SOLAR PV INTEGRATION INTO THE GRID: A TECHNO-ECONOMIC ANALYSIS IN THREE CLIMATE ZONES OF BURKINA FASO

Sami Florent Palm[1], Sebastian Waita[1], Thomas Nyangonda[1] and Ahmed Chebak[2]

[1] Condensed Matter Research Group, Department of Physics, University of Nairobi, Nairobi, Kenya

[2] Green Tech Institute, Mohammed VI Polytechnic University, Benguerir, Morocco

Abstract

Grid-Connected Solar Photovoltaic Systems (GCSPS) have emerged as effective means of decarbonizing the electricity sector and hastening the energy transition. The goal of this study is to investigate the feasibility of installing GCSPS in Burkina Faso's three climate zones, which are the Sahelian zone represented by Dori, the Sudan-Sahelian zone represented by Ouagadougou (Ouaga), and the Sudanese zone represented by Bobo-Dioulasso (Bobo). This study was carried out using the PV Syst software for design and Python for modelling the economic aspects of a 50MW GCPS in each climatic zone. The obtained results allowed for the comparison of annual production, Levelized Cost of Energy (LCOE), Net Present Value (NPV), Internal Rate of Return (IRR) and Pay Back Period (PBP). These comparisons show that the GCPS from Dori is more economically viable than those of Ouaga and Bobo-Dioulasso. This study will provide policymakers and private investors with information about the potential for investment in the installation of GCPS in the Sahel regions.

Keywords: Solar photovoltaic, Grid-connected, Techno-economic, Burkina Faso

1. Introduction

The combined effects of climate change, COVID19, and the Ukrainian crisis have significantly increased the cost of energy around the world (IRENA, 2022). Despite the various crises, the development of renewable energies, particularly solar Photovoltaic (PV), has continued to grow. For example, the world's installed solar PV capacity increased from 855162 MW in 2021 to 1046614 MW in 2022; a 22.4 % increase (Renewable Energy Agency, 2023).Thus, solar PV continues to be essential for accelerating the energy transition.

Burkina Faso, located in the heart of West Africa, continues to face significant challenges in increasing access to electricity in order to boost economic growth. Burkina Faso is the second most expensive ECOWAS country in terms of electricity costs after Guinea-Bissau (Moner-Girona et al., 2017) despite the country being well endowed with significant solar potential(Global, 2020). According to the 2020 National Electricity Society report, the Burkina Faso national grid's energy mix consists of only 3% solar PV injection, with thermal energy production based on fossil fuels accounting for more than half of national energy production(SONABEL, 2020). The contribution of mix energy in Burkina Faso in 2020 is depicted in Figure 1 below.

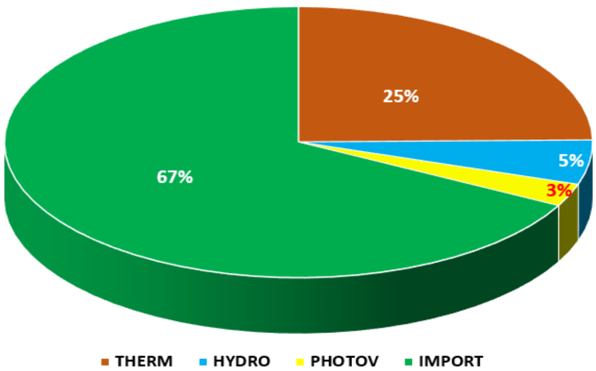

Fig. 1:Energy distribution in Burkina Faso in 2020 [5]

