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Economic and ecological constraints of hybrid systems with Bayesian networks

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ABSTRACT

To confront climate change and the shortage of fossil fuels, countries are turning to renewable energies, particularly solar energy, which is an abundant, inexhaustible energy with a low environmental impact. In Mali, hydraulic and thermal energy sources are insufficient, and the country has been facing a huge energy crisis in recent years. For this reason, the production of solar energy is a major solution. This work proposes a photovoltaic system coupled to the national distribution network to reduce this energy crisis or even resolve it definitively. A preliminary analysis was carried out to define the technical, economic, and ecological conditions for the construction of a 30 MW solar power plant at three interconnection points of the national distribution network of Mali. The objective of this analysis is to determine the economic and ecological constraints of the proposed hybrid system. For modeling, we used the Bayesian network, and for simulation, the BayesienLab simulation tool was used. The simulation results showed a considerable contribution of these three solar power plants in terms of energy deficits, economic deficits, and climate change.

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1. INTRODUCTION

The demand for energy is evolving exponentially, whereas conventional fossils-based energy sources are decreasing and climate change is becoming more and more evident. In this context, the use of renewable energies, a solution to be considered, is particularly interesting for Africa in general and Mali in particular. Since the 1980s, Mali, in cooperation with many development partners, has initiated various development projects and programs to increase the use of renewable energy sources. This strategy combines efforts to reduce poverty, validate national energy resources, and guarantee long-term security and environmental sustainability of energy supply.

Given the rapid increase in fuel prices imported, renewable energy sources are of growing interest. These renewable energy sources with less impact on the environment are abundant in Mali and contribute to the country's development. Currently, electricity demand is increasing by approximately 10% per year, with fuel transportation costs rising even further (African Bank for Development, 2010). This situation results in enormous difficulties for the Malian government and national operators and seeks to reduce imports of fossil fuels, as well as for the public utility and private investors striving to provide enough electricity at a reasonable price.

Much of the energy generation comes from large-scale hydro-electric power station produced on the Senegal and Niger rivers, but small and medium diesel generators still provide about 20% of the total output. Even if installations of electrical energy interconnections with Ghana and Ivory Coast are planned, political and economic decisions are being put in place to exploit renewable energies such as wind, solar and hydroelectric energy in the country. According to studies by The European Association of the Photovoltaic Industry (EAPI, 2013) [1], the capacity of photovoltaic production was estimated at 100 GWp in 2012.

In this context, the implementation of hybrid photovoltaic power plants and the electricity network is relevant. Besides, once these hybrid power plants are realized, the problem of managing solar energy produced according to the availability of solar irradiation poses a significant problem. We will find in the literature many studies on photovoltaic systems, among others, the analysis of the performance of a 171.36 kWp solar power plant connected to the network of the Island of Crete by Mungkin *et al.* [2]. Thirteen photovoltaic systems coupled to electrical networks of different technologies were evaluated by Toure *et al.* [3] in two locations in different countries (Cyprus and Germany).

Solar Energy Center in India conducted a performance evaluation study of different photovoltaic technologies consisting of, thin films, monocrystalline silicon, and polycrystalline silicon [4]. Nouadje *et al.* [5] evaluated the performance of a 300 KWc solar photovoltaic power plant connected to the network at DJIBOUTI using the various methods. Sharma *et al.* [6] analyzed the reliability of a single-phase converter with reactive power injection at night, considering mission profiles. A new approach to the study of reliability and reliability on renewable energies was provided respectively by Ichim-Burlacu *et al.* [7] and Anurag *et al.* [8]. Ma *et al.* [9] worked on the study of design and selection of reliable converters for hybrid photovoltaic power grid systems. The flexibility of power control of photovoltaic systems has been discussed by Blaabjerg *et al.* [10]. In an urban area of Mexico, Ferreira *et al.* [11] evaluated an autonomous photovoltaic system. A study on the configuration of a multi-state converter was carried out by Blaabjerg *et al.* [12].

Most of this work has focused on evaluating the performance of solar systems, and the reliability of converters and the maximum power point tracking for installed PVs. Our work will be focused on modeling the availability of solar production, to help the dispatcher, predict a reliable estimate of purchases from Manantali and the interconnection of Côte d'Ivoire suppliers using the Bayesian network to provide the interconnected system to meet three essential requirements: stability, economy and above all continuity of service. This is not always the case, because the network is often exposed to incidents that can interrupt this service and cause significant financial losses for industry and inconvenience for ordinary consumers. Our major contribution has been to combine analytical and probabilistic models with the Bayesian network in order to have a real decision-making tool that will allow the dispatching service to make better purchasing precision for energy and thermal productions. The objective is to reduce the overall costs of production and the emission of greenhouse gases. For the simulation, we have considered three scenario cases. The first scenario is to maintain thermal production as we have found to see the impact of solar production on the economic and ecological level. The second scenario is to maintain the energies purchased by allowing solar productions to reduce thermal productions with the same objectives that the first scenario. The third scenario is to play simultaneously on thermal production and purchased energy to allow the dispatching service to reduce economic and ecological impacts as much as possible. We have applied our approach on the interconnection networks of Mali.

The rest of the paper is structured as follows: i) Section 2 introduces the Bayesian estimation approach; ii) Section 3 presents a case study; iii) Section 4 discusses the simulation results for the best prediction; and iv) Finally, Section 5 provides the discussion and conclusion.

