Study of Decision Support for the Installation of Photovoltaic Systems Coupled to the Electricity Grid: Mali's case study

[1]Amaduo Foussini TOIRE, [2]Fabada DENIALKO

[1]Assistant Professor, Institute of Applied Sciences, University of Science, Techniques and Technologies of Bamako, Mali.
[2]Professor, Institute of Applied Sciences, University of Science, Techniques and Technologies of Bamako, Mali.

Abstract
As energy shortages around the world worsen, countries are starting to harness renewable energies of which solar power is becoming the first choice. Given the insufficient hydraulic and thermal resources in Mali, the hybrid photovoltaic system coupled to the grid is necessary and natural. This study aims to rise the involvement of renewable energy sources to Mali's national electricity production and pave the way for a good supply of electricity, ensuring the sustainable development of the Malian economy and society. The objective of this part is to allow the electricity supply service to know the most beneficial city for the installation of a photovoltaic system. We analyzed horizontal global irradiation (GHI), horizontal diffuse irradiation (DHI) and diffuse normal irradiation (DNI) using data collected at four selected sites namely (Fana Kayes, Kita and Ségou), we took the different localities with the different topologies in order to test and compare the solar performance of each city. For the simulation we used the PVsyst simulation tool which is software for photovoltaic systems.

***Index Terms*: Photovoltaic Systems, Electricity Grid, Decision Support, PVsyst**

I. Introduction

In a rapidly moving global energy framework, marked by a reduction in conservative fossil energy properties and a constant upsurge in greenhouse gas discharges, the expansion of renewable energies remains a means of preventive the belongings of human action on global warming. Among renewable energies, solar photovoltaic (PV) may be of particular interest to Africa. Since the 1980s, Mali, in cooperation with numerous development partners, has initiated various development projects and programs aimed at increasing the use of renewable energy sources (TOURE and al., 2021) [1]. These environmentally friendly sources are abundant in Mali and are becoming an increasingly competitive and become an increasingly competitive and essential precondition for the development of Malian society.

Although interconnections are intentional and installed to meet part of the request with electricity designed from usual gas in Ivory Coast and Ghana, there are still good radical and economic explanations to connect the country's plentiful renewable energy possessions, such as solar power, hydro energy and wind power (TOURE and al., 2021) [2]. At the end of 2012, the cumulative global installed capacity was estimated at more than 100 GWp according to the European Association of the Photovoltaic Industry (EAPI, 2013) [3].

In this context, the realization of large-scale solar power plants associated with the electricity grid is relevant. In addition, once the realization of these solar power plants is considered, the knowledge of the most profitable city for the implementation of the system remains problematic. Several studies have been carried out on photovoltaic solar power plants installed around the world. (Kymakis and al., 2009) conducted a study on the presentation investigation of a plant associated with the 171.36 kW grid on the island of Crete in 2002 [4]. (Makrides and al., 2010), evaluated thirteen different photovoltaic technologies in two localities (Nicosia, Cyprus and Stuttgart, Germany), all connected to the grid with a nominal power of 1 KWp [5]. (HASSAN and al., 2014) evaluated the performance of a 300 KWp photovoltaic solar power plant connected to the grid at DJIBOUTI using the different methods mentioned above [6]. (Ma and al., 2016) made a new approach to the study of reliability [7]. (Blaabjerg and al., 2017) conducted a study on the reliability of renewable energy systems [8]. (de Nazareth Ferreira and al., 2018) made a design study and selection of reliable converters for grid connected PV applications [9]. (Blaabjerg and al., 2018) discussed a study on the power control flexibility of solar systems [10]. (Perea-Moreno and al., 2018) studied an autonomous photovoltaic system in an urban area of Mexico [11]. (Chen and al., 2018), did a study on the reconfiguration of a multistate converter [12]. (TOURE and al., 2019) worked on the optimization of a photovoltaic system coupled to the electricity grid with an application case in Mali [13]. The application of artificial intelligence to the photovoltaic system has been studied in [14].

Most of these studies have been carried out on the assessment of the presentation of solar power plants, the reliability of converters, optimization, and monitoring of the maximum power point of production of installed PV modules. It is in this context that we were interested in the study of decision support for the installation of photovoltaic systems coupled to the electricity network. The objective is to allow the electricity supply service to know the most beneficial city for the installation of a photovoltaic system. This study aims to increase the contribution of renewable energy sources to Mali's national electricity production and to pave the way for a good supply of electricity, ensuring the sustainable development of the Malian economy and society.

II. Interconnected Network of Mali:

The Malian power grid is an interconnected system comprising central generating units, transmission members (lines, substations) and loads. It allows the transmission of electrical energy produced at power plants to consumers. For this, the electricity network must meet three essential requirements: stability, economy and, above all, continuity of service.

