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Technical-Financial Comparison Between a PV Plant and a CSP Plant

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Abstract

The paper deals with the economic-financial aspects of two typologies of solar energy sources: PhotoVoltaic (PV) plant and Concentrating Solar Power (CSP) plant. The aim of the paper is to analyze the initial costs, the maintenance costs and benefits deriving from both the government economic incentives and the selling of energy between a 40 MWp PV plant and a 40 MW CSP plant. Even if the two plants under test have the same rated power, it results that the produced energy, under the same environmental conditions, is different. This technical aspect influences the business plan, because the government incentives, as well as the selling of energy, are directly related to the produced energy. Finally, initial costs as well as maintenance costs are also different because of the different constitutive components and the operation principle.

Key-words: Concentrating solar power plant, Photovoltaic, Renewable energy sources

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Revista Eletrônica Sistenas & Gestão
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1. INTRODUCTION

The CO2 emissions are considered responsible of the climate changes of the Earth. As these emissions are produced also by burning the fossil fuels to produce electrical energy, many countries in the world are transforming their national electrical production systems, decreasing the electrical production deriving from fossil fuels and increasing the production deriving from Renewable Energy Sources (RES).

Among RES, solar technologies are capturing large interest. The PhotoVoltaic (PV) technology is nowadays largely used in many countries because of its modularity and ease of installation. Moreover PV technology is now mature and the degree of ageing is well known. (WOLDEN *et al.*, 2011).

On the other hand, Concentrating Solar Power (CSP) technology is now acquiring an increasing interest, especially if built with thermal energy storage (HERRMANN, KEARNEY, 2002)-(MORISSON *et al.*, 2008)-(MEDRANO *et al.*, 2010). Moreover, economic issues have been treated for CSP in order to verify which are the profit, the breakeven and so on (SIOSHANSI, DENHOLM, 2010).

The aim of this paper is to compare a PV plant with a CSP plant from the produced energy point of view as well as from the financial-economic one. Then, the paper introduces the two typologies of energy production systems, the respective common technologies and, finally, the comparison between two plants, supposing that they have the same rated power (40 MW) and they are installed in the same environmental conditions.

2. ENERGY PRODUCTION SYSTEMS UNDER TEST

2.1 PV PLANTS

The PV plants can be categorized into two main typologies from the point of view of the installation mode: stand alone and grid-connected. The first one refers to PV plants which are not connected to the electrical grid of the local energy utility company. This typology of PV plants is usually used to feed small electrical load (e.g. for street lighting) or when the electrical grid is too far (e.g. an isolated rural house or a small offshore application). Stand-alone PV plants have a storage battery with stabilizer in order to guarantee that: a) the battery is not over-charged by the PV plant; b) the charge of the battery is not less than a prefixed threshold; c) the supply voltage is just that required from the electrical loads (if the electrical loads have to be fed by DC voltage) or from the DC side of the inverter (if the electrical loads have to be fed by AC voltage). Anyway, stand-alone PV plants are not used for high power.

The second one refers to the PV plants directly connected to the electrical grid of the local energy utility company. In this case, there is no battery because the electrical storage is represented just by the electrical grid. In fact, the energy produced by the PV plants and not simultaneously absorbed by the electrical loads is injected in the electrical grid; then, when the electrical loads require more energy than that produced by the PV plant, the lacking part is taken by the grid. Obviously, all the energy exchanges are regulated by commercial agreement. Nowadays, it is very common that PV plants are used to contribute to the total energy mix of a whole country or region; in this case the PV plant has high rated power, do not feed local electrical loads (except ancillary services of the PV plant as lighting) and injects all the produced energy in the electrical grid in order to balance the global ratio (absorbed energy)/(produced energy) of the whole electrical grid.

For the aims of this paper only this last typology of PV plants (high-power grid-connected PV plants) is important; then the following sub-sections of this section regard only this specific typology of PV plants.

2.1.1 COMPONENTS AND OPERATION OF GRID-CONNECTED PV PLANTS

Figure 1 reports the scheme of a single part of a grid-connected multi-inverter PV plant. In fact the maximum rated power for a common photovoltaic inverter is 500 kWp, rarely 1MWp. Then, PV plants with rated power higher than 1 MWp have to be designed with some or many inverters which PV modules are connected to. The number of inverters depends on several factors: high partitioning guarantees the partial

Revista Eletrônica Sistemas & Gestão
Volume 6, Número 2, 2011, pp. 210-220
DOI: 10.7177/sg.2011.v6.n2.a9

operation of the PV plant during its maintenance or when a fault has happened, but it implies higher initial investments as well as higher maintenance costs. Then, a large PV plant is constituted by several blocks as in Figure 1 and linked each other as explained in the following.