2. PROPOSED METHOD

2.1. Introduction

In the literature, Bayesian networks have been applied in several studies, but most of these studies use them for predictive maintenance. Perea-Moreno *et al.* [13] and Chen *et al.* [14] conducted a study on predictive maintenance using dynamic probabilistic networks. Weber *et al.* [15] and Samé *et al.* [16] have studied predictive maintenance of complex multi-state systems with a reliability structure. Kareem and Owolabi have optimized maintenance planning in the industrial production sector with the Bayesian network [17].

Nevertheless, some studies have used Bayesian networks in the energy sector [18], [19]. We can mention, among others, Sica *et al.* [20], who studied a cognitive system for the default prognosis in power transformers, and Lee and Pan [21] have a cost-benefit analysis of offshore wind energy. However, the Bayesian network can be used in several domains to make the right prediction and diagnosis [22]. In our work, we used it in the photovoltaic system connected to the electricity grid, which constitutes our contribution in this context, as shown in Figures 1(a) and 1(b). The PV generator node represents the photovoltaic source, which has as child nodes control MPPT and converter DC/DC nodes. The MPPT control node controls the DC/DC converter to maintain the PV generator at its maximum output. It is based on information from the PV to drive the DC/DC converter.

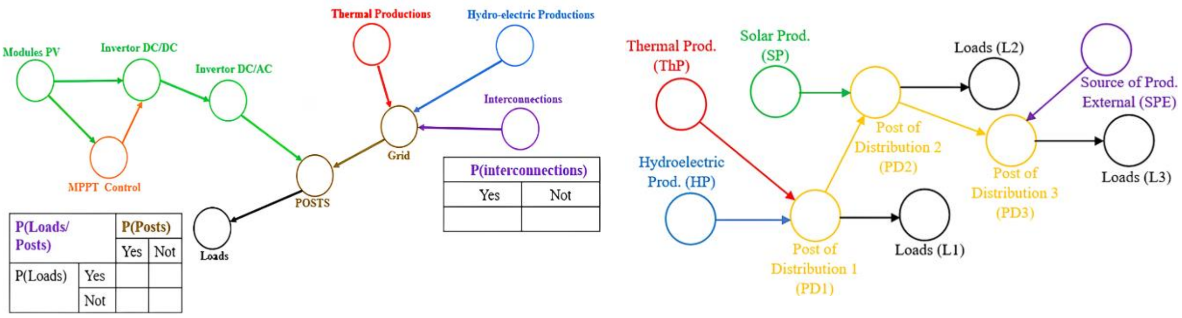
The DC/AC inverter node, whose parent node is the DC/DC converter node, converts the direct current produced by the PV generator into alternating current of the same nature as the grid. The node's thermal production, hydroelectric production, and interconnection are different sources of production that constitute the children of the grid node. The grid node is the sum of its child nodes that have a single point of production. The station distribution node has for parents DC/AC and grid inverter nodes, which interconnect the two sources and distribute them to consumers.

In our approach, we have combined analytical and probabilistic models with the Bayesian network in order to have a real decision-making tool that will allow the dispatching service to make better precise purchase of energy and thermal production. The objective is to reduce the overall costs of production and the emission of greenhouse gases.

2.2. Global approach

Based on the identification of the powers of the PV modules, a photovoltaic system is designed with a maximum power point tracking controller for PV modules. Then, we create a hybrid system with production sources including: hydroelectric power stations, imported energy, and thermal power stations. Once the hybrid system photovoltaic/power grid, we model and optimize this system in three steps [23].

The overall approach, which summarizes my approach, is as follows: this approach was developed in three phases (Figure 2). Step 1 involves designing a controller for maximum power point tracking (MPPT) of the PV system and integrating it with the electric grid. In step 2, the impact of productions photovoltaics on different productions has been developed, and we have analyzed the cost of the investigation supply service and CO_2 emissions.



(a) (b)

Figure 1. Modeling a PV system: (a) connected to the electricity grid and (b) global interconnection grid

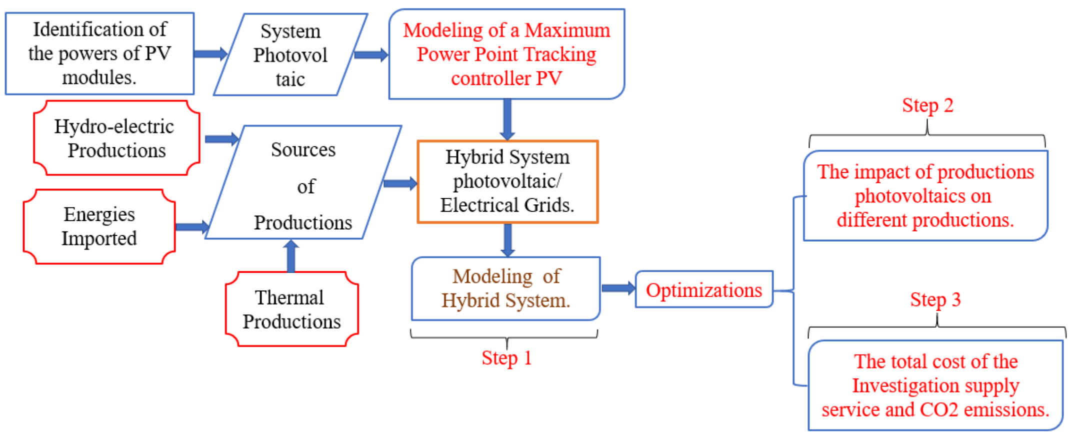


Figure 2. Global approach for our approach

2.3. Modelling of the hybrid system

Moreover, once these hybrid plants are installed, the problem of managing the variability of solar energy produced according to the availability of the sun poses a major problem. The Bayesian network can combine analytical and probabilistic models in order to have a real decision-support tool that allows the dispatching service to make better purchasing accuracy for energy and thermal production [24], [25]. The different production sources, distribution stations and loads will be modeled by Bayesian networks and then we will develop a timed influence diagram where the distribution will be injected into each node of interest at each moment.