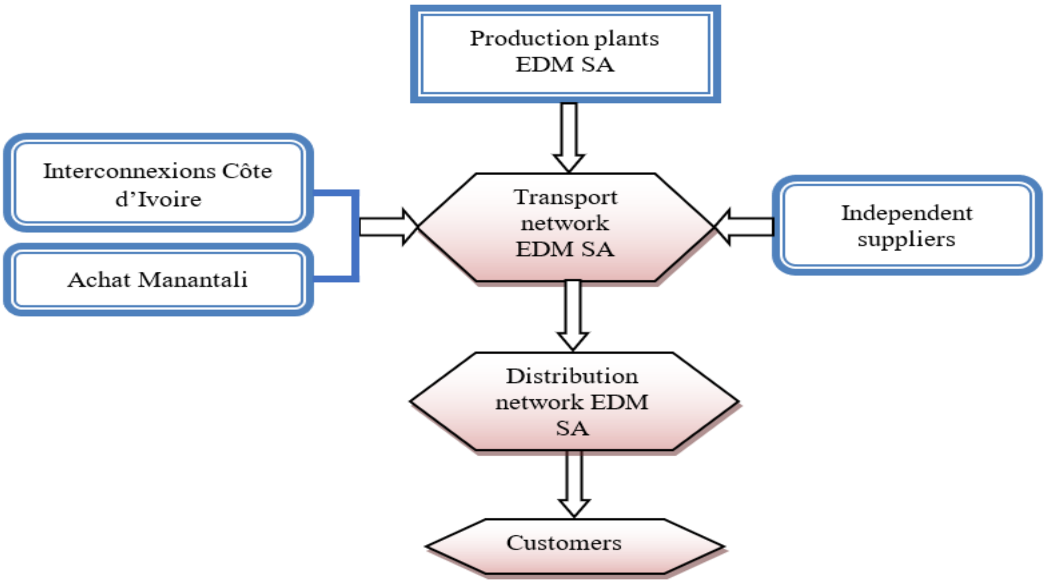

Figure 1 : Overview of the interconnected electricity grid of Mali [15]

The demand for electrical energy varies throughout the day and seasons. It is represented by a load curve, of which the National Center of Conduct and more precisely the Service Forecast and Purchase of Energy elaborates every day. It ensures that the production programs planned by the electricity suppliers make it possible to satisfy the total consumption. Besides, ancillary services are structuring below to enable the power grid to meet three essential requirements. This is not always the case, because the network is very often exposed to incidents that interrupt the service and generate significant financial losses for industrialists and inconveniences for the simple consumers.

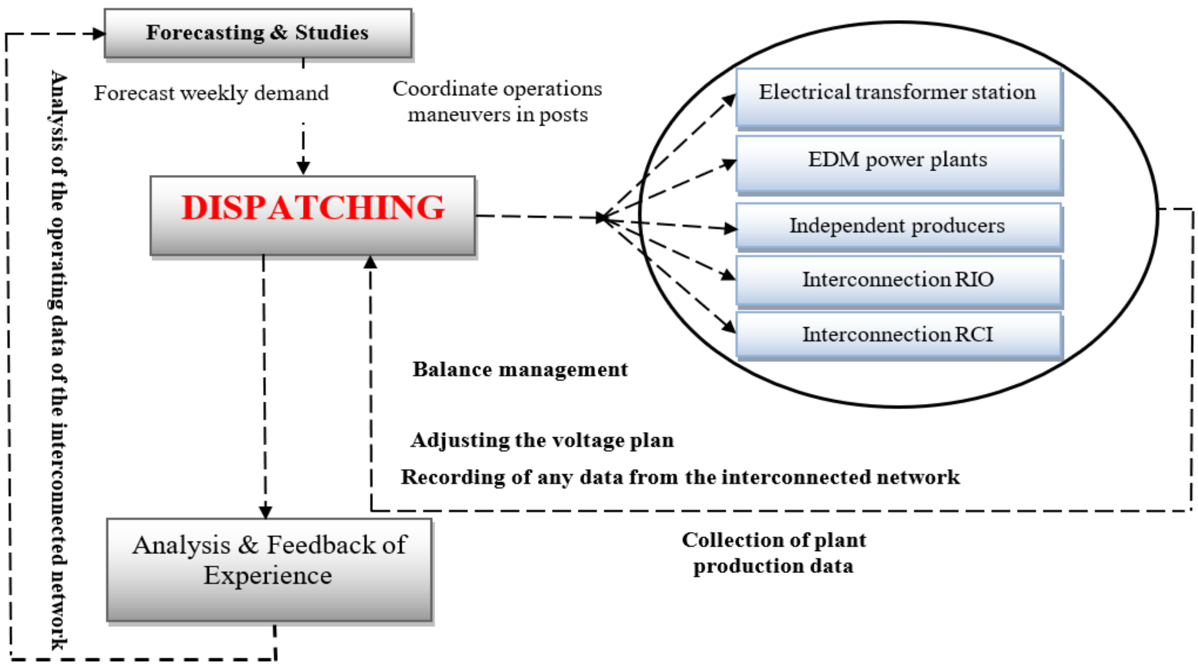

Figure 2 : Principle of conduct of the interconnected national network [15]

III. Approach

Our approach is applied to the Mali energy interconnection network (EDM-Sa). This network is shown in figure 3. Electricity demand is assured by EDM's specific hydroelectric power stations, thermal power stations and largely purchased from a neighboring country Ivory Coast, and Manantali's production. We have connected three solar power plants of 36 MW at four posts of electricity distribution (Kayes, Kita, Fana and Segou).

