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Article

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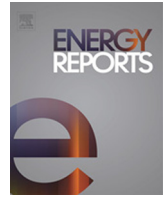
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Performance analysis and investigation of a grid-connected photovoltaic installation in Morocco



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ABSTRACT

The paper present an evaluation of a grid-connected photovoltaic (PV) system installed on the roof of a government building located in Tangier, Morocco. The experimental data was recorded from 1st January 2015 to December 2015 based on real time observation. The aim is to encourage the use of solar PV system for government, commercial and residence building in Morocco based on the obtained results. The system is made up of 20 modules of 250 Wp and one inverter of 5 kW. The assessed parameters of the PV installation includes energy output, final yield, modules temperature, efficiency module, performance ratio (PR) and others. The PV park supplied the grid with 6411.3 kWh during the year 2015. The final yield (Yf) ranged from 1.96 to 6.42 kWh/kWp, the performance ratio (PR) ranged from 58% to 98% and the annual capacity factor was found to be 14.84%. The final yield of PV installation is compared with other final yields of solar PV systems located at other places. Finally various power losses are given through a diagram loss.

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1. Introduction

The electricity generation in Morocco is largely based on fossil fuels such as oil, gas and coal, about 7.994 GW in 2014, of which 32% is based on renewable energy, Morocco's solar energy potential is vast, as the number of sunshine hours is very important, approximately 300 days/year. The average annual value of global solar radiation in Morocco is 2600 kWh/m²/year, which is of great importance in order to support the investor's expectations for system performance and the associated economic return. It is clear that PV solar energy will become one of the major future sources of electricity generation in Morocco considering climatic conditions and solar potential. Solar energy, PV in particular, is one of the important projects in Morocco, growing to become a leader in renewable energies. Therefore, Morocco already showed a clear strategy to achieve it by fixing 42% of produced electricity based on renewable energy. PVs represent a large part with a capacity of 2.000 megawatts in five major sites: Ouarzazate, Ain Bni Mathar, Fom Al Oued, Boujdour and Sebkhath Tah. Besides, wind energy 2000 megawatts by 2020, a scheduled electric Production driven

from renewable energy of 52% in 2030, which by this strategy Morocco will contribute to the reduction of the reliance on energy, environmental preservation through the limitation of greenhouse gases and the climate change 2015. The performance of a grid connected PV system depends more on technology cells, inverters and installation configuration than on the weather parameters as global irradiance, ambient temperature and soiling losses. Shukla et al. (2016a) analyzed the performance of a solar PV system and compared the performances of different PV technologies based on simulated energy. Saeed et al. (2015) compared the experimental behavior of these two common PV module technologies (m-Si and p-Si). Different studies have been conducted on the performance parameters of installed PV power plants in different geographical locations and different climatic conditions (Padmavathi and Daniel, 2013). Pioneering research in the field of Solar thermal, Solar PV and Solar radiation modeling has been carried out by various researches (Yadav and Sudhakar, 2015; Shukla et al., 2015a-b; Shukla et al., 2016b). The present paper's purpose is to determine results obtained from the monitoring of a PV installation in Tangier, Morocco during a period of one year, starting from January 2015 to December 2015. The PV system is characterized with different performance parameters including: Reference yield, ambient temperature, final yield, system losses, capacity factor and performance ratio then to offer baseline information for energy and economic evaluation of the polycrystalline PV produced electricity.

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Table 1
PV modules specifications.

PV module	Specifications
STC power rating	250 Wp
Peak efficiency	15.2%
Number of cells	60
V _{mp}	31.4 V
I _{sc}	8.77 A
I _{mp}	7.97 A
V _{oc}	37.5 V
Maximum system voltage	600 V

2. Description of photovoltaic installation

The PV power plant was installed on the rooftop of a state building in Tangier, Morocco. The grid connected park consists of 20 polycrystalline silicon solar modules 250 Wp each one and comprised 60 solar cells with an overall installed capacity of 5 kWp, covering a total surface area of 30 m² and inclined at 32° toward the south. The PV modules are arranged in 2 parallel strings, with 10 modules in each string and connected to a 5000 W Sunny Boy SB5000TL inverter feeding directly into the grid. Its efficiency is 96% in the worst case conditions. At the outlet of the inverter there is a single phase alternating voltage of 230 V, 50 Hz and at the front there is a display to read out the voltage and DC current values, output power, daily and total amounts of electrical energy generated by the solar PV modules. Fig. 1 shows a schematic block circuit diagram of the PV system. Technical data of the PV module are given in Table 1.