From this Bayesian network, with the help of expert knowledge and the availability of a database, we can act on thermal production, which is a source of pollution, depending on the availability of alternative photovoltaic sources and the consumer demand. In addition, the dispatcher can be based on the hours of production of PV sources to reduce daily, monthly, or even annual purchases near interconnected suppliers. For the mathematical modeling, we will use the principle of energy conservation, which states that the sum of the energies produced must be equal to the sum of the energies consumed plus the sum of the losses. For n sources and consumption point we have (1).

$$\forall\, n \epsilon \mathbb{N}\ \sum_{i=1}^{n} P_i(Produites) = \sum_{i=1}^{n} P_i(Consommées) + \sum_{i=1}^{n} P_i(Pertes) \quad (1)$$

Figure 1(b) consists of the model of our approach, which includes the essential elements of an electrical interconnection network, namely: the sources of production, a post of distribution, and a point of consumption (load). The operating principle is such that at post of distribution 1 (PD1), if thermal production (ThP) and hydroelectric production (HP) are not sufficient to assure the electricity demands of the load 1 (L1), post of distribution 2 (PD2) will support it to compensate for the overload. At post of distribution 2, if the electricity demands of the load 2 (L2) and the demand of the post of distribution 1 (PD1) are higher than solar production (SP), then the interconnection network will come into support (IN). We have modeled this operating principle using (2) and (3):

- At the post of distribution 1.

$$\begin{cases} if\ PD1 - ThP - HP \geq 0\ \Rightarrow\ PD2 = PD1 - ThP - HP \\ if\ \ PD1 - ThP - HP < 0\ \Rightarrow PD2 = 0 \end{cases} \quad (2)$$

- At the post of distribution 2.

$$\begin{cases} if\ PD2 + PD1 - SP \geq 0\ \Rightarrow\ IN = PD2 + PD1 - SP \\ if\ \ PD2 + PD1 - SP < 0\ \Rightarrow IN = 0 \end{cases} \quad (3)$$

For the construction of the Bayesian model, we use these mathematical models, (9) and (10) to define a binary state variable of the post of distribution *PD2(t)* and the interconnected network *IN(t)* as (4).

$$\forall\ t: P\big(PD2(t)\big) = P(PD1|ThP, HP)\ et\ P\big(IN(t)\big) = P((PD2 + PD1)|SP) \quad (4)$$

In other words:

$$PD2(t) = \begin{cases} 1\ \ if\ PD1 - ThP - HP \geq 0 \\ 0\ \ else \end{cases} \quad (5)$$

$$IN(t) = \begin{cases} 1\ \ if\ PD2 + PD1 - SP \geq 0 \\ 0\ else \end{cases} \quad (6)$$

The probabilities for all intervals must be equal to 1. In the case of variables that have parent nodes, such as Post Bamako, it uses the intervals defined for the thermal power station node and those described for the load Bamako node. The user must be expert enough to determine appropriate discrete intervals for each context variable so that all scenarios (a combination of parent intervals and variable) include representative data for probability function calculations. The process of calculating the probability functions of the model is called formation when BN defines the probability functions according to the values observed from the data. By using probability values with possible reasoning, the BNs can deduce based on the evidence (observed data). Indeed, once formed, the BNs can answer the following question: "What is the probability of the presence of a target node (eg, purchase RCI), given the values observed for the variable context (for example, thermal power station and solar).

3. MODELLING AND SIMULATION

We applied our approach to the Mali energy interconnection grid (EDM-sa), as shown in Figure 3, which ensures the supply of electricity to 4 regions and their major cities, as well as the capital of Mali. Hydroelectric power plants specific to the EDM, thermal power plants, and a large part of energy purchased either from a neighboring country (Ivory Coast) or from the production of Manantali (a private sector) ensure Mali's electricity demand. Three 30 MW solar power plants were connected to 3 electricity distribution points (Kayes, Kita, and Fana). Thermal production is colored red, EDM-sa's own hydroelectric production sources are colored blue, photovoltaic production is green, and purchase points are purple. Distribution stations and consumption points are coded in yellow and black, respectively. From the analysis of these data, we noted that the electricity supply service of Mali bought 54% against 46% from its own sources of production. Among these 46%, thermal production is 34%, and 12% hydroelectric production, which is insignificant.

3.1. Environmental assessment

For our case study, the thermal power plants use fuel oil as a fuel source, so their emission rates are 730 g/kWh and on this basis, we can calculate the amount of CO_2 emitted by the sources of thermal energy production in Mali. This rate will be multiplied by the annual energy produced by thermal production, which is 589,838.94 MWh according to our database. According to calculations, the thermal power plants emitted 430,582,428 kg of CO_2 in a year. The emission rate for hydroelectric is 6 g/kWh and summing all the hydroelectric generation in our system, we will have 1,136,325 GWh/year [23]. According to calculations, the emissions from hydroelectric production are 6,817,950 kg/year. The total CO_2 emission is 437,400,378 kg/year.