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Techno-economic assessment of Energy system is one of the best ways to know the benefit of a solar PV system. Various researchers around the world have tried to carry out solar PV studies using different approaches. Kazem et al., (2017) used numerical simulation to conduct a technical-economic feasibility study of a 1MW grid-connected PV power plant in Adam City, Oman, and discovered that the appropriate inverter size is 800kWh with 250Wp PV modules. The cost of producing electricity is $0.2258/kWh, with a 10-year payback period. These findings indicate that the construction of a 10MW PV plant in Adam is feasible. Garni & Awasthi, (2017) investigated the techno-economic feasibility of a grid-connected PV system with different tracking using HOMER in Saudi Arabia's Makkah region. Solar irradiation, ambient temperature, load profile, and electricity cost were all used in this study. This study found that optimal tracking significantly lowers the cost of electricity in this area, so tilting and orienting the PV modules at specific times could make grid-connected PV energy production more profitable. Liet al., (2018) used HOMER software to conduct an objective analysis of the technical-economic feasibility study of grid-connected PV systems in five Chinese climatic zones: Beijing, Harbin, Shanghai, Guangzhou, and Kunming. According to the findings of this study, grid-connected PV systems in these five zones are economically, technically, and environmentally feasible. Using the HOMER software, Das et al., (2021) investigated the technical-economical and environmental feasibility of a stand-alone and grid-connected hybrid system in five climatic zones of Bangladesh. HOMER software was used by Mohand Kaci et al., (2022) to assess the technical and economic feasibility of two different PV system configurations (grid/PV and grid/PV/battery) in five different areas of Algeria. The grid/PV system was the most feasible, according to the findings. Battery cost subsidization and the development of a regional pricing system should aid in the effective implementation of the grid/PV/battery system.. Mohamed& Maghrabie, (2022) used the Feed-in-Tariff (FIT) mechanism to carry out a technical and financial feasibility study of the 1600 MW Benban solar park in Egypt. The findings revealed a 12% interest rate with a 10.1-year payback period. The advantages of implementing the FIT are amply supported by this study. Boddapati et al., (2021) have carried out a technical and economic study of a 50MW PV power plant in India, taking into account the effect of power evacuation curtailment, using measured data and simulation using PVsyst software. This study showed firstly that the measured results and the simulated results were very close, and secondly that the payback period of the PV power plant increased with the effect of power evacuation curtailment. The results obtained differ depending on the specificity of each zone. Nonetheless, the grid-connected hybrid system configuration produces the best results in each climatic zone. Ouedraogo & Yamegueu, (2019) evaluated the integration of solar PV into the Burkina Faso electricity grid using the Levelized Cost of Energy (LCOE) technique based on the estimated capacity of electricity consumption. According to the findings of this study, injecting large amounts of PV energy into Burkina Faso's electricity grid was both economically and environmentally feasible. Burkina Faso's electricity costs would be reduced as a result. This study did not consider the technical aspects of integrating PV energy into the power grid.

Until now, not much work has been done on the techno-economic feasibility study of grid-connected PV power plants in different climatic zones of Burkina Faso using actual site data. This paper will focus on the techno-economic analysis of PV integration into the grid in different climatic zones of Burkina Faso, a comparison study that we have not come across evidence that it has been done for the three zones. The rest of this paper is divided in four parts. First, the study area; then the methodology, Results and discussions and conclusion.

2. Methodology

2.1 The three climatic zones of Burkina Faso

Burkina Faso is composed of three different climatic zones: the sudanese zone in the south, the sudano-sahelian zone at the centre and the sahelian zone in the north. Figure 2 shows these different climatic zone. For this study, the cities of Bobo-Dioulasso, Ouagadougou and Dori were used to represent these three climatic zones respectively.

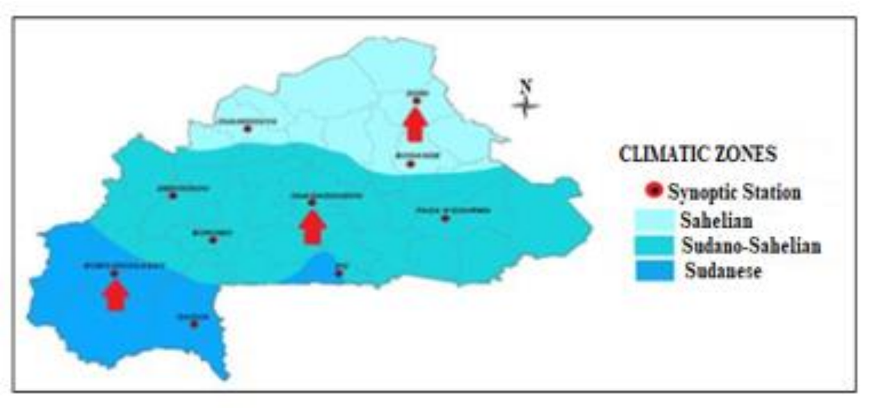

Fig. 2:Burkina Faso Climatic zones(Sanou et al., 2023)

2.2 Meteorological parameters

Data on insolation, ambient temperature, wind speed and humidity was collected at the Agence Nationale de la Meteorologie (ANAM) of Burkina Faso for the period of 2010 to 2020.

Figure 3 depicts the monthly variation of daily insolation for the cities of Ouaga, Bobo, and Dori from 2010 to 2020, with a general insolation value greater than 5h for these three regions. The lowest values are observed in August due to the very cloudy skies during this time of year, while the highest values are obtained in November-January, and this is attributed to a much clearer sky. It is also observed that insolation is more in Dori, then Ouaga, and finally Bobo in that order.

