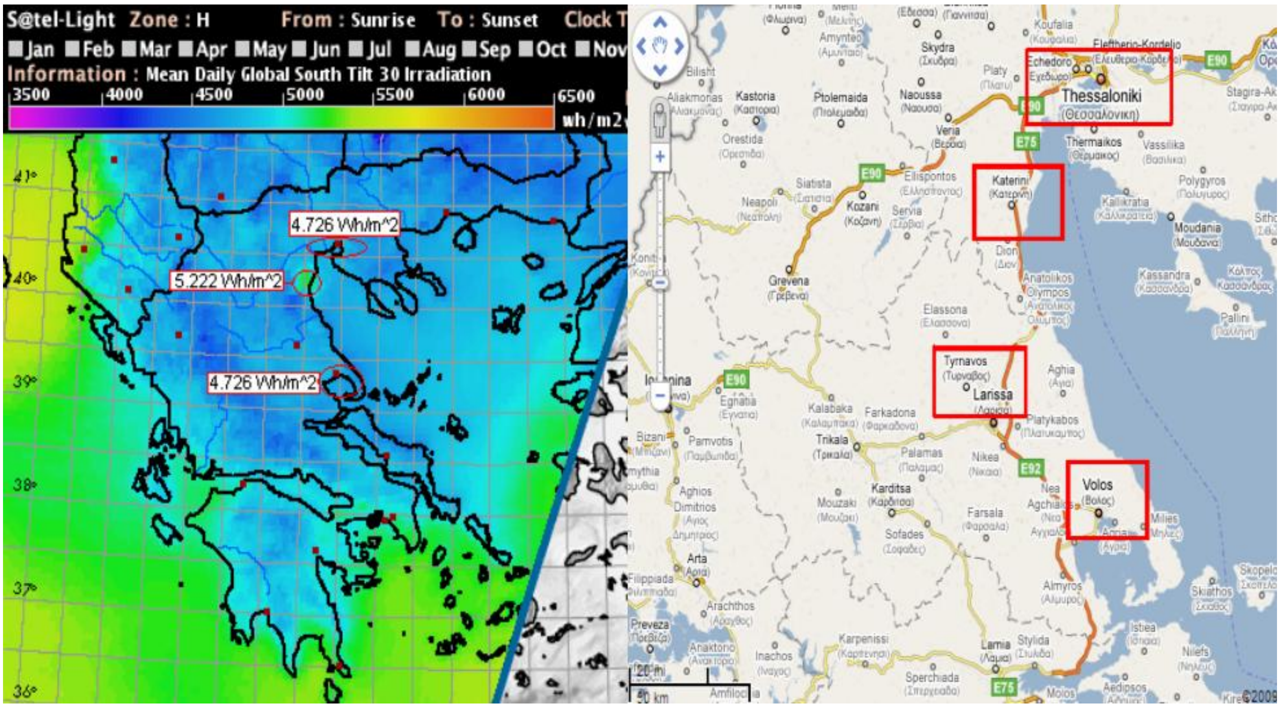


Figure 84: a) 1996-2000 mean daily global irradiation b) GoogleMap with locations of interest marked

In previous figure, we can check that there are multiple meteorological stations all over Greece. Particularly, the nearest stations from Katerini are located in Larissa, Volos and Thessaloniki. So in the figure 84 a) we have indicated these locations with red circles showing the particular irradiance values (obtained through an interactive map) for these four places.

At first sight can be noted that mean daily global irradiance in Larissa, Volos and Thessaloniki for panel tilt of 30º, is very close (about 4.726 Wh/m^2). However, for the location in Katerini this irradiance gets to an average value of 5.222 Wh/m^2. Which means that for very close locations as mentioned, there is a important irradiance increase of about 10.5%.

Now, as long as Katerini does not have any “station” over its surface, METEONORM climatic database (and consequently PVSYST) will proceed interpolating data from nearest stations available, so the weather data used for PVSYST simulation when location is Katerini will have an input entrance miscalculation around 10.5%, which justify to a great extent the deviation between real and simulated energy reflected when using PVSYST software.

In terms of explaining why Katerini´s location has a so particular behaviour, comparing with other close locations, could be due to the near presence of mountains acting as a barrier for the entrance of clouds, and causing a higher probability of clear days.