3. PV power plant characteristic parameters

The final yield (Y_f), array yield (Y_a), reference yield (Y_r), energy efficiency (η), and the total energy generated by the PV system E_{AC}, were used in accordance with the IEC 61724 standard to evaluate the performance of a grid connected PV installation.

Array yield

The array yield (Y_a) is the ratio of the energy output delivered by the PV modules over a defined period by the PV rated power and is given as (Sharma and Chandel, 2013):

$$Y_a = \frac{E_{DC}}{P_{PV, \text{rated}}} \quad (1)$$

The daily array yield (Y_{a,d}) and the monthly average array yield (Y_{a,m}) are given as (Ayompe et al., 2011):

$$Y_{a,d} = \frac{E_{DC,d}}{P_{PV, \text{rated}}} \quad (2)$$

$$Y_{a,m} = \frac{1}{N} \sum_{d=1}^N Y_{a,d} \quad (3)$$

where E_{DC} is the DC energy output delivered by the PV modules (kWh).

Final yield

The final yield can be defined as the total AC energy during a specific period divided by the rated power of the installation. It is an important parameter for our system performance comparison with other existing PV systems. The final yield is given as (Al-Otaibi, 2015; Kymakis et al., 2009; Mondol et al., 2005)

$$Y_{f,d} = \frac{E_{AC}}{P_{pv, \text{rated}}} \quad (4)$$

$$Y_{f,m} = \frac{1}{N} \sum_{d=1}^N E_{AC,d} \quad (5)$$

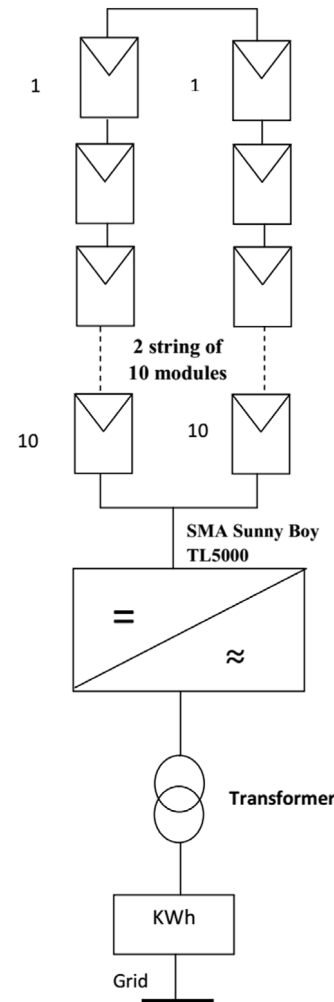


Fig. 1. Schematic block circuit diagram of the PV system.

where E_{AC} is the energy at the output of the PV installation inverter and is given by (Ayompe et al., 2011)

$$E_{AC,m} = \sum_{d=1}^N E_{AC,d} \quad (6)$$

With E_{AC,m} being the monthly AC energy output and N the number of days in a month.

Reference yield

The reference yield is the ratio of the global solar radiation H_t (kWh/m²) and the PV's reference irradiance. The reference yield is given as (Kymakis et al., 2009):

$$Y_r = \frac{H_t (\text{kWh/m}^2)}{H_R} \quad (7)$$

where, H_R = 1 kW/m².

Performance ratio

The performance ratio (PR) is depending on the total losses in the system resulting from conversion operations made by different components as PV modules, inverters and cables. Weather conditions as ambient temperature are also impacting factors.

The performance ratio (PR) can be defined as the final yield divided by the reference yield and is given as (Shiva kumar and Sudhakar, 2015; Chaivant et al., 2009):

$$PR = \frac{Y_f}{Y_r}$$

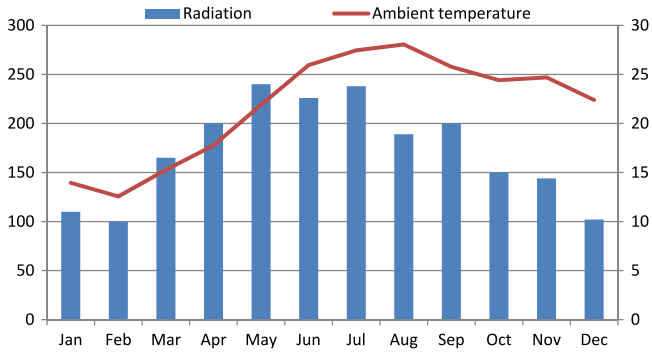


Fig. 2. Global solar radiation in (kWh/m²), at the angle of 32° and ambient temperature.