3.2. Construction of the Bayesian model

The Bayesian network in Figure 4(a) is the typical model of our interconnection network, and Figure 4(b) is the dynamic model of Mali's grid. The transition to the Bayesian network is done so that at the Bamako distribution post, if thermal production and its own hydroelectric power stations are not sufficient to cover the loads of the city of Bamako, the post of the city of Fana will come to support to compensate for the overload. At the Fana post, if the load of the city of Fana and the demand from the Bamako post are higher than the available solar production of Fana, then the Segou post will support. Sikasso's post works the same way as Fana's. If no PV and thermal production is available, all the charges will be supplied by the own hydroelectric production and the Ivory Coast and Manantali interconnection networks. The assumption is that the availability of thermal production and solar energy should reduce purchases at the levels of Manantali and the Ivory Coast. Our model was modeled and simulated using BayesianLab networks software (Figure 4).

In our case study, the nodes of the solar productions, each having a production capacity of 30 MW, which don't have parental nodes, were discretized using ten continuous intervals equidistant according to probabilistic relationships. Their probability distributions are made on the basis of solar production data from the different sites. The nodes of the different loads are discretized on continuous intervals with a probabilistic distribution. The nodes of the posts followed deterministic relations with conditional equations and were discretized on equidistant intervals. The Manantali and Ivory Coast purchasing nodes, which can take on all the charges in the case of unavailability of other sources, are discretized over equidistant intervals and follow probabilistic relationships. The probabilities for all intervals must be equal to 1. For the work, we relied on the one-year database collected at the level of the electricity distribution structure in Mali.

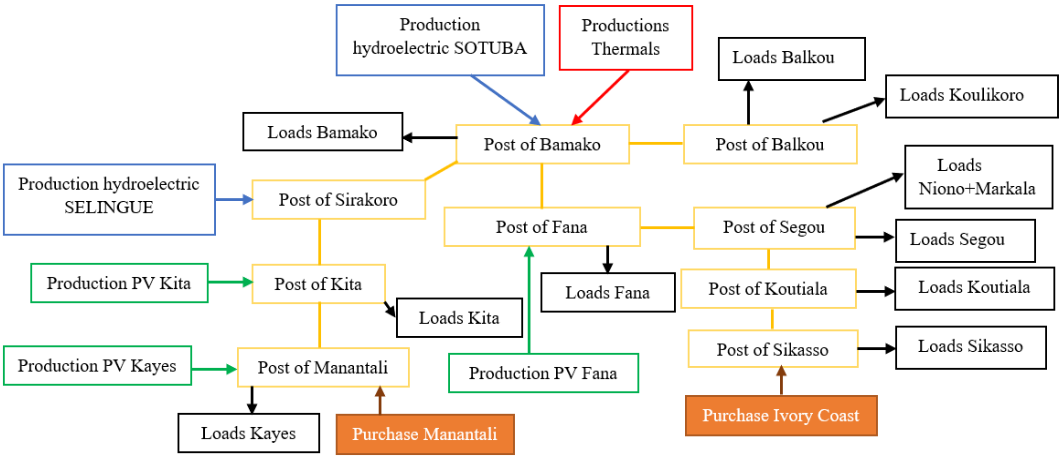
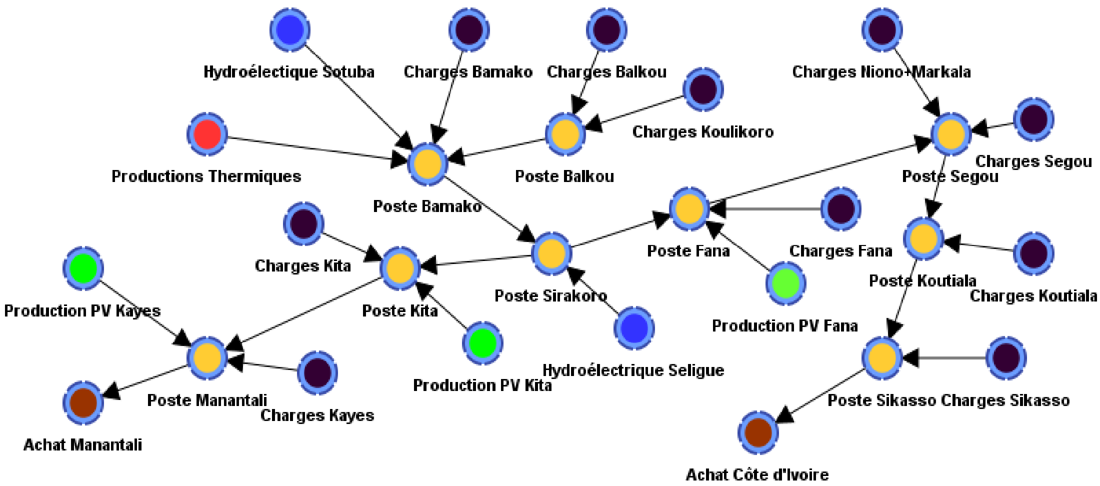
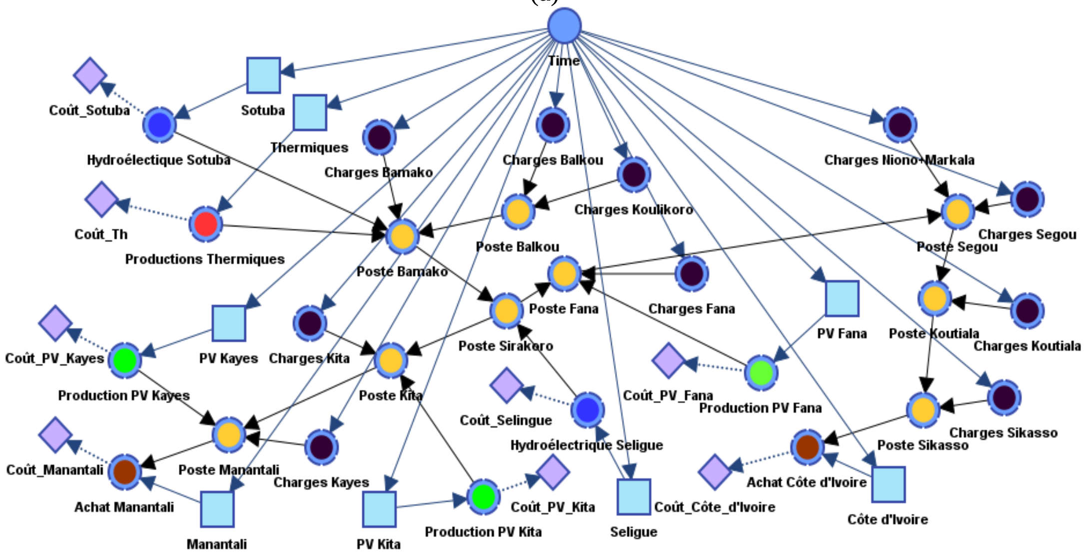