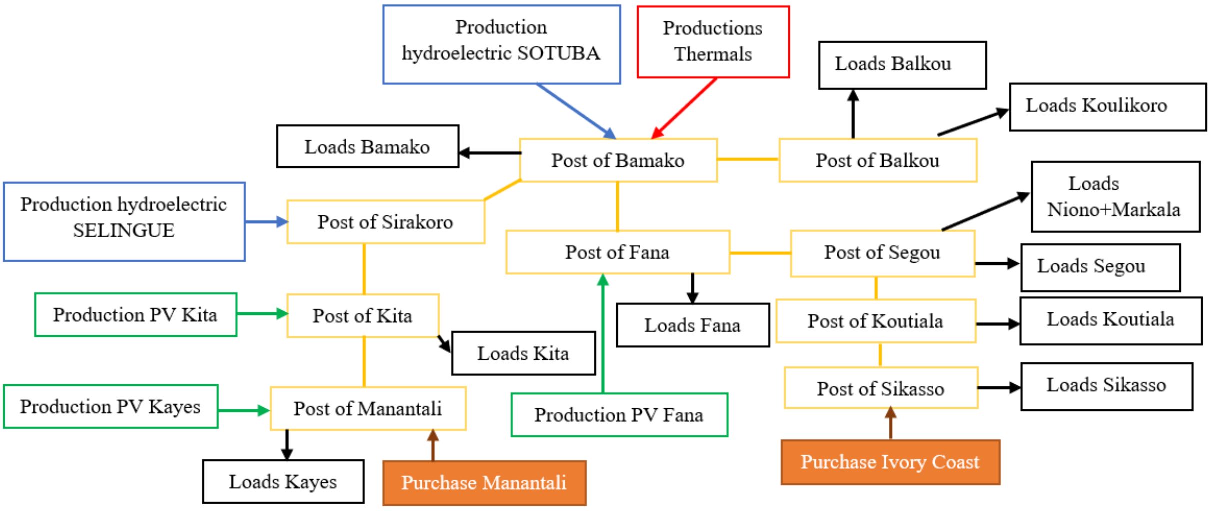

Figure 3 : Mali electricity supply interconnection network.

This interconnection network ensures the supply of electricity to four (4) regions and these big cities and the capital of Mali. It includes different sources of production including points of purchase (Ivory Coast and Manantali), distribution posts and consumption points. EDM-sa's own hydroelectric production sources are coded in blue, thermal production in red, photovoltaic production in green and purchasing points in purple. The distribution posts are coded in yellow and the consumption points are in black.

To achieve the objective, which is to help the electricity supply service to know the most beneficial city for the installation of a photovoltaic system, we will analyze horizontal global irradiation (GHI), horizontal diffuse irradiation (DHI) and diffuse normal irradiation (DNI) using data collected at the selected sites. We will take the different localities with the different topologies in order to test and compare the solar performance of each city. The scheduled normal values of DHI, GHI and DNI for all twelve months of the year will be analyzed. This investigation intentions to explore the availability of solar possessions based on the data accessible from these dissimilar sites. Solar irradiation data for a specific site can be extracted using the different averages, for example, they can be obtained by metrological stations that are distributed across the country in question or by transporting them to the NASA website from the latitude and longitude coordinates of the region.

IV. Case Study

For our case study, we applied our methodology to four (4) towns of Mali's energy interconnection network Mali: Kayes, Kita, Fana and Segou. A preliminary analysis defines the technical, economic and environmental conditions for the installation of 36 MW solar power plants these four (4) towns. The power of 36 MW is compatible with the capacity of Mali's interconnected grid to absorb the electrical energy produced. For the location of the sites, several criteria were considered for a final implementation (local climatic conditions, proximity to the interconnected network, source of cooling water, social and environmental impact of the project). For simulations of the technical process and the economic evaluation of the study, we used the PVsyst modeling and simulation tool, which is a good decision help tool for photovoltaic systems.

Table 1:The geographic coordinates of the different cities.

Sites	Longitude (E)	Latitude (N)
Kayes	-11.433	14.433
Kita	-9.467	13.067
Fana	-6.961	12.779
Ségou	-6.150	13.400

We analyzed horizontal global irradiation (GHI), horizontal diffuse irradiation (DHI) and diffuse normal irradiation (DNI) using data collected at four sites selected namely (Fana Kayes, Kita and Segou). The impression of the solar energy probable of these four cities can be found in Table (1). The scheduled usual values of GHI, DHI and DNI for all twelve months of the year 2020 were analyzed.

Figures 4 and 5 compare the restrained ethics of GHI and DNI for the four cities. The maximum overall horizontal irradiation was produced between March and April, with approximately 6.40 kWh/m² as maximum for Kayes, 6.30 kWh/m² for Kita and 6.84 kWh/m² for Fana and Segou. The minimum GHI for Kayes was 4.74 kWh/m², 5.06 kWh/m² for Kita, 5.35 kWh/m² for Ségou and 5.45 kWh/m² for Fana, all observed in December. The maximum diffuse irradiation was observed between March and April except for the town of Kayes which was observed in June and the minimums in November.