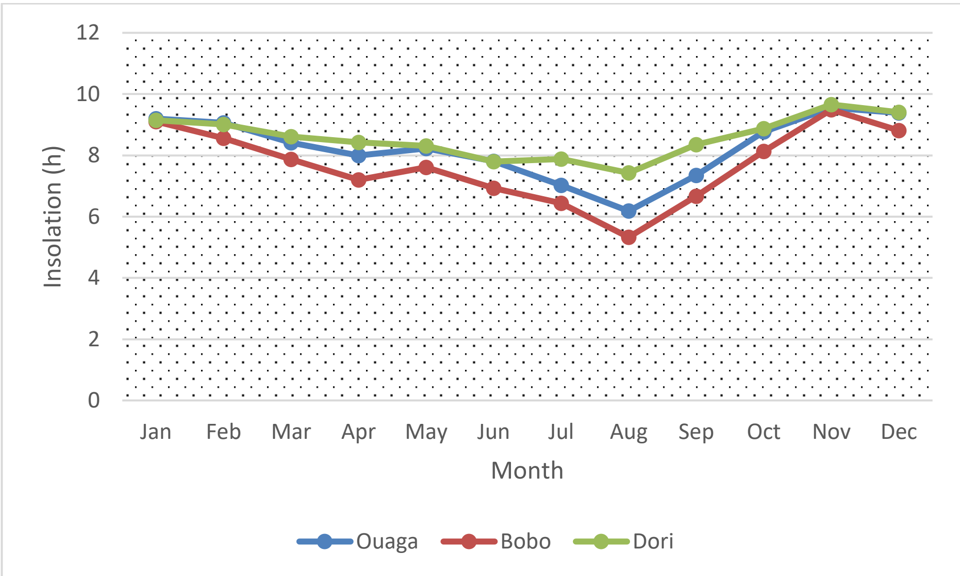

Fig. 3:Monthly Insolation(ANAM Burkina Faso, 2021)

Figure 4 depicts the monthly evolution of the daily temperature in Ouaga, Bobo, and Dori from 2010 to 2020. These curves clearly show that the average temperature in each of these three regions is above 24 degrees Celsius. Dori is warmer than the other two cities, with minimum temperatures in January and August in Ouaga and Bobo, and maximum temperatures in April and May in Ouaga and Bobo, respectively. High temperatures during these months have a negative impact on the yield of solar photovoltaic plants.

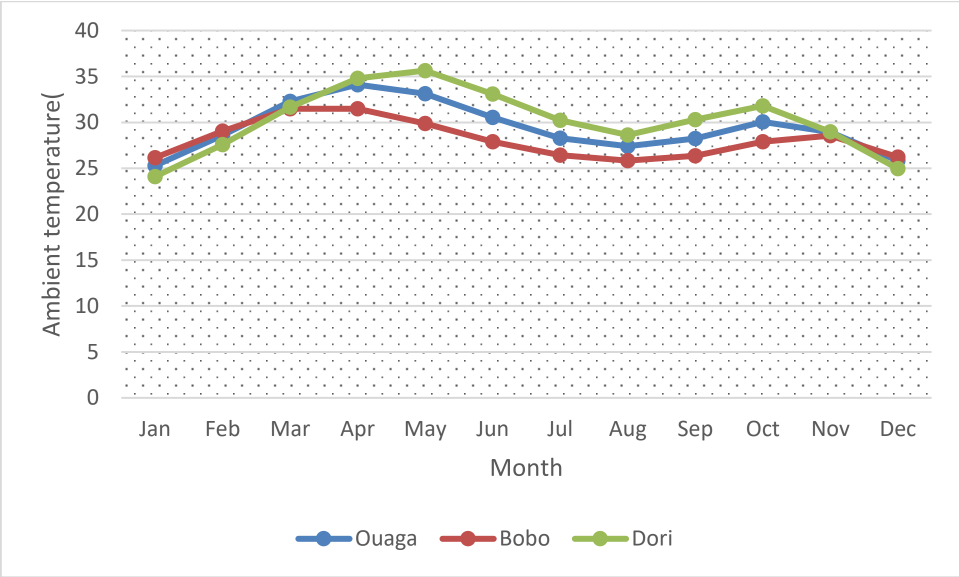

Fig. 4:Monthly Ambient temperature(ANAM Burkina Faso, 2021)

Figure 5 shows the monthly behavior of the daily wind speed from 2010 to 2020, which is clearly less than 5 m/s. This explains why wind speeds are lower in these three areas. Nonetheless, wind speeds in Bobo are higher than in the other two cities, Ouagadougou, and Dori, with average wind speeds ranging from 1.88 m/s in November to 3.22 m/s in May in Ouagadougou, 2.88 m/s in October to 4.7 m/s in February in Bobo, and a minimum of 0.7 m/s in November to 0.7 m/s in February in Dori. In general, wind speed varies continuously throughout the measurement period. Low wind speeds will have less of an impact on solar PV systems in Burkina Faso, but given their variability, the impact may be noticeable at times when instantaneous wind speeds are very high Putting dust on solar PV modules.