Figure 3. Mali's electricity supply interconnection network



(a)



(b)

Figure 4. Bayesian model of the Mali interconnection network: (a) dynamic Bayesian model of the Mali interconnection network and (b) under BayesianLab software

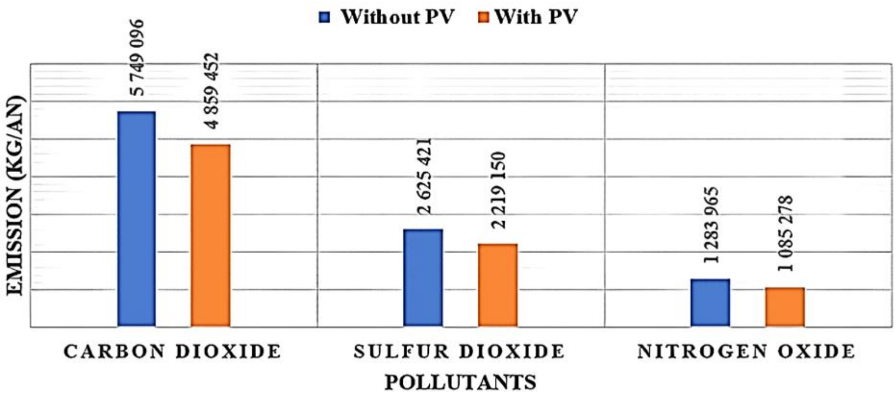
4. RESULTS AND DISCUSSION

For the simulation, we injected the 8760 data from each production system (equivalent to one year of measurement) into our model. The production costs of the SELINGUE and SOTUBA production systems have not been examined, since they are EDM's own hydroelectric productions and which have negligible ecological impacts compared to thermal productions. In Figure 5(a), we can see a reduction in greenhouse gas emissions, which are still significant, but these values are only the emissions from the sources of production of the energy purchased. The total CO_2 emitted has been reduced from 458,503,525 kg/year to 455,358,714 kg/year. Here, we have made a simulation using PV systems without playing on any of the productions (thermal and purchased energy). The objective is to see if it would be beneficial to distribute the energies produced by PV systems between the energies purchased and thermal production.

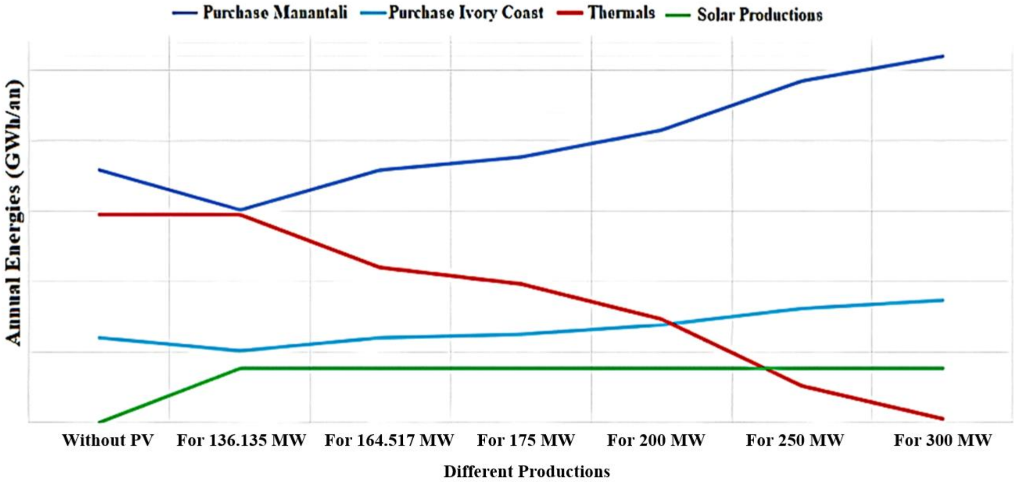
Another important objective of this part is to get an idea of how many MW per day the supply service must buy to stay in the previous scenarios. For the simulation, we fixed the value of energy purchases and increased it gradually so as to balance the distribution of solar production. For the first scenario, the service must buy around 136.135 MW per day. For the second scenario, the service must plan to buy 164.157 MW per day to remain in this scenario.