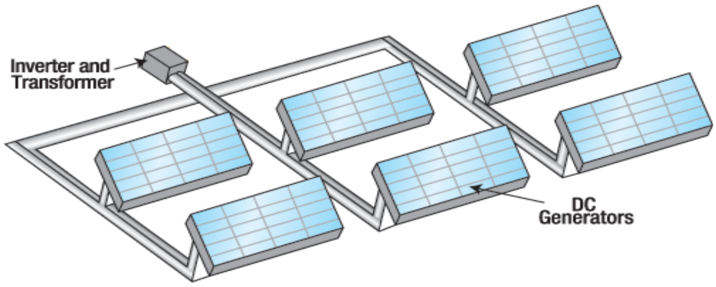

Figure 1 Single part of a multi inverter grid-connected PV plant

The main constitutive components of a grid-connected multi inverter PV plant are the following:

1. PV modules, which collect sun's rays and transform them in DC current.
2. Inverters, which convert the DC waveforms in AC waveforms.
3. Medium Voltage (MV) / Low Voltage (LV) Cabin, which raises the voltage level.
4. High Voltage (HV) / MV cabin which links the PV plant to the electrical grid. This last one is needed only for rated power higher than a prefixed threshold; for example, in Italy this threshold is 6 MWp. As in this paper we will compare PV plant and CSP plant with 40 MW of rated power, then it has to be considered.

Three typologies of radiation collide the PV modules: direct radiation, reflected radiation, diffuse radiation. Depending on the constitutive material of the PV cells, a PV module shows a different efficiency of energy conversion. For example, mono-crystalline cells are more sensible to the direct radiation, whereas thin film cells are more sensible to the diffuse radiation. Nowadays combinations of other materials, such as cadmium, copper, indium, gallium, selenium, and tellurium, are also used to manufacture PV devices (WOLDEN *et al.*, 2011). As the mono-crystalline PV modules have the maximum conversion efficiency for commercial PV modules, just this typology of PV modules will be considered in this paper. In this paper a medium efficiency of 17% is considered, even if some PV modules can reach higher values. Efficiency of 17% implies that the maximum peak power of a module is the 17% of the solar radiance.

Inverter for PV plants have specific characteristics other than to convert the DC waveforms in the AC ones. For example, they have internal devices to disconnect the PV plant from the electrical grid when the grid voltage or the grid frequency exceeds prefixed thresholds. Moreover they have an internal device for tracking the Maximum Power Point (MPP) in order to maximize the production of energy.

Also MV/LV cabin for PV plants has specific characteristics. In fact many countries impose specific conditions to connect a PV plant to the grid. Then the cabin, when you buy it, is often already equipped with all the needed protection devices and the other ancillary services. Often the manufacturer realizes the cabin, complete with inverter, transformer, and so on. Analogous considerations can be made for the HV/MV cabin, if present.

The operation principle is simple. When the sun's rays collide the PV modules, the electrons exceed the conduction gap and a DC electrical current flows through the terminals of the PV module. It happens for each PV module. Several PV modules, connected each other to increase the total peak power, inject DC

Revista Eletrônica Sistenas & Gestão
Volume 6, Número 2, 2011, pp. 210-220
DOI: 10.7177/sg.2011.v6.n2.a9

current in the input port of the inverter, which convert it in AC waveform, suitable for the grid connection. Before the connection it is needed to raise the voltage level; for this aim a MV/LV cabin is needed and, in this specific case, also an HV/MV cabin, because the rated power exceeds the threshold fixed by the energy utility company.

For the energy efficiency point of view, sometimes the whole PV plant is considered as constituted by two parts: PV modules and Balance Of System (BOS). Then, the BOS includes all the components of a PV plant except the PV modules. When this schematization is used, the global efficiency of the PV plant is evaluated taking into account the efficiency of the PV modules and the losses due to the BOS.