Array capture losses

Array capture losses (L_C) are due to the PV array losses and are given as (Ayompe et al., 2011)

$$L_C = Y_r - Y_a \tag{8}$$

System losses

The system losses (L_S) are caused by the inverter losses (Ayompe et al., 2011).

$$L_S = Y_a - Y_f \tag{9}$$

Capacity factor

The capacity factor (C_f) during a specific period is the AC energy produced by the PV system divided by the AC energy that can be generated if the system operated with its nominal power during that same period. The annual capacity factor is given as (Kymakis et al., 2009)

$$C_f = \frac{E_{AC}}{P_{PV, rated} * 8760} \tag{10}$$

System efficiencies

Main groups of PV system efficiencies are: PV module efficiency, inverter efficiency and system efficiency. The PV module efficiency is calculated as (Adaramola and Vagnes, 2015)

$$\eta_{PV} = \frac{100 * E_{DC}}{H_t * S} (\%) \tag{11}$$

The monthly PV module efficiency ($\eta_{PV,m}$) is calculated as (Filippo and Fabio, 2013; Chaiyant et al., 2009)

$$\eta_{PV,m} = \frac{\sum_{i=1}^n E_{DC}}{S * \sum_{i=1}^n H_t} \tag{12}$$

where E_{DC} is a total energy produced by the solar PV modules, n is the number of days in a month and S (m²) the total area occupied by the PV modules. The inverter efficiency is given as (Adaramola and Vagnes, 2015)

$$\eta_{inv} = \frac{100 * E_{AC}}{E_{DC}} (\%) \tag{13}$$

The temperature losses coefficient (η_{tem}) is given as (Suresh et al., 2014; Kymakis et al., 2009):

$$\eta_{tem} = 1 + \beta * (T_c - 25) \tag{14}$$

where (T_c) is the PV cell temperature, (T_a) is the air temperature and β is the temperature factor of the PV module.

$$T_c = T_a + \frac{P}{800} (T_{NOCT} - 20) \tag{15}$$

where P is the power density at a specific time and T_{NOCT} is the normal operating cell temperature.

4. Results and discussion

In this section, data from a 5 kWp PV installation located on the CCIS building in Tangier are analyzed based on meteorological and characteristic performance parameters for a one year period, from January 2015 to December 2015. The photovoltaic system used for this study is installed in a state building (Chambre de commerce d’industrie et de services (CCIS)) in Tangier with a latitude 35.7595°N and longitude 5.8340°W and about 49 m above sea level in Northern Morocco. A pyranometer and temperature sensors constitute the monitoring equipment of the grid connected PV system, data of the meteorological parameters including global solar radiation and global solar energy, ambient temperature and PV module temperature are recorded on 5 min intervals. The global solar irradiance data was recorded on an hourly, daily and monthly basis for twelve-month period, from January, 1st 2015 until December, 30th 2015 and constitute the basis of this analysis. The global solar energy (Ht) per one square meter at an angle of 32° to the horizontal plan is shown in Fig. 2, the monitored solar irradiance and power data are shown in Fig. 3.

The monthly average module (η_m), system (η_{sys}) and inverter (η_{inv}) efficiencies results are shown in Table 2. Those values vary from 11.80% in September to 13.22% in February for modules efficiency, 11.41% in September to 12.93% in February for system efficiency and from 96.7% in February to 96.8% in December for inverter efficiency. The average module conversion efficiency (η_m) is 12.39%. The monthly Performance ratio Eq. (7) as shown in (Table 3) vary from 58% in December to 98% in January. The PR of other monitored PV systems include: Thailand ranged from 70% to 90% (Chokmaviroja et al., 2006), Germany from 37.8% to 88.3%