5. CONCLUSIONS

Conclusions have been divided in two sections:

- "Local" conclusions, where we describe main conclusions referred to our **concrete** PV system under analysis.
- "Global" conclusions, where we describe some conclusions that, from our concrete PV system, can be extensive to a more general PV framework.

5.1 "Local" conclusions.

Through present report we have analysed a particular PV system installed in the north of Greece. Global results obtained have been extremely satisfactory and energy production during first half year of work has been even higher than expected.

The final design implemented has shown to be close to the optimum:

- Considering the optimum tilt (30º) and locating the installation in open field (therefore no shading scenario), has improved global system performance.
  - Additionally, the placement of the installation in Katerini has turned out to be one of the most favourable places for solar production all over north of Greece, thanks to special irradiation conditions present in the area.
- Manufacturers selected for the installation (SHARP panels and SMA inverters) have turned out to be reliable, offering trustable solutions according with expected.
- There is research aimed at inverter efficiency improvement. However, there are designing mechanism -available nowadays!- capable of getting better conversion performance. For example, maintaining the inverter at or near full load in order to operate in the high-efficiency region, existing two different ways:
  - **Use of multiple inverters** of the same rating to cover the full range of power levels with better inverter saturation

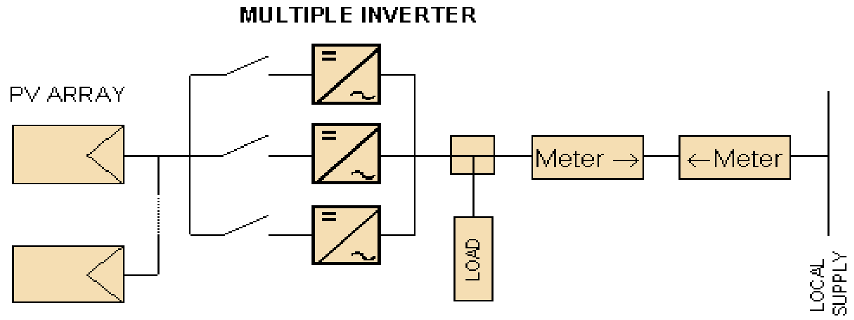


Figure 85: Grid-connected PV System with Multiple Inverters

- **Under-sizing** of the inverter with respect to the installed PV peak power, loosing some energy in peak generation but increasing efficiency in low power levels.

The final decision taken, based on inverters' under-sizing, leaded us to an important improvement in the system performance, not only because of energy production increase but also for the important savings on investment.

All the improvements mentioned show the importance of system design optimisation for PV technology. However, in the future further works can be executed with the purpose of developing innovative technologies assuring increasing profitability.

5.2 "Global" conclusions.

Beyond our particular system, results obtained throughout this report are positive for the whole future of PV industry in Greece, especially now that Greece's Parliament has approved (15 January 2009) Europe's most generous PV incentive program after a moratorium of almost 2 years. So results obtained in Katerini can be extrapolated (making always the required particular analysis) to other placements in Greece, as long as PV's potential and development in this sunny country has been shown.

Additionally, the actual international context in Europe makes Greek's situation even more encouraging. In 2008, the most important European PV markets (Germany, Spain, Italy, France and the newcomer Greece) registered a newly installed PV capacity of more than 3 GW. However, within the last years the situations has changed profoundly:

- The number of market players in the PV business has been increased significantly, so promotions caps now control market growth (especially in Spain).
- On the other hand, regression rates of feed-in tariffs have been significantly elevated (especially in Germany).

Against this background, important indicators reveal that Greece can be expected to be in few years the next major photovoltaic market in Europe.

6. FUTURE RESEARCH

Following we depict some future works and open question that, starting from present report, can be tackled in future studios.

6.1 Proposal for improving monitoring system.

Present report has focused on analysing the whole PV system from data measurements acquired by SMA inverter device. Therefore we have been able to verify that the whole system is working properly and close to optimum design, as can be checked when comparing real VS expected (PVSYST) results.

So like the global system worked as expected, we can assert that:

- Inverters are working properly.
- Solar panels are working properly.

In fact, we have been able to analyze in detail inverters' behaviour thanks to the monitoring system which offered us enough electrical information at both sides of inverter (actual voltage, current and power at the input (DC) and output (AC) of the inverter).