2.1.2 CHARACTERISTIC PARAMETERS OF THE PV PLANT

The layout of the PV plant for this paper is the following: twenty series-connected PV modules of 250Wp rated power constitute a single array. One hundred arrays are connected to the DC side of each 500-kWp inverter. Two inverters are linked to a 1MW LV/MV transformer in a single MV/LV cabin. Finally, eighty MV lines are collected in a single HV/MV cabin which allows to inject the AC electrical energy into the grid. Table 1 resumes the parameters of the PV plant.

2.2 CSP PLANTS

The CSPs can be categorized into three main technologies, based on the process of collecting and concentrating solar radiation (GLATZMAIER, 2011): a) Parabolic Trough, b) Solar Tower for Central Receiver, c) Parabolic Dish. It exists also a forth technology (Linear Fresnel Reflector), but it is less common than the previous ones.

The first one uses parabolic trough shaped mirrors to concentrate the incident Direct Normal Irradiation (DNI) onto a receiver tube which is placed at the focal line of the trough. This is the most commercial technology for CSPs because it is the most mature technology. As this technology is considered in the paper, an in depth description is reported in the next sub-section.

In Solar Tower technology the solar collector field contains a radial arrangement of several sun tracking large mirrors that concentrate the solar energy onto the receiver placed on the top of a central tower.

The third technology uses a parabolic dish-shaped solar concentrator that concentrates the sunlight onto a receiver placed at the focal point of the dish.

Table 1 – Parameters of the PV plant

Number of mono-crystalline PV modules	160.000
PV module Efficiency in Standard Test Conditions (STC)	0,17
Losses of the BOS	0,15
Number of 500-kWp inverters	80
Number of MV/LV cabins	8
Number of HV/MV cabins	1
Area needed for 1 MWp	$1,5 \times 10^4$ m^2
Total area	60×10^4 m^2
Total electrical rated power	40 MWp
Yearly produced energy	56 GWh/year

2.2.1 COMPONENTS AND OPERATION OF THE CSP PLANT

This section focuses the attention on the CSP based on parabolic through. An Italian pilot project, based on this technology, has been realized by ENEL (Italy's largest power utility) and ENEA (Italian national agency for new technologies, energy and sustainable economic development) in the south of Italy, named Archimede.

S&G Revista Eletrônica
Revista Eletrônica Sistemas & Gestão
Volume 6, Número 2, 2011, pp. 210-220
DOI: 10.7177/sg.2011.v6.n2.a9

The CSP under investigation is constituted by the following main components:

- linear parabolic trough-shaped mirrors to focus sun's rays onto a receiver pipe running along the focal line and containing a flowing fluid, named collectors;
- hydraulic circuit with molten salts that connects the field of reflectors and the storage system, including the control system for controlling the temperature of the salts and the devices for loading and unloading of the salts;
- pumping systems of the salts;
- storage system made of two tanks with a circular section;
- electrical power station equipped with two steam turbines (high and low pressure, respectively), a molten salt steam generator, a condenser with an appropriate cooling system (water or air) and the feed water preheating system.

The reflectors concentrates the sun's rays on the receiver and the heated fluid is transported to the energy conversion system. During this step a part of the fluid can be stored for a successive use. Then the remaining part is utilized to produce electrical energy. The energy conversion system is similar to a common fossil fuel plant utilizing a thermal steam Rankine cycle. Usually, a mineral oil is used but it is expensive and highly flammable, then it can lead to important problems if it leaks at the operating temperature (290°-390°C). For these reasons, it has been considered a fluid constituted by a mixture of salts, sodium and potassium nitrate; this fluid is largely used in the industry because chemically stable until 600°C and without corrosion problems. Moreover, the thermal storage allows to store the solar energy which can be used when the radiation is not present or limited (by night, in presence of clouds and so on). This is a very important task for each solar plant. In fact the unpredictability of the energy production is the main disadvantage of solar plants, which are usually used by the detractors of the solar energy plants. The thermal storage allows to decouple the collect of the thermal energy from the electrical energy production, i.e. it is not needed to produce and to use the electrical energy just when the thermal energy is collected. In this way it is possible to have a more efficient operation of the electrical generator eliminating the stops due to cloudiness and making the system more compatible with the demands of the electricity grid. Figure 2 reports a simplified scheme of the CSP. Three circuits are present:

1. primary loop, devoted to the harvesting, distribution and storage of the solar thermal energy;
2. secondary loop, where the thermal energy stored in the hot tank is utilized into the steam generator;
3. thermal cycle, where the thermal energy is transformed in the electrical one.