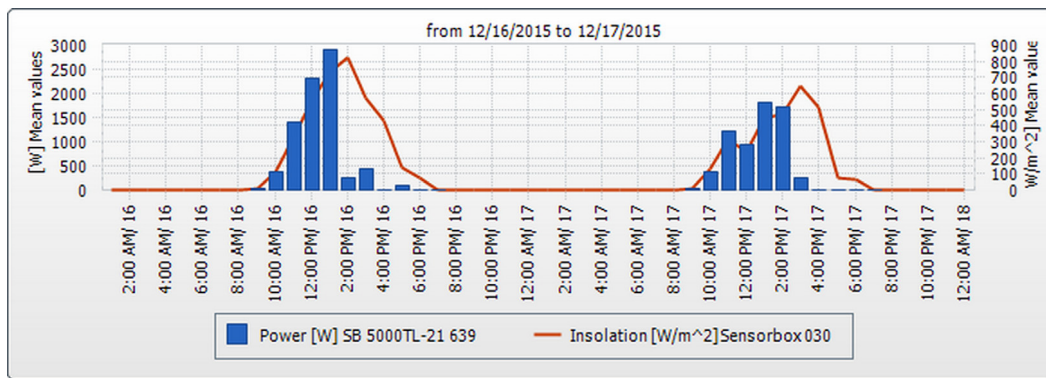
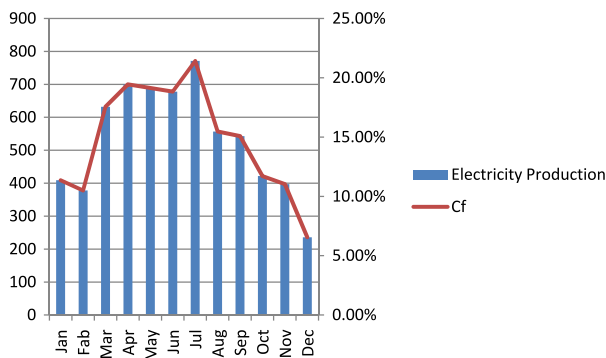
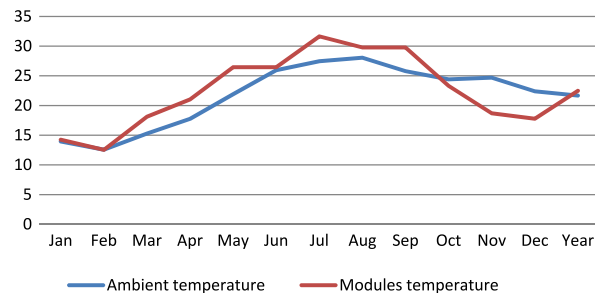


Fig. 3. Hourly average power and irradiance over 2 days.

Table 2

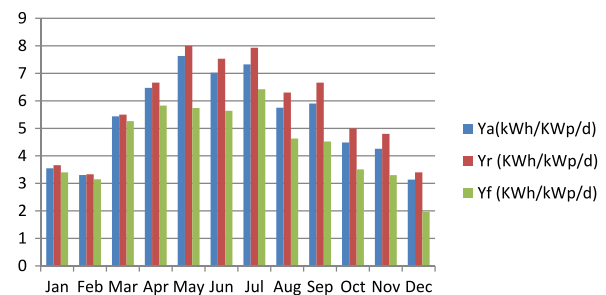
Energy output, ambient temperature, module efficiency, system efficiency, inverter efficiency, performance ratio and capacity factor over the monitored period.

Months	Ambient temperature (°C)	Electricity (kWh)	Modules efficiency η_m (%)	System efficiency η_{sys} (%)	Inverter efficiency η_{inv} (%)	Performance ratio (PR)	Capacity factor (%)
January	13.90	409	12.90	12.40	96.8	98%	11.36
February	12.60	378	13.22	12.93	96.7	95%	10.5
March	15.30	632	13.18	12.75	96.8	96%	17.56
April	17.80	700	12.94	12.51	96.6	88%	19.44
May	21.90	689	12.72	12.30	96.7	72%	19.14
June	25.90	678	12.43	12.02	96.7	75%	18.83
July	27.50	771	12.31	11.90	96.7	81%	21.42
August	28.10	556.76	12.17	11.77	96.7	74%	15.47
September	25.80	542.94	11.80	11.41	96.7	68%	15.08
October	24.40	421.61	11.96	11.56	96.7	70%	11.71
November	24.70	397.12	11.83	11.44	96.8	69%	11.03
December	22.40	235.87	12.30	11.90	96.8	58%	6.55
Year	21.74	6411.3	12.39	12.00	96.7	79%	14.84

**Fig. 4.** The total monthly electricity production in CCIS building during 2015 in (kWh) and capacity factor.**Fig. 5.** Monthly average hourly ambient air and PV module temperature measured during 2015.