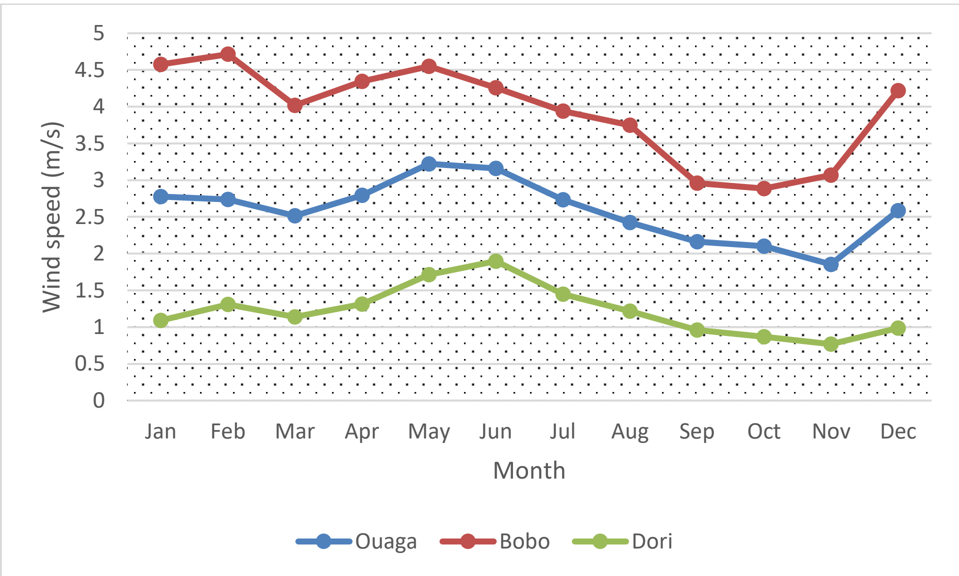

Fig. 5:Monthly wind speed(ANAM Burkina Faso, 2021)

Figure 6 represents the monthly evolution of daily relative humidity for Ouaga, Bobo, and Dori, displaying a bell-shaped curve with high relative humidity values observed from June to October. Between February and March, the minimums are around 20%, and the maximums are around 80% in August. Humidity is a factor that affects the efficiency of a solar PV system by dropping the power output (Mekhilef et al., 2012).

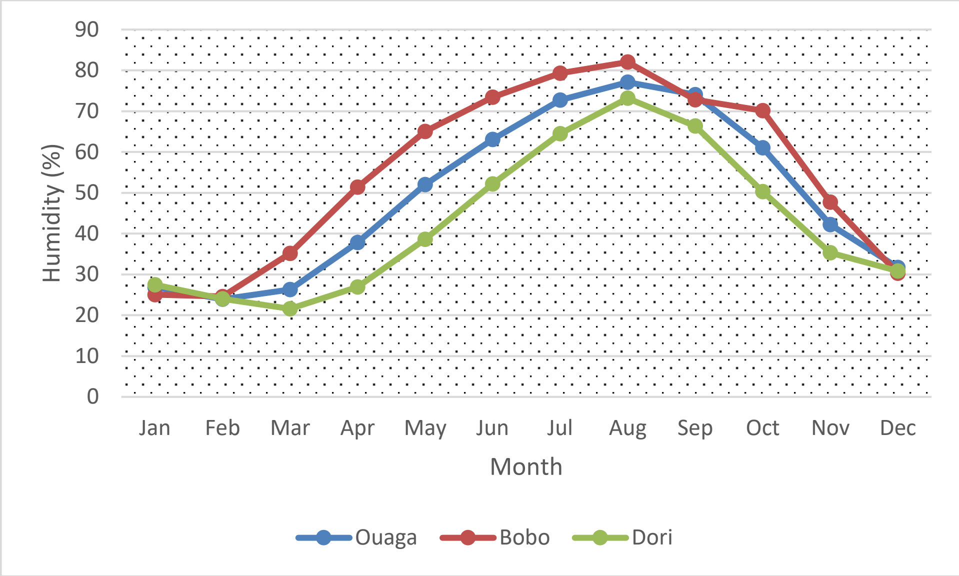

Fig. 6:Monthly relative humidity(ANAM Burkina Faso, 2021)

2.3 Energy production and solar PV plants design

Using the PVGIS solar irradiation database, PVsyst software was used to design a 50 MW PV system to be installed in each of the three climatic zones. Jinko Solar 585Wp modules and Ingeteam inverters were used for this purpose.