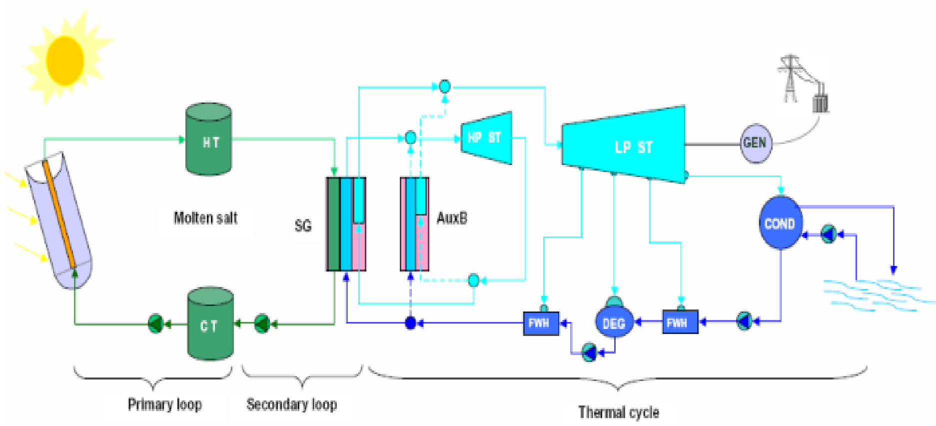

Figure 2 CSP under investigation

Revista Eletrônica Sistenas & Gestão
Volume 6, Número 2, 2011, pp. 210-220
DOI: 10.7177/sg.2011.v6.n2.a9

The operation principle of the CSP plant under investigation is the following.

When direct solar radiation is present, the thermal fluid, taken from the cold tank at the temperature of 290°C, flows into the receivers and heats up until 550 °C. Then, it is pumped in the hot tank where it is stored. The flow capacity of the molten salts into the primary circuit is adjusted with respect to the solar radiation in order to maintain constant the input temperature of the hot tank. As the molten salts have high temperature of solidification (238°C), it is needed to maintain a minimum flow capacity when the solar radiation is not present or to provide heating systems of the pipes in order to avoid that the fluid temperature falls below it.

When electrical energy is requested, the salts stored into the hot tank are pumped into the heat exchanger, where the steam at high pressure and temperature is produced. Then, the molten salts are collected into the cold tank. As already said, the thermal cycle is similar to a common fossil fuel power station. Two turbines for high and low pressure are present, while the superheated steam has temperature of 525 °C and pressure of 120 bar when it expands through the high pressure turbine. The electrical rated power of the CSP is 40MW, while the efficiency of the thermal cycle is equal to 42.3%.

An in depth analysis of the thermal performance of this CSP plant is reported in (VERGURA, DI FRONZO, 2012)

2.2.2 LAYOUT AND CHARACTERISTIC PARAMETERS OF THE CSP PLANT

Figure 3 reports the layout of the modeled CSP. It can be observed that the thermal power station (turbines, steam generator, condenser, tanks) is in central position while the solar field is constituted by 3 areas: 2 of them containing 33 Solar Collector Assembly (SCA) and the third one containing 70 SCA. The SCA are parallel-connected each other. Each SCA of each area is constituted by 6 series-connected collectors and each collector is 100m long and has a span of 5,76 m. Then, one SCA is 600m long while the distance between two SCA is equal to 2 times the span of a collector. Table 2 reports the main parameters of the CSP.

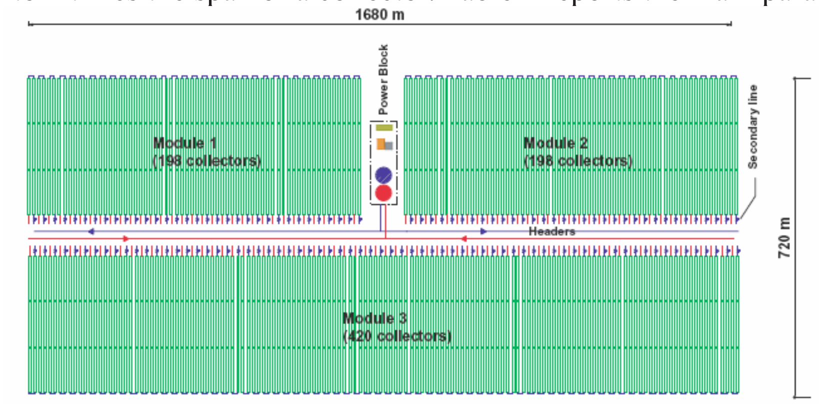

Figure 3 Layout of the CSP

3. COMPARISON BETWEEN PVPLANT AND CSP PLANT

In this section, the PV plant and the CSP plant are compared. The hypotheses are: a) the two plants have the same electrical rated power (40 MW); b) the two plants are installed in the same location, then they are under the same environmental conditions. The installation site is Bari, a city in the south of Italy.