(Jahn and Nasse, 2004) and Poland from 50% to 80% (Pietruszko and Gradzki, 2004). The monthly average capacity factor calculated using Eq. (10) is high for July amounting to 21.42% and is less for December amounting to 6.55% with an annual average of 14.84%, this value can be explained as the period of time during a year when the PV system is generating energy at its full power output, as a result the PV system is able to produce full power energy in about 55 days in a year. As an example, the average CF of a typical plant in Norway is 10.58% (Adaramola and Vagnes, 2015), in India is 15.69% (Padmavathi and Daniel, 2013), in Malaysia is 32% (Effendy et al., 2014) and in Serbia is 12.88% (Dragana and Tomislav, 2015).

The monthly average daily PV system's final, array and reference yields over the monitored period are shown in Fig. 6. The monthly average daily final, array and reference yields varied between 1.96 kWh/kWp/day in December, 6.42 kWh/kWp/day in July, 3.13 kWh/kWp/day in December, 7.63 kWh/kWp/day in May, 3.33 kWh/kWp/day in February and 8 kWh/kWp/day in May respectively. The yields values noticed for the months of December and February are low because of the low irradiation in

**Fig. 6.** The variation of the monthly average daily yields.

those months as shown in Fig. 2. Also the reduced sun hours in this period of time is a contributing factor.

July and May are the months with the highest energy output compared to June as shown in Fig. 4, with May having a close level of irradiance to July (Fig. 2), this is due to the combination of the high irradiance with lower temperature compared to the previous months. The overall average temperature is given by 22.4 °C, while the average ambient temperature per month varied between 12.56 °C in February and 28.05 °C in August. The modules temperatures ranges from 12.53 °C in February to 31.65 °C in July given form Fig. 5.

The monthly total energy generated by the PV system over the monitored period as shown in Fig. 4 varied between 235.87 kWh in December and 771 kWh in July. The energy outputs for the months of December, February, November, January, October and August are low, particularly on December, the energy output from this period was affected by the reduced number of sun hours due to the amount of cloudy days in this period of the year, in addition to high temperatures in August as shown in Fig. 5 and probably soiling losses due to the dust cover during the summer period and absence of preventive maintenance. Also climate changes and drought are possible reasons in 2015 year.

A comparison of available data from some publications about this subject is presented in Fig. 7. The annual average daily final yield of other monitored PV systems previously reported: India, 3.8 kWh/kWp/day (Padmavathi and Daniel, 2013), Germany, 1.8 kWh/kWp/day (Jahn and Nasse, 2004), Japan, 2.7 kWh/kWp/day (Jahn and Nasse, 2004), Ireland, 2.4 kWh/kWp/day (Ayompe et al., 2011), Norway, 2.55 kWh/kWp/day (Adaramola and Vagnes, 2015), Spain, 3.8 kWh/kWp/day (Sidrach and Mora, 1999) Oman, 5.1 kWh/kWp/day (Kazem et al., 2014) and in Kuwait, 4.5 kWh/kWp/day (Al-Otaibi, 2015). In the present study based in Morocco the annual final yield is 4.45 kWh/kWp/day. This trend is according to expectation due to the high solar potential and more sunshine hours duration in Morocco. The final yield of the CCIS PV system is reported to be close to the Kuwait's PV system final yield, lower to Oman's final yield and higher than the others.

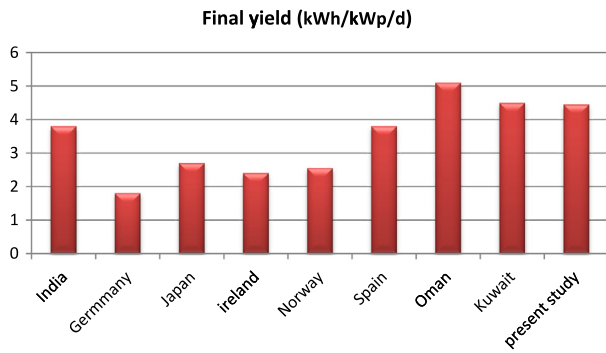


Fig. 7. Comparison of final yield in several sites.

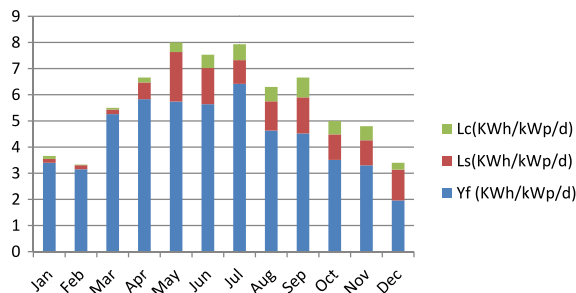


Fig. 8. Installation final yield and corresponding capture and system losses per month.