2,4 Economic assessments

The LCOE, NPV, IRR, and DPBP were used as economic evaluation parameters. The project was estimated to last 25 years, and the discount rate in Burkina Faso was 4.25% (indexmundi, 2020). Table 1 shows the details of the investment cost (CAPEX), equipment replacement cost, operation and maintenance costs(O&M).

Tab. 1:Economic parameters

Designation	Cost ($/KWp)	Total cost ($)
Modules	540	27,000,000
Inverters	400	20,000,000
Installation	145	7,250,000
Structure	158	7,900,000
DC and AC cables	75	3,750,000
Insurance	10	500,000
Study & Control	90	4,500,000
Land cost(12m^2/kWp) in Burkina $20/m^2	240	12,000,000
Total Capital cost	1718	82,900,000
O&M (1.5% CAPEX)	……..	……..
Inflation rate (2%)	………	……..
Inverters replacement (each 10 year)	400	20,000,000

- Net Present Value (NPV)

The NPV is used to assess the profitability of long-term projects (Mohand Kaci et al., 2022). The higher the NPV value, the more economical the investment. The NPV is the difference between the present values of all cash inflows and cash outflows over the course of an investment project. The NPV expression is given as in equation 1(Kebede, 2015):

$$NPV = -C_o + \sum_{t=1}^{n} \frac{NCF_t}{(1+i)^t} \qquad \text{(eq. 1)}$$

Where C_o is the initial investment in year 0, NCF_t is the net cash flow in year t (which is the revenue minus expenses in year t), i is the discount rate in % and n is the project lifetime. From monetary benefit viewpoint, the NPV needs to have a positive value (NPV >0)(Oloya et al., 2021).

$$NCF_t = Revenue_t - (C_{i,t} + C_{O\&M,t}) \qquad \text{(eq. 2)}$$

$$Revenue_t = E_t \times Energy\ cost \qquad \text{(eq. 3)}$$

$$E_t = (0.99)^{(t-1)}.\ E_1 \qquad \text{(eq. 4)}$$

- The Internal Rate of Return (IRR)

The IRR is a financial parameter used to assess the attractiveness of an investment opportunity. It can be calculated by setting the NPV of the total investment to zero, it should be greater than the discount rate for an investment to be viable. The IRR is useful when comparing projects with the same initial investment costs. It can be determined as (Oloya et al., 2021)(Bouacha et al., 2020) (Ilse et al., 2019).

$$NPV = -C_o + \sum_{t=1}^{n} \frac{NCF_t}{(1+IRR)^t} = 0 \qquad \text{(eq. 5)}$$

- Levelzied Cost of Energy (LCOE)

The LCOE is the cost of per unit(kWh) produced from the solar plant over a specified time (Ahmed et al., 2021) **.** It is an economic assessment of the total cost to building and operating a solar PV installation over its lifetime divided by the total energy output of the asset over that lifetime. It can also be expressed as the minimum price at which electricity must be sold to break-even over the project's lifetime. (Oloya et al., 2021).The LCOE can be expressed by:

$$LCOE = \frac{Lifetime\ cost}{Lifetime\ Energy\ Produced} \qquad \text{(eq. 6)}$$

or

$$LCOE = \frac{C_0 + \sum_1^n \frac{C_{i,t} + C_{O\&M}}{(1+i)^t}}{\sum_1^n \frac{E_t}{(1+i)^t}} \qquad \text{(eq. 7)}$$

Where $C_{i,t}$,$C_{O\&M}$ and E_t are the investment cost (such as replacement cost),operation and maintenance cost and electricity generated at year t respectively.

- Discounted Payback Period (DPBP)

The DPBP represents the time required to recoup the PV power plant initial investment. It is commonly used to assess the level of risk in long-term investments [Rawat R et al]. A DPBP of less than the lifetime of the projects indicates that the investment is favorable (Mohand Kaci et al., 2022).By comparing projects with the same initial investment cost, smaller is DPBP, more the project is viable. The DPBP can be given by the following equation:

$$\sum_{t=1}^{DPBP} \frac{NCF_t - C_{O\&M}}{(1+i)^t} = C_0 \qquad \text{(eq. 8)}$$

3. Results and discussions

For each of the 50MWp solar power plants, 85468 modules of 585Wp and 14 centralized inverters of 2876 KVA are used. To ensure the operation of the panels in the voltage range of each inverter (873-1300V), 23 modules are placed in series. This results in a total of 3716 strings of 23 modules in series. PVsyst allows us to obtain this design as can be seen in figure 7.