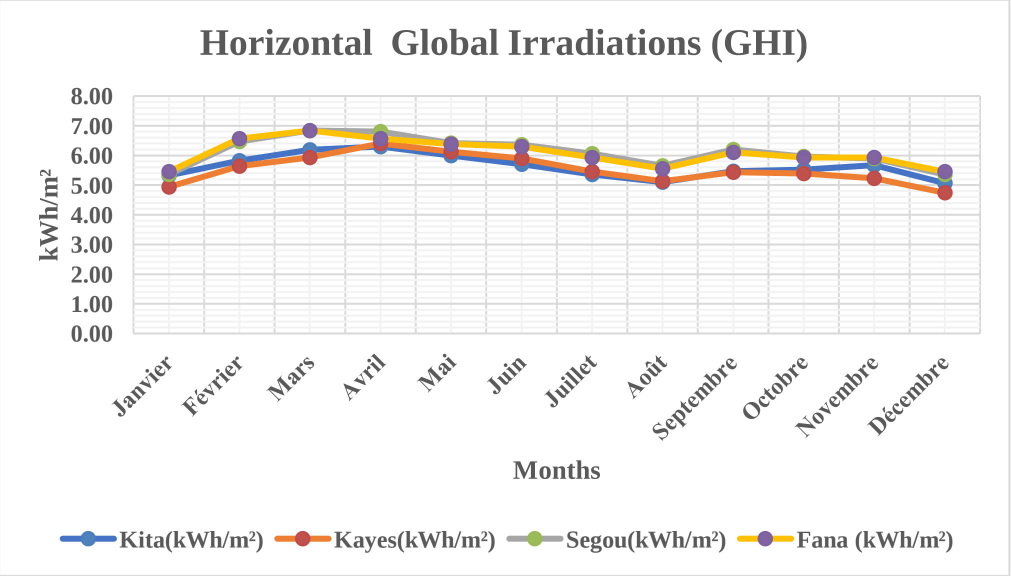

Figure 4 : The different horizontal global irradiations of the four cities.

Advanced International Journal of Multidisciplinary Research
E-ISSN: XXXX-XXXX editor@aijmr.com
Volume 1, Issue 1, July – August 2023

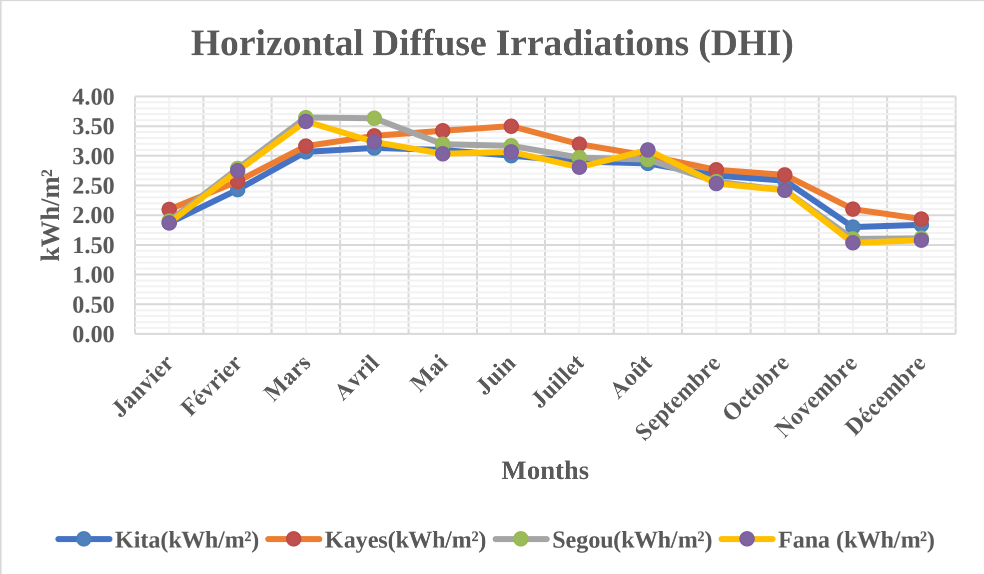

Figure 5 :The different horizontal diffuse irradiations of the four cities.