Table 3
The inverter losses over the monitored period.

Months	Inverter loss (kWh)
January	31.55
February	19.07
March	24.95
April	25.39
May	26.58
June	27.11
July	28.37
August	30.24
September	35.29
October	35.60
November	34.29
December	29.76
Year	348.2

The monthly average daily final yield Eq. (5), capture and system losses over the monitored period as shown in Fig. 8. The system losses varied between 0.14 kWh/kWp in January and 1.89 kWh/kWp in May. The capture losses ranged from 0.025 kWh/kWp in February to 0.76 kWh/kWp in September. Important losses can be observed in summer period due to the soiling, dust and absence of scheduled maintenance during this period.

The temperature losses coefficients were calculated using Eq. (15), the annual losses were summed to 7.23%. The PV modules under continuous operation become covered with a layer of speck and dust, the power loss due to the soiling (η_{soil}) depends on the amount of rainfall, geographical region and local environment type. The monthly coefficients were empirically estimated based on the model of soiling related PV system study (Kimber et al., 2006). The soiling losses were 4%–5% during the winter and 6%–20% during the summer period, resulting in annual losses at 8.75%. The PV degradation losses can reach 5% with a lifetime of 20 year warranty (Dunlop, 2003). The conversion losses were calculated by subtracting the array DC output power from the AC output power and by normalizing the DC wiring and interconnection losses, results are equal to 16%. The availability and grid connection

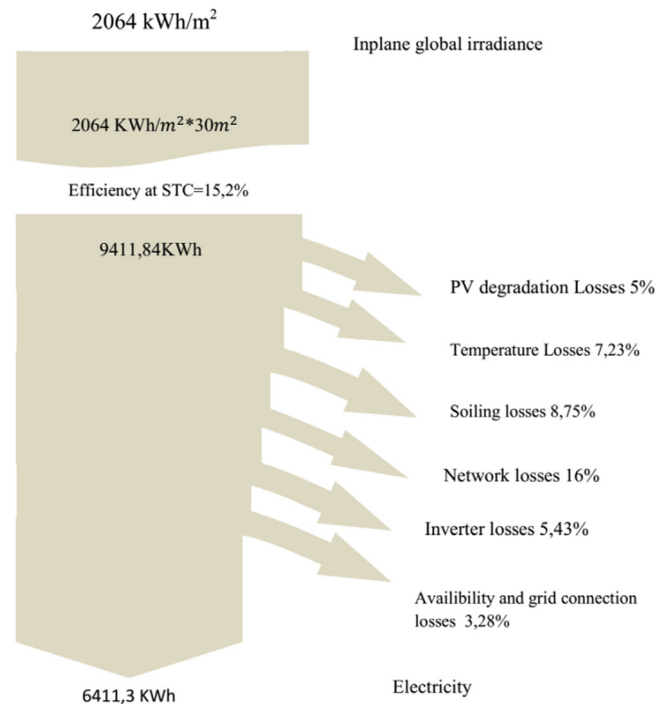


Fig. 9. Diagram of estimated losses in the PV system.

losses can be calculated as the grid off periods divided by the grid on period, results are equal to 3.28%. The calculated losses with inverter losses are equal to 5.43% (Table 3). The various annual losses of the PV system can be summarized in Fig. 9.

5. Conclusion

In this paper a 5 kWp grid connected PV system in the CCIS building in Tangier, Morocco has been monitored along the year 2015 and its performance was assessed on a daily basis, as a conclusion the following results are obtained:

- The total annual electricity delivered to the grid was found to be 6411.3 kWh.
- The annual average final yield was compared with other systems installed in different locations world-wide, its value was found 4.45 kWh/ kWp and the average annual performance ratio of the installation was found 79%.
- The average annual capacity factor was found 14.83%.
- The annual average module, system and inverter efficiencies were: 12.39%, 11.99% and 96.7% respectively. Compared to other results from other publications, the PV system has higher average daily final yield.
- The electricity generated by PV systems can be used to power, air conditioning, lighting and other electrical appliances of the state building.
- A losses diagram is detailed for more evaluation precision. Further studies can be made to develop preventive actions to increase efficiency by reducing losses.

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