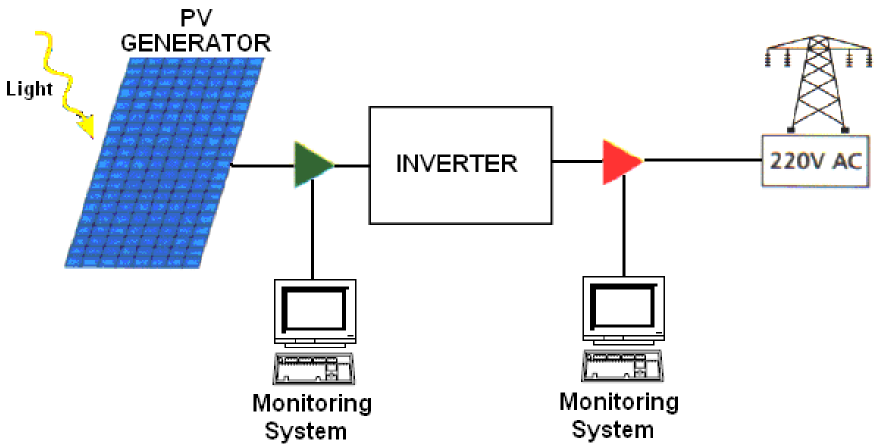


Figure 86: Actual monitoring system (inverter)

However, when talking about solar panels, we can assert they are working properly as long as the whole system does it. But the absence of monitoring system for irradiance makes we could not make a detailed analysis on panel's efficiency (and therefore, its performance and behaviour).

For solar panels the *energy conversion efficiency* (η), is the percentage of power converted (from absorbed light to electrical energy) and collected, when a solar panel is connected to an electrical circuit. This term is calculated using the ratio of the power at every moment, P_m, divided by the input light *irradiance* (E, in W/m^2) in that moment and the *surface area* of the solar cell (A_c in m^2).

$$\eta = \frac{P_m}{E \times A_c}$$

Nowadays there are many commercial radiometers (instrument for measuring radiant energy) which continuously monitor incoming solar radiation and some other parameters of interest (such as temperature). Adding this device to our PV system, we could go one step beyond on its complete analysis, including accurate considerations not only about inverters and energy generation but also about solar panels' performance and effects of temperature on our system.

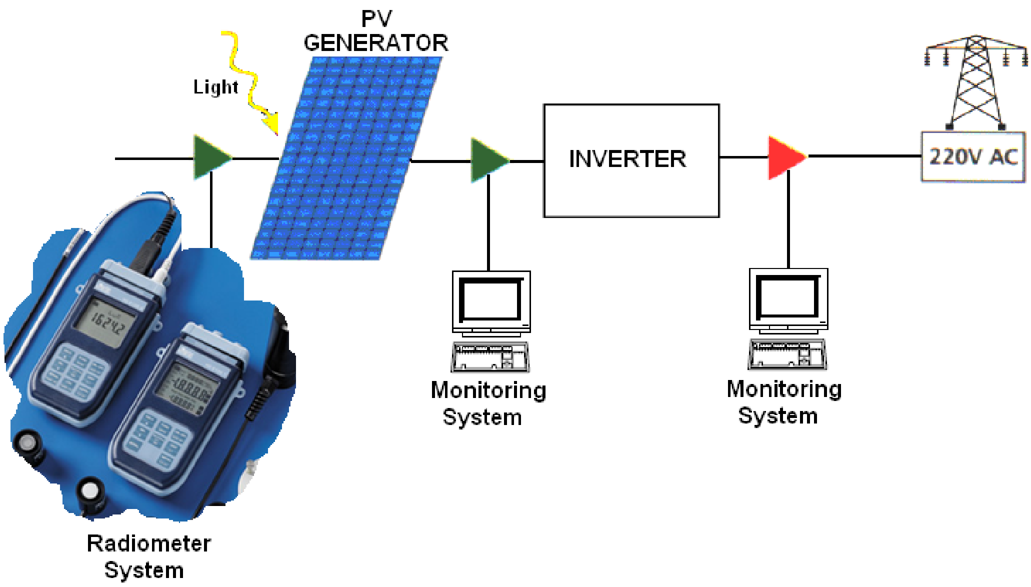


Figure 87: Proposed new monitoring system (solar panel + inverter)

6.2 Optimum association of panels.

When studying about photovoltaic, there is a vast theoretical known on the matter:

- Equivalent electrical circuit of solar cells.
- Mathematical tension-current relation for a PV panel (N_P rows in parallel, each one with N_S cells in series).
- I-V and Power curve of the PV panel.