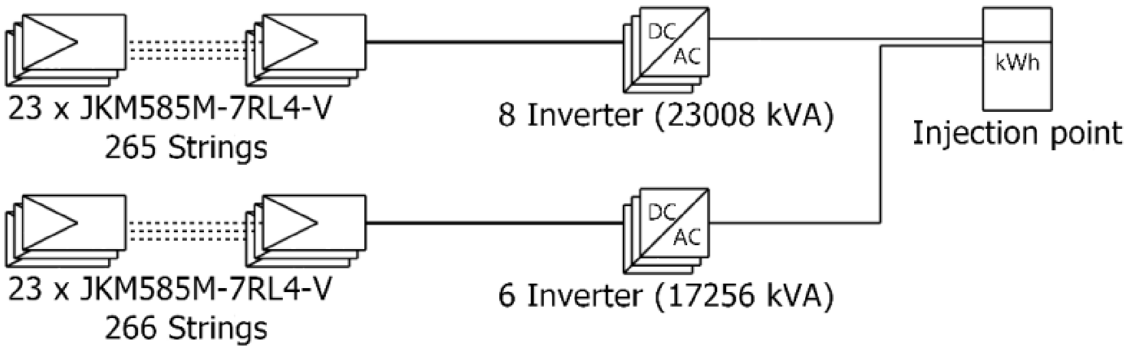

Fig. 7:50 MWp solar park design by PVsyst

Figure 8 below show all the different losses involved in converting the energy collected from the sun into electrical energy that can be fed into the grid, depending on the efficiency of the PV module chosen, in this case the module has an efficiency of 21.4%. The significant losses are due to temperature. These losses are higher in the hottest areas such as Dori which represents -12.6% followed by Ouaga -11.8% and finally Bobo -11.6% Soiling comes second in terms of losses, the soiling margin is between 2% and 5% according to the literature our study, we choose 3% for each region by considering that the difference in soiling effect is negligible. consequently, the performance ratio values in Ouaga, Bobo and Dori are respectively 79.45%;79.7% and 78.4%. To significantly reduce the effect of temperature and soiling, constant cleaning of the PV modules should be considered, which could generate huge costs and make the modules more fragile in the long term. The effect of mismatch should be considered as an important factor in degrading the efficiency of grid-connected PV systems. The modules chosen should have very similar characteristics to avoid the mismatch effect as much as possible. The efficiency of the inverter is also determinant for the energy production at its output. In our case the inverter has an efficiency of 98.6%. It is also noticed that the inverter loss due to voltage threshold is high in Dori than the others region because of the temperature influence in voltage. The final energy at the output of the inverter is $9.1\text{x}10^7$Kwh; $9.0\text{x}10^7$kWh and 9.4 $\text{x}10^7$kWh respectively in Ouaga, Bobo and Dori after all losses. Dori's production is the highest, followed by Ouaga and Bobo due to the higher sunshine in Dori. Nevertheless, an experimental study on these 3 sites should be considered to evaluate the difference on the effect of soiling.