After having found the conditions of purchase for the two scenarios, we proceeded to a series of simulations by increasing the powers to buy. These simulations have the objective of playing with the operating cost. We have analyzed the forecast cases of 175 MW, 200 MW, 250 MW, and 300 MW in Figures 4-6. Figure 4 illustrates the trend of different productions depending on the power demand. We note that the more the forecast of energy purchases increases, the more the production of thermal energy decreases. Thermal production becomes lower than solar production when we plan to buy 250 MW/day. For a purchase forecast of 300 MW/day, thermal production is almost insignificant Figure 5(b).

Figure 6 summarizes the emission balance for carbon dioxide (CO_2), which is the most polluting element in greenhouse gases. We observe that the CO_2 emissions are proportional to the thermal production and inversely proportional to the purchase of energy. For a purchase forecast of 136,135 MW/d, there was an annual energy purchase of 803.36 GWh/year and thermal production of 589.84 GWh/year, resulting in an emission of 458,500,000 kg/year (Figure 5). This emission decreased to 87,840,000 kg/year and 15,660,000 kg/year for a purchase forecast of 250 MW and 300 MW, corresponding respectively to an annual thermal production of 103.86 GWh/year and 9.54 GWh/year (Figure 6).



(a)



(b)

Figure 5. Ecological and economic impact of the use of PV systems: (a) greenhouse gas emissions before and after the use of PV systems; and (b) the trend of different productions according to forecasts

Figure 7 shows the costs of thermal production, the costs of energy purchased, and the total cost of using these energy sources by the electricity supply service in Mali. It shows that the use of PV systems has helped to reduce production costs. It can be observed that by increasing the forecast to buy more, the total cost of use is considerably reduced. The forecast to buy 136.135 MW/day is the most expensive at around 136.55 billion FCFA for a cost of thermal production of 90.36 billion and a cost of energy to buy of 46.19 billion (Figure 7, curve cost_total). By increasing the forecast to buy, the cost of thermal production decreases by reducing the total cost of use. This total cost will be reduced to 90.2 billion and 80.035 billion FCFA for a forecast of 250 MW and 300 MW per day, respectively (Figure 6). Through the analysis of Figures 5 and 6, we note that for the forecast to buy 300 MW/day, thermal productions to decrease from 103.86 GWh/year to 9.54 GWh/year (Figure 6) but the cost of thermal production has only decreased from 16 billion to 14.75 billion FCFA Figure 7, the ratio is really low. So, it would not be desirable to exceed a

250 MW/day purchase forecast. We also notice that thermal production is expensive and not recommended for supplier service.