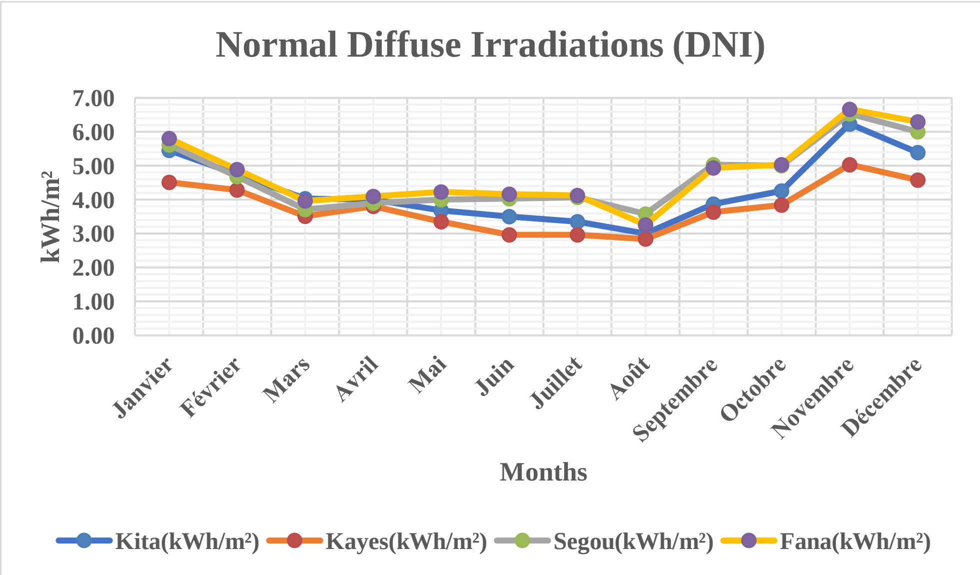

Figure 6 :The different diffuse normal irradiations of the four cities.

The minimum horizontal diffuse irradiation annual was observed in the city of Kita from January to May, at Fana from September to December and the maximum in the cities of Fana and Segou between January and April, in the town of Kayes between the month of May and the month of December (figure 5).

For diffuse normal irradiation, we observed the maximums in November and the minimums in August. Solar irradiations started to increase from January to reach their maximums in March and April and then decrease to reach their minimum for the first time between August and September. A new increase was observed from the month of September until the month of November to decrease once again (Figure 6), we observed the smallest annual average diffuse normal irradiation at Kayes and the largest at Fana.

The comparative histogram of the different solar irradiations of the four cities is shown in Figure 7.

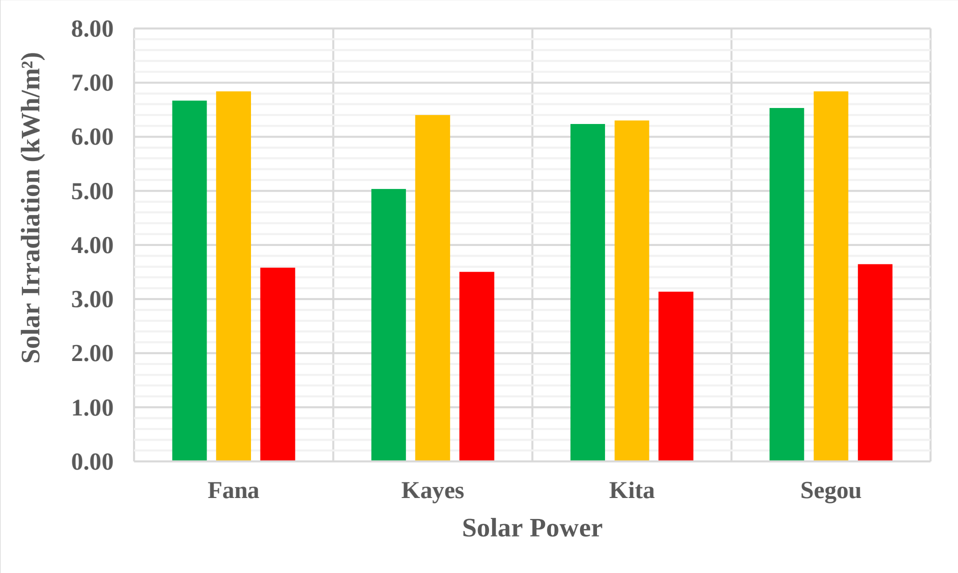

Figure 7 : The comparative histogram of the different solar irradiations of the four cities.

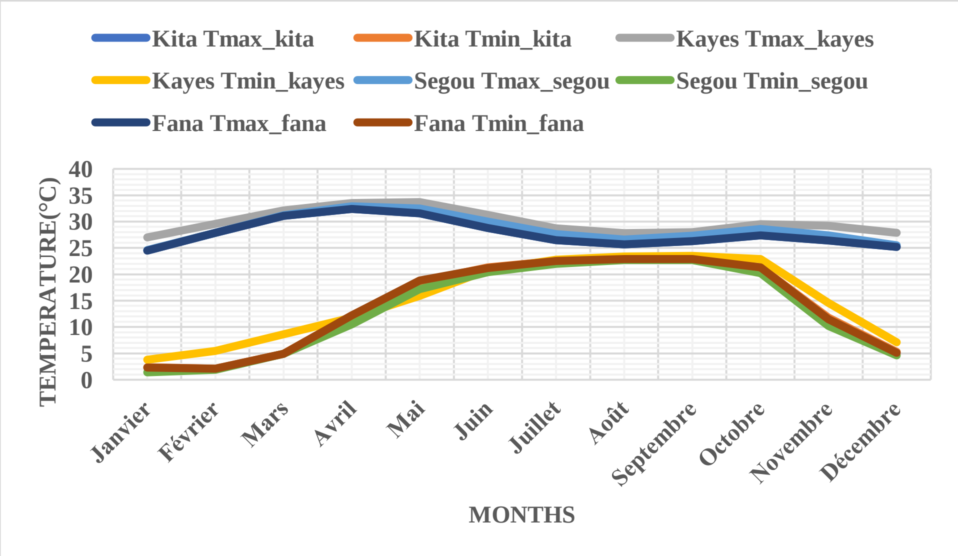

Figure 8 : The maximum and minimum temperatures of the four cities.