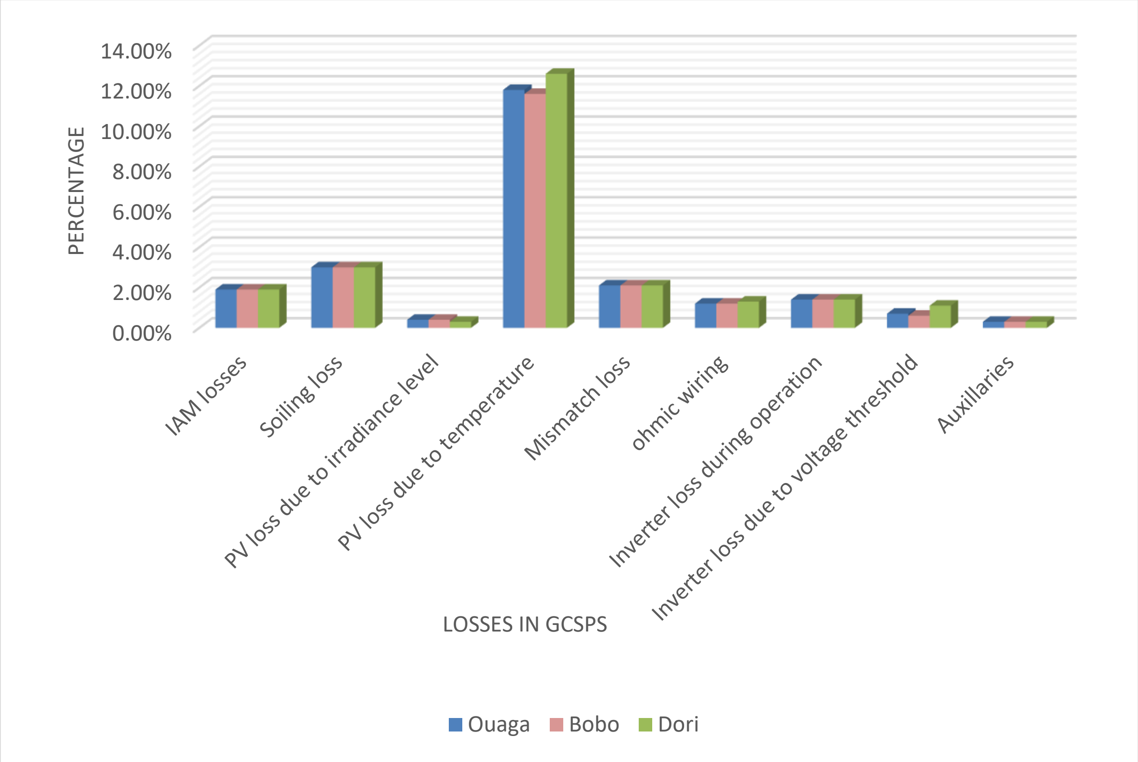

Fig. 8:Losses diagram in the three different locations

Tables 2 and 3 show respectively the electrical parameters of the PV array and inverter as determined by simulation with PVSyst.

Tab. 2:PV array electrical parameters

Manufacturer	Jinkosolar
Model	JKM585M-7RL4-V
Nominal Power	585 Wp
Number of modules	85468 Units
Pmpp at 50°C	45.61 MWp
Umpp at 50°C	926 V
Impp at 50°C	49242 A
Total PV Power	49999 Kwp
Module area	233676 m^2

Tab. 3:Inverter electrical parameters

Manufacturer	Ingeteam
Model	Ingecon Sun 3600TLC615 Preliminary
Nominal Power	2876 kWac
Number of inverter	14 Units
Total power	40264 kWac
Operating voltage	873-1300 V
Maximum Power	44744 kWac
Pnom ratio (DC:AC)	1.24

Figure 9 below shows the LCOE and NPV for each area. It can be seen that the NPV and LCOE As can be seen, the highest NPV is that of Dori, followed by that of Ouaga and finally that of Bobo. This result clearly shows that the PV installation in Dori is more beneficial than in the other two regions, because the LCOE is lower in Dori.

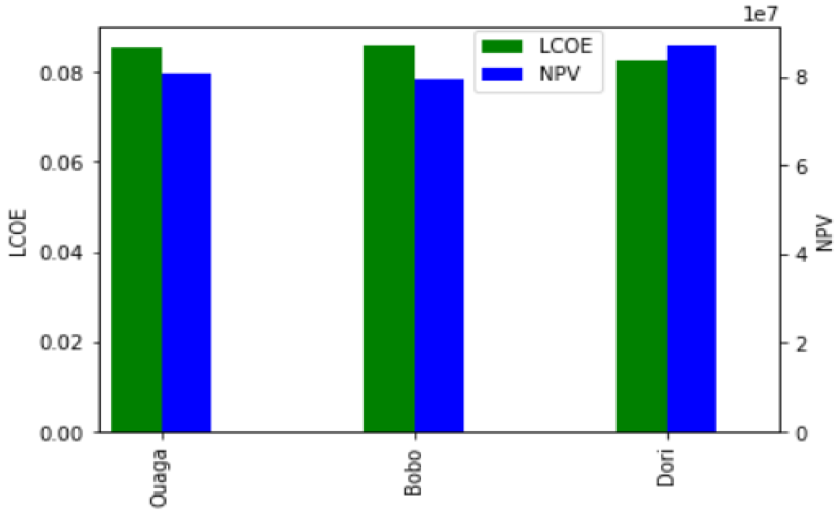

Fig. 9:LCOE & NPV for each climatic zone

Figure 10 shows the evolution of the NPV as a function of the discount rate in the three regions. It can be seen that when the discount rate increases, the NPV decreases, which explains why the uncontrolled inflation rate could make the PV system installation project less viable. Also, the limit of the discount rate that should not be exceeded depends on each region. For Ouaga and Bobo, the maximum discount rate that should not be exceeded is around 12%, and the maximum discount rate for Dori is around 13%, with the cost of the kWh being fixed at $0.15. This clearly explains why, if the discount rate is high, the installation of solar PV plants remains more feasible in Dori than in the other two cities. Figure 11 shows the cumulative NPV over the lifetime of the grid-connected PV project in each of the three regions, with a payback period of between 5 and 10 years for an estimated electricity cost of $0.15/kWh. However, the payback period is quickly reached in Dori, then in Ouaga and finally in Bobo. This period could be the same for all these regions if different electricity costs are applied, which means that PV electricity would be more expensive in Bobo than in the other two regions. There is also a decrease in NPV in years 10 and 20 due to the cost of replacing equipment such as the inverter which has a life span of 10 years. The results for each of the three climate zones are summarized in table 4. These results clearly show the advantage of installing GCSPS in the three locations,