3.1 PRODUCED ENERGY

The total energy produced by the PV plant is 56 GWh/year, while CSP plant produces 168 GWh/year. This great difference of the produced energy is due to the fact that CSP has the storage system constituted by the hot tank, which allows to produce the same amount of energy also when the radiation is low or inexistent. The storage system of CSP is its strength with respect to other renewable energy sources, which have the weakness of the unpredictability of the produced energy.

Revista Eletrônica Sistemas & Gestão
Volume 6, Número 2, 2011, pp. 210-220
DOI: 10.7177/sg.2011.v6.n2.a9

Table 2 – Parameters of the CSP

Number of the collectors	816
Area of each collector	3.317,76 m^2
Total collector area	45 x 10^4 m^2
Distance between collectors	11,5 m
Peak power of the solar field (with radiation of 900W/m^2 and efficiency of the collector equal to 0,79)	321 MWt
Solar field area	90 ha
Temperature of the hot tank	550 °C
Temperature of the cold tank	290 °C
Storage capacity	3.000 MWh
Rated electrical power	40 MWe
Thermo-electrical efficiency in rated electrical	0,423
Produced energy for year	168 GWh/year
Load factor (ratio between produced energy and energy obtained if the CSP works in the rated conditions during the whole year)	0,48
Mean collector efficiency for year (depending on the annual direct radiation)	0,67

3.2 INITIAL INVESTMENTS

Tables 3 and 4 report the initial investment for a PV plant and for a CSP plant, respectively. Comparing the total cost/unit (about 1.900,00 €/kWp for PV plant and about 3.450,00 €/kWe for CSP), it can be noted that, nowadays, CSP plant requires a higher initial investment than that necessary for a PV plant with the same rated power.

3.3 MAINTENANCE COSTS FOR 20 YEARS

Both the plants show degradation in the energy performance during the whole life-cycle; for both of them the degradation can be estimated in 0,5% to 1% for year. As CSP plant produces more energy than PV plant, this degradation has worse absolute economic effects for CSP plant than for PV plant. For PV plant the ordinary maintenance costs are equal to 1% of the initial investment for each year, then around 750 k€ per year, while, for CSP plant, the annual maintenance costs are equal to 2%, due to the major complexity of the plant, then the yearly maintenance costs are around 2.600 k€.

Revista Eletrônica Sistenas & Gestão
Volume 6, Número 2, 2011, pp. 210-220
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Table 3 – Initial investments for PV plant

PV plant				
Rated power	40.000	KWe		
	Costs/unit		Units	Total Cost (€)
PV modules	1,20	€/Wp	40.000.000	48.000.000,00
Inverters	151,00	€/kWp	40.000,00	6.040.000,00
Cabin MV/LV	150.000,00	€/cabin	8,00	1.200.000,00
Cabin HV/LV	180.000,00	€/cabin	1,00	180.000,00
Other electrical components	179,00	€/kWp	40.000,00	7.160.000,00
Other (design cost, purchase of the land)	162,00	€/kWp	40.000,00	6.480.000,00
Taxes (in %)				10.00%
Taxes (in €)				6.906.000,00
TOTAL				75.966.000,00
Cost/unit		€/kWe		1.899,15

Table 4 – Initial investments for CSP plant

CSP plant			
Rated power	40.000	KWe	
	Cost/unit		Total Costs (€)
SCA	97,20	€/m^2	47.727.968,26
Hot and cold tanks	8,70	€/kWh_t	26.100.000,00
Hp and Lp turbines	650,00	€/KWe	26.000.000,00
Steam generator	124,00	€/kWh_e	4.960.000,00
Other (design cost, purchase of the land)	270,00	€/kWh_e	10.800.000,00
Other thermal and electrical components	248,76	€/kWh_e	9.950.538,66
Taxes (in %)			10.00%
Taxes (in €)			12.553.850,69
TOTAL			138.092.357,61
Cost/unit		€/kWe	3.452,31