Figure 8 illustrates the max and min temperatures of the different cities. The maximum temperature varies between 24.5 °C observed at Fana and Kita in December and 33.7 °C at Kayes. The minimum temperature varies between 1.4 °C in the city of Segou and 23.5 in the city of Kayes. We also observe that Kayes is the hottest city of the four cities and Fana the least hot. The temperatures of Segou and Fana are almost similar.

The solar data used for our study case are obtained from @meteonorm [16]. We can notice that these data are favorable at Segou and Fana, then Kita and Kayes occupy the last position (figure 7).

V. Simulation And Discussion Of Results

For the reproduction we used the PVsyst simulation tool which is software for photovoltaic systems. We dimensioned a PV system with a capacity of 36 MW and simulated it under the climatic conditions of the different cities in our study case. The aim of the simulation is to see in which city production will be important relative to each other. Table 2, summarizes the monthly and annual productions of the different cities where E_PV is the energy fashioned by the PV modules and E_R is the energy injected into the grid after conversion.

Table 2 :Monthly and annual productions of the four cities.

Months	**Kita**		**Kayes**		**Ségou**		**Fana**	
	E_PV (MWh)	**E_R (MWh)**	**E_PV (MWh)**	**E_R (MWh)**	**E_PV (MWh)**	**E_R (MWh)**	**E_PV (MWh)**	**E_R (MWh)**
January	5817	5589	5349	5143	6105	5869	6179	5939
February	5469	5257	5215	5012	6161	5923	6157	5919
March	5948	5714	5846	5611	6543	6295	6554	6304
April	5502	5284	5645	5421	5947	5716	5905	5676
May	5264	5045	5405	5183	5629	5402	5601	5374
June	4880	4672	5042	4831	5385	5162	5365	5146
July	4792	4579	4910	4695	5446	5219	5388	5166
August	4782	4572	4848	4635	5287	5068	5202	4985
September	5157	4949	5165	4956	5832	5601	5742	5514
October	5586	5363	5548	5331	6074	5834	6066	5827
November	5890	5662	5399	5186	6141	5908	6173	5937
December	5682	5457	5219	5012	6027	5793	6112	5876
Annual	**64769**	**62143**	**63591**	**61016**	**70577**	**67790**	**70444**	**67663**

We observed an annual production of 62,143 MWh of energy injected into the electrical grid for the city of Kita, 61,016 MWh for Kayes, 67,790 MWh for Segou and 67,663 MWh for the city of Fana (Figure 9).

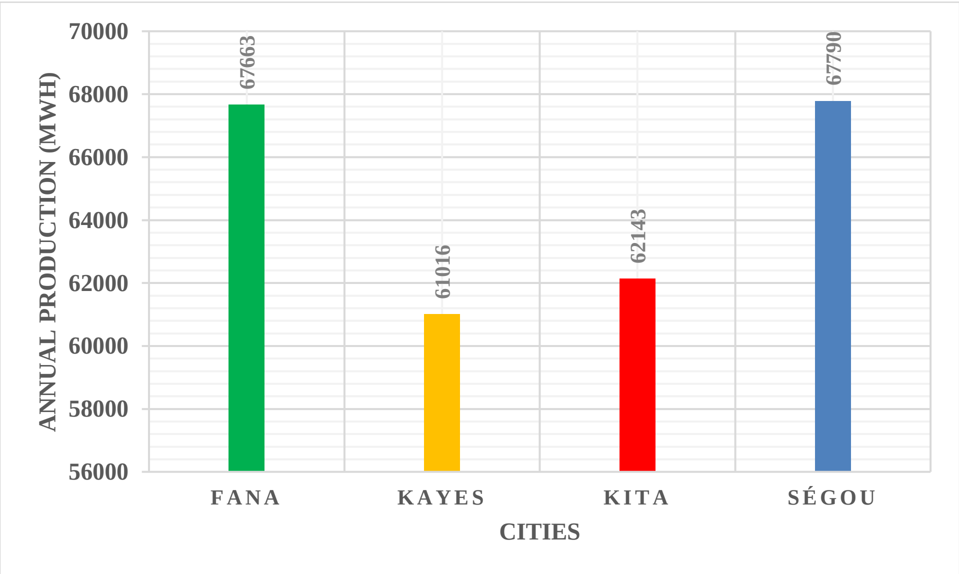

Figure 9 : The annual energies of the solar system of 30 MW, if implanted in the different cities.

Figure 10, illustrates the maximum and minimum monthly productions of the different cities. For Fana, the maximum production is 6,304 MWh and the minimum production is 4,985 MWh. A maximum production of 5,611 MWh has been observed at Kayes and its minimum production is 4,635 MWh, a maximum production of 5,714 MWh for the town of Kita with a minimum production of 4,572 MWh. It was observed in the city of Ségou, a maximum production of 6,295 MWh and a minimum production of 5,068 MWh. The maximum productions were all observed in March and the minimum productions in August figure 11.