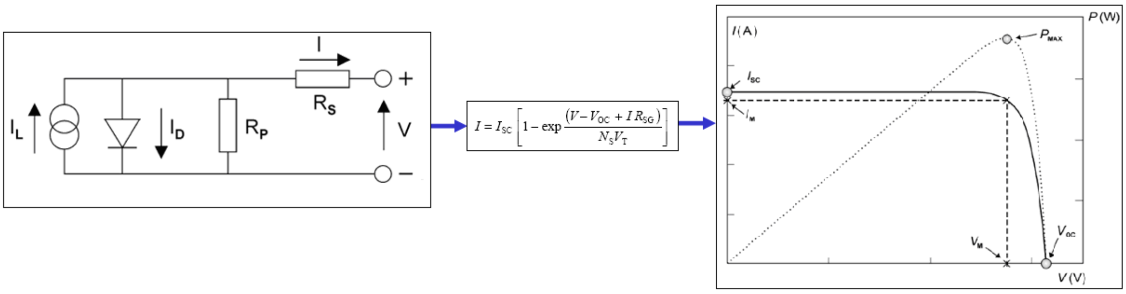


Figure 88: Electrical principles of solar systems

When joining identical panels in series and in parallel, is also well known that:

- Association in series: the new voltage is the addition of individual voltages of each module (current keeps invariable).
- Association in parallel: the new current is the addition of individual currents of each module (voltage keeps invariable).

However, all these assertions only come true when every cell joined inside a panel and every panel associated inside a PV array, are **identical**, which in practice is not possible.

For example, in the system under analysis during this report, there was some power dispersion in panels used. The logic criteria used for grouping the panels in arrays was to associate in series those panels with similar current as shown in figure:

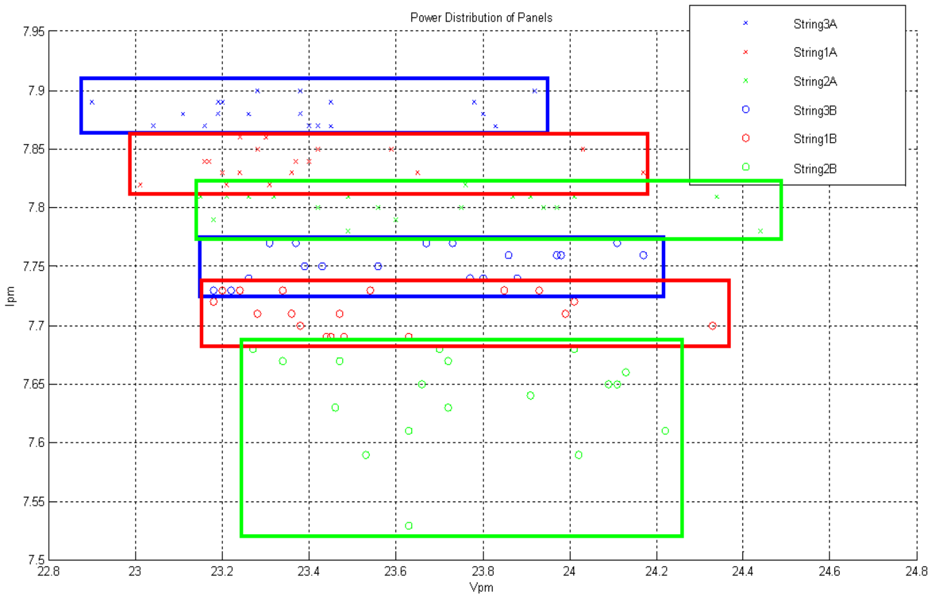


Figure 89: Association of panels

However, keeping the logic criteria of joining those panels with similar maximum current, there are a big amount of possible associations, so **a further study on which is the optimal one could be done**.

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