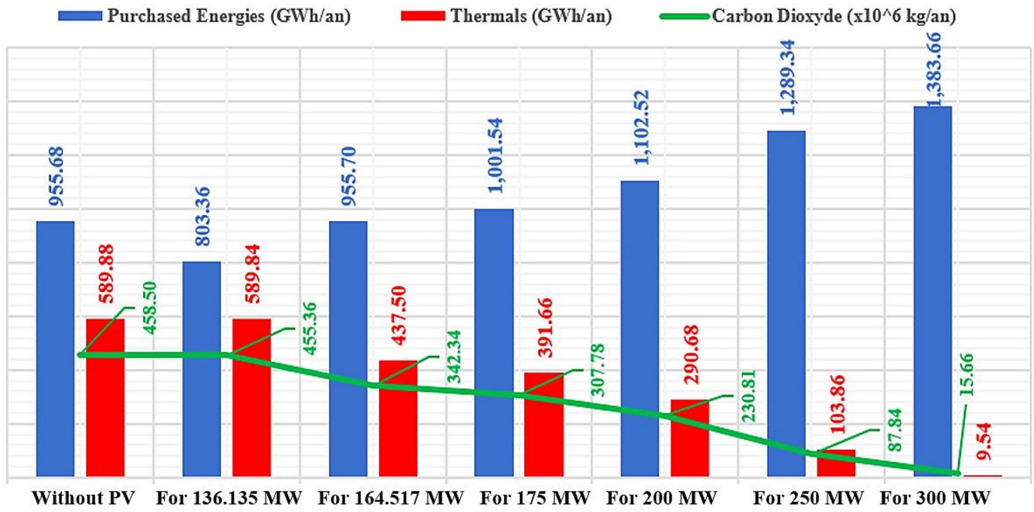


Figure 6. The amount of carbon dioxide emitted for the different forecasts

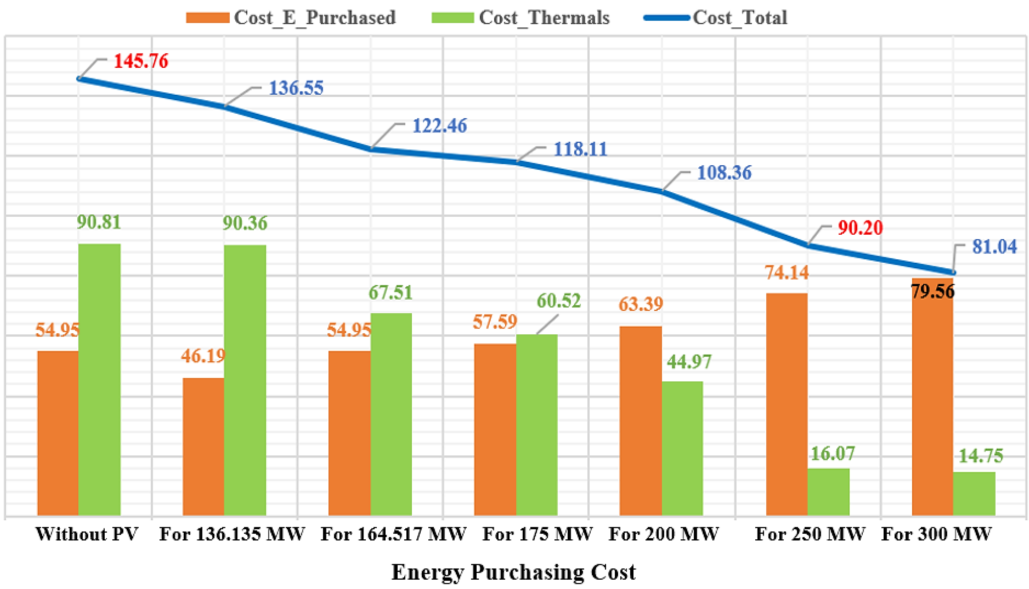


Figure 7. The annual production costs of the different productions

5. CONCLUSION

The Mali electricity supply service called Mali energy (EDM-sa) includes its production systems, constituting hydroelectric power stations and thermal power stations, production systems Manantali and the interconnection network Ivory Coast, whose service buys energy. The total energy produced during 2018 was 1,726,164 GWh/year, of which 237,046 GWh/year was purchased from the neighboring country, Ivory Coast, i.e. 14% of total production, and 697,818 GWh/year was purchased on the interconnected grid of Manantali, 40% of the total production. The total energy purchased by Mali's electricity supply service was 934,864 GWh/year (75% for Manantali and 25% for Ivory Coast). Thermal production was 589,839 GWh/year or 34% of total production, and the hydroelectric production specific to EDM Selingue and Sotuba was, respectively, 169.73 GWh/year and 31,731 GWh/year, i.e. 10% and 2% of total production. We have used Bayesian Networks to model our case study. The goal was to allow the dispatching service to have a decision support tool that would allow the dispatching service to make better purchasing precision for energy and thermal production. For that, we have combined analytical and probabilistic models with the Bayesian network.

A first simulation was made without the photovoltaic systems to make the economic and ecological assessment of the year. The simulation of this scenario does not bring enough effect; the total cost of production only reduced from 145.76 billion FCFA to 136.55 billion FCFA per year, a gain of 9.21 billion FCFA, and CO_2 emissions have been reduced from 458,503,525 kg/year to 455,358,714 kg/year. The second scenario was to play simultaneously on thermal productions and purchased energies in order to reduce the investigation cost of the electricity supply service in Mali using PV. In this part, we have increased the forecast of the energies to buy and observed the economic and ecological effects. The results of the simulation showed us that by increasing the purchase forecast, the total investigation cost decreases, as well as the CO_2 emissions. In conclusion, thermal production is the costliest economically and ecologically.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
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Abdoulaye Sissoko		✓	✓			✓		✓	✓	✓	✓			
Fadaba Danioko	✓			✓			✓			✓	✓	✓	✓	✓
David Tchoffa					✓					✓		✓	✓	
Abderrahman El Mhamedi				✓	✓		✓			✓		✓		✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Derived data supporting the findings of this study are available from the corresponding author, [AFT], on request.

REFERENCES

[1] A. F. Touré, S. Addouche, F. Danioko, B. Diourté, and A. Mhamedi, "Hybrid systems optimization: Application to hybrid systems photovoltaic connected to grid. A Mali case study," *Sustainability*, vol. 11, no. 8, p. 2356, Apr. 2019, doi: 10.3390/su11082356.

[2] M. Mungkin, H. Satria, D. Maizana, M. Isa, S. Syafii, and M. Y. Puriza, "Analysis of the feasibility of adding a grid-connected hybrid photovoltaic system to reduce electrical load," *International Journal of Power Electronics and Drive Systems (IJPEDS)*, vol. 14, no. 2, p. 1160, Jun. 2023, doi: 10.11591/ijpeds.v14.i2.pp1160-1171.

[3] A. F. Toure, F. Danioko, B. Diourte, and N. Keita, "Study of decision support for the installation of photovoltaic systems coupled to the electricity grid: Mali's case study," *Journal of Emerging Science and Engineering*, vol. 3, no. 1, p. e29, Dec. 2024, doi: 10.61435/jese.2025.e29.

[4] E. Kymakis, S. Kalykakis, and T. M. Papazoglou, "Performance analysis of a grid connected photovoltaic park on the island of Crete," *Energy Conversion and Management*, vol. 50, no. 3, pp. 433–438, Mar. 2009, doi: 10.1016/j.enconman.2008.12.009.

[5] B. A. M. Nouadje, P. Tiam Kapen, V. Chegnimonhan, and R. Tchinda, "Techno-economic analysis of a grid/fuel cell/PV/electrolyzer system for hydrogen and electricity production in the countries of African and Malagasy council for higher education (CAMES)," *Energy Strategy Reviews*, vol. 53, p. 101392, May 2024, doi: 10.1016/j.esr.2024.101392.

[6] V. Sharma, A. Kumar, O. S. Sastry, and S. S. Chandel, "Performance assessment of different solar photovoltaic technologies under similar outdoor conditions," *Energy*, vol. 58, pp. 511–518, Sep. 2013, doi: 10.1016/j.energy.2013.05.068.