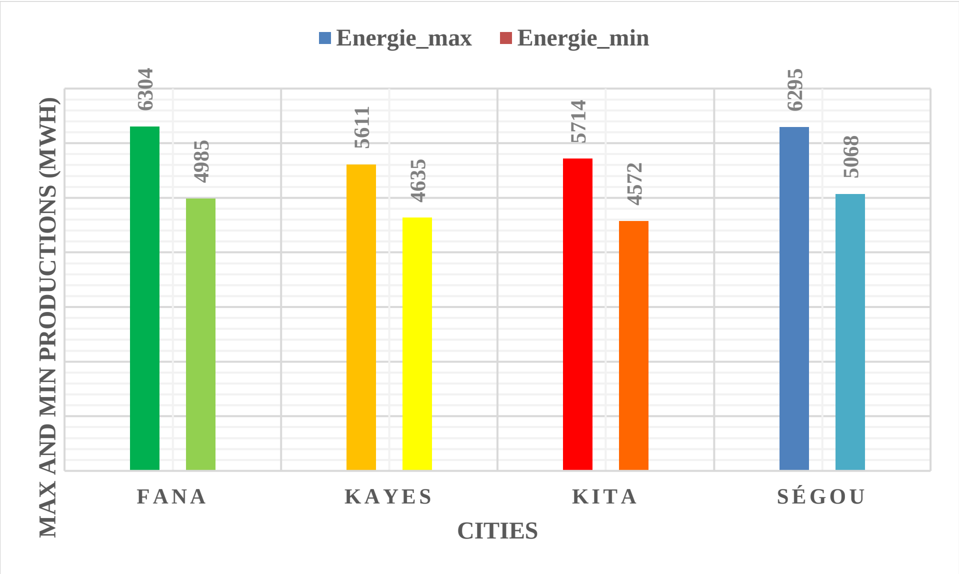

Figure 10 : The maximum and minimum production of the different cities.

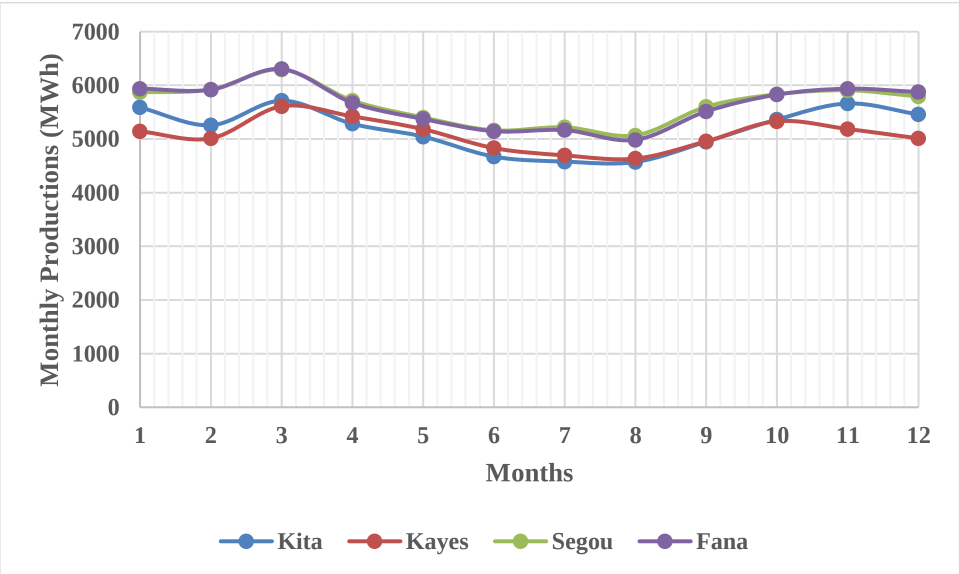

Figure 11 : The curve of the various monthly productions during the twelve (12) months.

From the analysis of Figures 10 and 11, we can conclude that the installation of the 36 MW system will be more beneficial in the cities of Ségou and Fana, less beneficial in the city of Kita compared to the two previous cities. From March to September Kayes's production is lower than that of Kita but her production is higher than that of Kita from October to March. We can conclude that the city of Kayes is the most unfavorable among the four cities studied.

VI. Conclusion

In this article we conducted a decision help study for the installation of photovoltaic systems coupled to the electricity grid, an application case in Mali. The objective was to allow the electricity supply service to know the most beneficial city for the installation of a photovoltaic system. Four (4) cities of Mali including Kayes, Kita, Fana and Segou were chosen for the application of our methodology. A comparative study for the installation of a solar power station of 36 MW was developed for the four (4) cities.

In a first step, the horizontal global irradiations (GHI), the horizontal diffuse irradiations (DHI) and the diffuse normal irradiations (DNI) were analyzed using the data collected on four selected sites namely (Fana Kayes, Kita and Ségou). According to the analysis of the monthly average values of GHI, DNI, and DHI for a year, we found that these data are favorable in the cities of Ségou and Fana, then Kita and Kayes occupy the last position (Figures 4, 5, 6 and 7). Following the analysis of the maximum and minimum temperatures of the different cities, we observed that the city of Kayes is the hottest city of the four cities and Fana the least hot. The temperatures of the city of Ségou and Fana are almost similar (Figure 8).