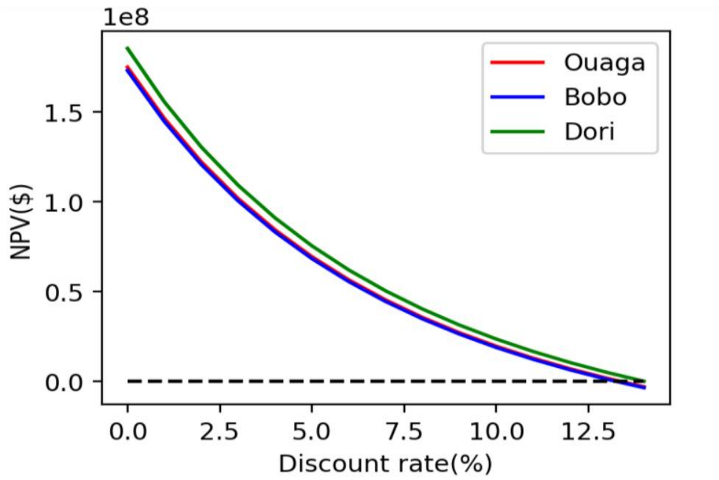

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Fig. 10:NPV with different discount rate

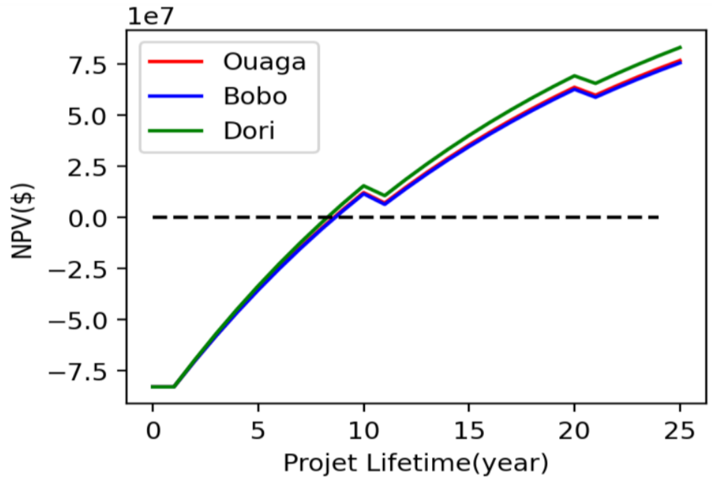

Fig. 11:NPV with project implementation time

Tab. 4:Economic results in the three different climatic zones

City	PV capacity (MWp)	LCOE ($/kwh)	NPV ($)	Discount rate(%)	Energy produced(kWh/year)	Actual LCOE ($/kwh)
Ouaga	50	0.0853	80512952	4.25	9.1 x10^7	0.25
Bobo	50	0.0859	79353487	4.25	9.0 x10^7	
Dori	50	0.0825	87017962	4.25	9.4 x10^7	

4. Conclusion

.This study determined the technical and economic feasibility of a 50 MW GCSPS in each of Burkina Faso's three climate zones, considering each zone's unique characteristics. PVsyst software was used to design a 50 MW GCSPS, and Python software was used to model the system's economics in each climate zone. The results showed that energy production in Ouaga, Bobo, and Dori was 9.1x10^7 kWh, 9.0 x10^7 kWh, and 9.4 x10^7 kWh, respectively. In comparison to the other two zones, this result clearly confirms that Dori is the most privileged zone for the implementation of a PV plant. The LCOE in each zone is approximately $0.08/kWh, which is significantly lower than the current cost of producing electricity in Burkina Faso, which is $0.25/kWh. Finally, the payback period in each zone is less than ten years, implying that the installation of PV power plants is highly viable in Burkina Faso. However, the initial investment cost remains very high due to taxes, transportation costs, land costs, and a lack of subsistence subsidies.With the continued decline in the cost of modules and the advancement of more efficient PV technology, the prospects for the development of GCSPS are bright.

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5. Acknowledgments

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