3.4 ECONOMIC RETURNS: GOVERNMENT INCENTIVES AND SELLING OF THE PRODUCED ENERGY

Power generation from renewable sources includes the use of recent technologies, and then projects become very expensive. Therefore, governments need to create economic incentives to enable the development of new power generation plants. Sometimes the incentives are linked to the initial investments as co-financing,

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Revista Eletrônica Sistemas & Gestão
Volume 6, Número 2, 2011, pp. 210-220
DOI: 10.7177/sg.2011.v6.n2.a9

whereas other times they are linked to the produced energy. This last solution is more interesting because it encourages the plant manager to manage the plant optimally. Usually two typologies of economic benefits can be available: government one related to the energy production (feed-in tariffs) and commercial one related to the selling of the produced energy to the local energy utility company.

As example, Table 5 reports the economic comparison as stated by the Italian law. In Italy, economic incentives for CSP plant and PV plant are regulated by two different laws. It can be noted that the total economic incentive for the CSP plant is equal to three times that related to the PV plant with the same rated power. Moreover, the incentive for the PV plant is limited to 20 years, while the incentive for the CSP plant continues until 25 years. Then larger initial investments of the CSP plant (Table 4) are annually compensated with larger total incentives.

Table 5 – Economic returns for CSP and PV plants

	PV	CSP
Rated power (MW)	40.000	40.000
Equivalent yearly operation hours (h)	1.400	4.200
Yearly produced Energy (MWh)	56.000	168.000
Feed-in Tariff (€/MWh)	240	270
Total Period of feed-in tariff (years)	20	25
Yearly government incentive (€) (A)	13.440.000	45.360.000
Yearly selling of the produced Energy (€) (B)	5.040.000	15.120.000
Yearly total incentive (A+B)	18.480.000	60.480.000

3.5 FINANCIAL PARAMETERS

The aim of this section is to evaluate the Internal Rate of Return (I.R.R.) and the Net Present Value (N.P.V.) of the PV and CSP plants considering a rate of 9% of return per year, considering that inflation is around 3% per year, and that the risk free rate is around 1,5% per year.

To calculate the I.R.R. and the N.P.V. it was necessary to estimate the residual value of the PV and CSP plants. The estimations have been made using the depreciation of 1% per year in the 20 years. So, the residual values has been 80% of the initial investment.

The annual flow, along the total period of 20 years, is the difference between the government incentives and the costs of maintenance. This flow is responsible to turn these projects financially viable. The following Tables 7 and 8 show the I.R.R. and N.P.V. for PV and CSP plants.

Revista Eletrônica Sistenas & Gestão
Volume 6, Número 2, 2011, pp. 210-220
DOI: 10.7177/sg.2011.v6.n2.a9

Table 7: Values for PV plant

(-) Initial investments	€ 75.966.000,00
(+) Annual government incentive	€ 18.480.000,00
(-) Annual costs of maintenance	€ 750.000,00
(+) Residual value of a PV plant at the end of the 20th year	€ 60.772.800,00
Internal Rate of Return	23,21 % per year
Net Present Value of the PV plant (with a rate of 9% in a year)	€ 96.726.859,50

Table 8: Values for CSP plant

(-) Initial investments	€ 138.092.357,61
(+) Annual government incentive	€ 60.480.000,00
(-) Annual costs of maintenance	€ 2.600.000,00
(+) Residual value of a CSP plant at the end of the 20th year	€ 110.475.886,10
Internal Rate of Return	41,88 % per year
Net Present Value of the CSP plant (with a rate of 9% in a year)	€ 409.980.176,40

4. CONCLUSIONS

The paper has proposed a technical-economic comparison between two solar technologies: photovoltaic one and concentrating one. It results that, for the same rated power and under the same environmental conditions, CSP plant produces more energy than PV plant. This implies that the economic return of CSP is greater. Moreover, the area occupied by CSP plant is smaller than that occupied by PV plant. Nevertheless, the initial investment to install the CSP plant is very higher than that needed to make the PV plant as well as the ordinary maintenance costs. As usual, there are advantages and disadvantages for each technology. Then, it is not possible to say a-priori that one technology is better than the other one. This paper has highlighted some of the main issues that is needed to take into account before to decide which solar technology is the better one for a specific case.

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