[7] C. Ichim-Burlacu, C.-L. Rat, C. Panoiu, and C. Cuntan, "PV panel monitoring using Arduino and LabVIEW," in *2023 5th Global Power, Energy and Communication Conference (GPECOM)*, IEEE, Jun. 2023, pp. 270–275. doi: 10.1109/GPECOM58364.2023.10175667.
[8] A. Anurag, Y. Yang, and F. Blaabjerg, "Reliability analysis of single-phase PV inverters with reactive power injection at night considering mission profiles," in *2015 IEEE Energy Conversion Congress and Exposition (ECCE)*, IEEE, Sep. 2015, pp. 2132–2139. doi: 10.1109/ECCE.2015.7309961.
[9] K. Ma, H. Wang, and F. Blaabjerg, "New approaches to reliability assessment: Using physics-of-failure for prediction and design in power electronics systems," *IEEE Power Electronics Magazine*, vol. 3, no. 4, pp. 28–41, Dec. 2016, doi: 10.1109/MPEL.2016.2615277.
[10] F. Blaabjerg, D. Zhou, A. Sangwongwanich, and H. Wang, "Design for reliability in renewable energy systems," in *2017 International Symposium on Power Electronics (Ee)*, IEEE, Oct. 2017, pp. 1–6. doi: 10.1109/PEE.2017.8171658.
[11] V. de N. Ferreira, A. F. Cupertino, H. A. Pereira, A. V. Rocha, S. I. Seleme, and B. de J. C. Filho, "Design and selection of high reliability converters for mission critical industrial applications: A rolling Mill case study," *IEEE Transactions on Industry Applications*, vol. 54, no. 5, pp. 4938–4947, Sep. 2018, doi: 10.1109/TIA.2018.2829104.
[12] F. Blaabjerg, A. Sangwongwanich, and Y. Yang, "Flexible power control of photovoltaic systems," in *Advances in Renewable Energies and Power Technologies*, Elsevier, 2018, pp. 207–229. doi: 10.1016/B978-0-12-812959-3.00006-X.
[13] A.-J. Perea-Moreno, Q. Hernandez-Escobedo, J. Garrido, and J. Verdugo-Diaz, "Stand-alone photovoltaic system assessment in warmer urban areas in Mexico," *Energies*, vol. 11, no. 2, p. 284, Jan. 2018, doi: 10.3390/en11020284.
[14] W. Chen, E. Hotchkiss, and A. Bazzi, "Reconfiguration of NPC multilevel inverters to mitigate short circuit faults using back-to-back switches," *CPSS Transactions on Power Electronics and Applications*, vol. 3, no. 1, pp. 46–55, Mar. 2018, doi: 10.24295/CPSSTPEA.2018.00005.
[15] P. Weber, P. Munteanu, and L. Jouffe, "Dynamic Bayesian networks modelling the dependability of systems with degradations and exogenous constraints," *IFAC Proceedings Volumes*, vol. 37, no. 4, pp. 207–212, Apr. 2004, doi: 10.1016/S1474-6670(17)36120-7.
[16] A. Samé, L. Bouillaut, P. Aknin, and A. Ben Salem, "Dynamic Bayesian networks with continuous exogenous variable for the classification of singular points on a railroad track (in French: Réseaux bayésiens dynamiques à variable exogène continue pour la classification des points singuliers d'une voie ferrée)," *Revue d'intelligence artificielle*, vol. 21, no. 3, pp. 353–370, Jun. 2007, doi: 10.3166/ria.21.353-370.
[17] A. F. Toure, D. Tchoffa, A. El Mhamedi, B. Diourte, and M. Lamolle, "Modeling and control maximum power point tracking of an autonomous photovoltaic system using artificial intelligence," *Energy and Power Engineering*, vol. 13, no. 12, pp. 428–447, 2021, doi: 10.4236/epe.2021.1312030.
[18] V. Olabi and H. Jouhara, "An assessment of current hydrogen supply chains in the Gulf Cooperation Council (GCC)," *Energy*, vol. 299, p. 131576, Jul. 2024, doi: 10.1016/j.energy.2024.131576.
[19] G. Yingkui and L. Jing, "Multi-State System Reliability: A New and Systematic Review," *Procedia Engineering*, vol. 29, pp. 531–536, 2012, doi: 10.1016/j.proeng.2011.12.756.
[20] F. C. Sica, F. G. Guimarães, R. de O. Duarte, and A. J. R. Reis, "A cognitive system for fault prognosis in power transformers," *Electric Power Systems Research*, vol. 127, pp. 109–117, Oct. 2015, doi: 10.1016/j.epsr.2015.05.014.
[21] D. Lee and R. Pan, "Predictive maintenance of complex system with multi-level reliability structure," *International Journal of Production Research*, vol. 55, no. 16, pp. 4785–4801, Aug. 2017, doi: 10.1080/00207543.2017.1299947.
[22] L. Hichem, O. Amar, and M. Leila, "Optimized ANN-fuzzy MPPT controller for a stand-alone PV system under fast-changing atmospheric conditions," *Bulletin of Electrical Engineering and Informatics*, vol. 12, no. 4, pp. 1960–1981, Aug. 2023, doi: 10.11591/eei.v12i4.5099.
[23] A. F. Touré, "Decision support for the siting of grid-connected photovoltaic stations: a case study in Mali (in French: Aide à la décision pour l'Implantation des Stations Photovoltaïques couplées au Réseau électrique : Cas d'application au Mali)," Université de Paris8, 2020.
[24] F. Danioko, S.-A. Addouche, and A. El Mhamedi, "Formalization of an approach for improvement of maintenance policy on multi-state systems," *International Journal of Engineering Research and Development*, vol. 10, no. 8, pp. 36–44, 2014.
[25] N. Ghorbel, "Management of periodic replenishments of spare parts under uncertainty for the MCO of equipment fleets: controlling the risk of stock shortages (in French: Gestion des réapprovisionnements périodiques de pièces de rechange sous incertitudes pour le MCO de," 2013.

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