The results of the different simulations have shown that the installation of a solar system of 36 MW will be more beneficial in the cities of Ségou and Fana, less beneficial in the city of Kita compared to the two previous cities. From March to September, production at Kayes is lower than that at Kita but her production is higher than that of Kita from October to March. In conclusion, the city of Kayes is the most unfavorable among the four cities studied and the city of Segou is more favorable (figures 10 and 11).

References

[1] Toure, A. F., Danioko, F., & Diourte, B. (2021). Application of Artificial Neural Networks for Maximal Power Point Tracking. *International Journal of Sustainable and Green Energy*, *10*(2), 40-46. https://doi.org/10.11648/j.ijrse.20211002.12

[2] Toure, A. F., Tchoffa, D., El Mhamedi, A., Diourte, B., & Lamolle, M. (2021). Modeling and Control Maximum Power Point Tracking of an Autonomous Photovoltaic System Using Artificial Intelligence. *Energy and Power Engineering*, *13*(12), 428-447. https://doi.org/10.4236/epe.2021.1312030

[3] Gaëtan Masson, Marie Latour, Manoël Rekinger, Ioannis-Thomas Theologitis, and Myrto Papoutsi. Global market outlook for photovoltaics 2013-2017. European Photovoltaic Industry Association, pages 12–32, 2013. URL http://www.fotovoltaica.com/fv-look.pdf.

[4] Emmanuel Kymakis, Sofoklis Kalykakis, and Thales M Papazoglou. Performance analysis of a grid connected photovoltaic park on the island of crete. Energy Conversion and Management, 50(3) :433–438, 2009. URL https://doi.org/10.1016/j.enconman.2008.12.009.

[5] George Makrides, Bastian Zinsser, Matthew Norton, George E Georghiou, Markus Schubert, and Jürgen H Werner. Potential of photovoltaic systems in countries with high solar irradiation. Renewable and Sustainable energy reviews, 14(2) :754–762, 2010. URL https://doi.org/10.1016/j.rser.2009.07.021.

[6] STC conditions standard de Test. Suivi experimental des performances d'une centrale solaire photovoltaique a djibouti.

[7] Ke Ma, Huai Wang, and Frede Blaabjerg. New approaches to reliability assessment: Using physics-of-failure for prediction and design in power electronics systems. IEEE Power Electronics Magazine, 3(4) :28–41, 2016. URL https://doi.org/10.1109/MPEL.2016.2615277.

[8] Frede Blaabjerg, Dao Zhou, Ariya Sangwongwanich, and Huai Wang. Design for reliability in renewable energy systems. In 2017 International Symposium on Power Electronics (Ee), pages 1–6. IEEE, 2017. URL https://doi.org/10.1109/PEE.2017.8171658.

[9] Victor de Nazareth Ferreira, Allan Fagner Cupertino, Heverton Augusto Pereira, Anderson Vagner Rocha, Seleme Isaac Seleme, and Braz de Jesus Cardoso Filho. Design and selection of high reliability converters for mission critical industrial applications: A rolling mill case study. IEEE Transactions on Industry Applications, 54(5) :4938–4947, 2018. URL https://doi.org/10.1109/TIA.2018.2829104.

[10] Frede Blaabjerg, Ariya Sangwongwanich, and Yongheng Yang. Flexible power control of photovoltaic systems. In Advances in Renewable Energies and Power Technologies, pages 207–229. Elsevier, 2018. URL https://doi.org/10.1016/B978-0-12-812959-3.00006-X.

[11] Alberto-Jesus Perea-Moreno, Quetzalcoatl Hernandez-Escobedo, Javier Garrido, and Joel Verdugo-Diaz. Stand-alone photovoltaic system assessment in warmer urban areas in mexico. Energies, 11(2) :284, 2018. URL https://doi.org/10.3390/en11020284.

[12] Weiqiang Chen, Ethan Hotchkiss, and Ali Bazzi. Reconfiguration of npc multilevel inverters to mitigate short circuit faults using back-to-back switches. CPSS Transactions on Power Electronics and Applications, 3(1) :46–55, 2018.

[13] URL https://doi.org/10.24295/CPSSTPEA.2018.00005.

[14] Touré, A. F., Addouche, S. A., Danioko, F., Diourté, B., \& Mhamedi, A. E. (2019). Hybrid Systems Optimization: Application to Hybrid Systems Photovoltaic Connected to Grid. A Mali Case Study. Sustainability, 11(8), 2356. https://doi.org/10.3390/su11082356

[15] Touré, A. F. (2020). *Aide à la décision pour l'Implantation des stations photovoltaïques couplées au réseau électrique: cas d'application au Mali* (Doctoral dissertation, Paris 8). https://www.theses.fr/2020PA080014

[16] https://meteonorm.com/en/download

[17] Touré, A. F., Cotfas, P. A., Cotfas, D. T., & Diourte, B. (2023). STUDY OF THE ELECTRICAL CHARACTERISTICS OF ELECTRONIC COMPONENTS UNDER THE NI LABVIEW ENVIRONMENT. In *INTED2023 Proceedings* (pp. 6576-6585). IATED. 10.21125/inted.2023.1752