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Research Article

Optimal Planning of Renewables Energies Management in Power Energy Systems

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Abstract

Optimal management of renewable energy resources is a priority, especially in a global energy mix where fossil fuels are increasingly exploited. The major challenge associated with these renewable resources lies in their intermittency. Complementarity and optimal management of these resources are therefore essential. This article proposes a model for managing renewable energies in power grid systems with a storage system. The resulting model has been tested. Python 3.10 programming language was used to solve the optimization problem, using mixted integer linear programming. To test the model, a special case study was carried out in the South of Togo, representing almost 96% of the country's electrical loads. In this study, resources were first evaluated for one year, then compared according to their evolution over the years. The results showed that the country's energy potential is considerable, but unevenly distributed. The study showed that in the north and center of the country, solar energy and biomass are the main resources available. In the south, on the other hand, energy potential is based on solar, wind, hydro and biomass. The optimization results obtained for the south of the country have enabled to plan better the management of these resources over the course of the year. The results show a composition of maximum load satisfaction, with 39% from grid compared with 8% from hydro, 10% from wind, 12% from batteries systems and 31% from photovoltaic systems. The storage required for energy management is estimated at 220 kWh, with an optimal annual value for the objective cost function of around 67885.10212 USD. The model thus obtained provides a decision-making tool for the optimal management of renewable resources.

Keywords

Optimal Management, Model, Renewable Energy, Programming, Optimization

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1. Introduction

The need to meet ever-increasing energy demand while respecting environmental protection requirements, in particular the reduction of greenhouse gas emissions, is the major challenge facing the global energy system today. In 2022 alone, according to the International Energy Agency (IEA), fossil fuels will account for almost 82% of primary energy consumption and around 61% of electricity generation worldwide [1]. What's more, by 2030, the agency estimates that fossil fuels will account for 73% of the global energy mix. The global energy mix is made up of renewable and non-renewable resources, including fossil fuels. This increase in global consumption of primary fossil fuels is all the more worrying in that they are not extensible, and their over-exploitation contributes significantly to climate change and increasingly frequent ecological disasters. To meet this challenge, the international community is increasingly turning to renewable energy sources that are more readily available and, above all, less polluting [2, 3]. However, these renewable energy resources are often intermittent and associated with challenges due to non-uniform meteorological and seasonal variations resulting in varied production [4]. Optimum management of these resources is essential if we are to find solutions to these challenges. Many different resource systems are thus coupled [5, 6]. D. P. E Silva and al [7], for example, propose an optimization of a microgrid based on a hybridization system of renewable energy resources; a strategy for controlling and managing the energy supply in a microgrid in order to achieve higher efficiency, reliability and economy, are proposed in the studies [8, 9]. Other studies carried out in the reduction of systems exploiting non-renewable fossil energy resources and advocating renewable resources, are presented in articles [10-13].

Renewable energy resources include solar, wind, hydraulic and biomass power, as well as a storage system, constituting an energy reserve and production system. The aim of this work is therefore to propose a management model for electrical energy systems in an energy mix made up of grid power, solar, wind, hydraulic and battery systems. A specific study of the case of Togo was taken into account. The proposed model is then solved in a mixed integer linear programming language, using Python.

2. Theoretical Background

2.1. Solar Power

Solar energy is the most abundant form of energy. In fact, this energy can be harnessed by solar photovoltaic and battery systems. Each photovoltaic system is made up of solar panels, which in turn are made up of solar cells. The current-voltage characteristic of a photovoltaic cell can therefore be expressed mathematically [14, 15]:

$$I = I_{ph} - I_0.(exp\left(\frac{q(V+R_sI)}{AKT} - 1\right) - \frac{V+R_sI}{R_{sh}} \quad (1)$$

it can be expressed in more detail as a diffusion current and a generation-recombination current:

$$I = I_{ph} - I_{0d}.(exp\left(\frac{q(V+R_sI)}{KT} - 1\right) - I_{0g}.(exp\left(\frac{q(V+R_sI)}{2KT} - 1\right) - \frac{V+R_sI}{R_{sh}} \quad (2)$$

And the current network is then expressed temporally as follows, according to Kamal Anoune [15]:

$$I(t) = n_pI_{ph} - n_pI_0.(exp\left(\frac{q(V+R_sI)}{n_sAKT} - 1\right) \quad (3)$$

Thus, the power obtained from a photovoltaic panel is a function of the output voltage [16]:

$$P(t) = I(t) \times V(t) \quad (4)$$

However, the maximum power produced by a photovoltaic solar panel can be calculated directly as a function of irradiation, using the formula [17, 18]:

$$P_s(t) = \eta \times \varepsilon \times S \times I(t) \times (1 - k\Delta t) \times X_s^d \quad (5)$$

With

$$\Delta t = T_c - T_{c,ref} \quad (6)$$

Irradiation is expressed according to [19] as:

$$I(t) = I_0(t)(a + b\frac{n}{N}) \quad (7)$$

$$I_0(t) = \frac{24\times3600\times G_{sc}}{\pi}\left(1 + 0.033 \times cos(\frac{360\times n_d}{365})\right) \times \left(cos\emptyset cos\delta sin\omega_s + \frac{\pi\omega_s}{180}sin\emptyset sin\delta\right) \quad (8)$$

$$\delta = 23.45sin\left(360\frac{248+n_d}{365}\right) \quad (9)$$

$$\omega_s = cos^{-1}(-tan\emptyset tan\delta) \quad (10)$$

a= 0.33; b=0.43; $G_{sc} = \frac{1367W}{m^2}$

Solar power generation can be made possible either with energy storage, or without energy storage.

2.2. Battery Systems

Battery systems are not only electrical energy storage systems [20], they are also energy production systems. In fact, when there is a surplus of energy, they enable the surplus to be accumulated, while at the same time acting as an electrical energy compensator in the electrical system when there is a deficit. Technical references for battery examples are provided [21, 22]. The state of charge and power of the battery [23, 24, 25, 26] at each simulation instant is formulated as follows:

$$soct(t+1) = soct(t) + \frac{p_{bat}(t)\times\Delta t}{N_{bat}\times C_{bat}\times V_{bat}}\eta_{bat} \quad (11)$$

$$soct^{max}(t) \geq \tau \times E_{bat}^{limit} \quad (12)$$

$$soct^{min}(t) \leq \tau' \times E_{bat}^{limit} \quad (13)$$

$$E_{bat}^{limit} = p_{bat}(t) \times \Delta t \quad (14)$$

$\tau, \tau' < 1$

$$p_{bat}(t) = P_s(t) - \frac{P_{charge}(t)}{\eta_{onduleur}} \quad (15)$$

$$P_{bat}^{min}(t) = N_{bat}\, min\{0,\, C_{bat} \times V_{bat} \times (soct^{min} - soct(t))/\Delta t\} \quad (16)$$

$$P_{bat}^{max}(t) = N_{bat}\, max\{0,\, C_{bat} \times V_{bat} \times (soct^{max} - soct(t))/\Delta t\} \quad (17)$$

2.3. Wind Power

Techniques for harnessing wind resources are essential, especially as the exploitation of these primary natural resources is now a priority. Indeed, knowledge of the availability of the wind resource is necessary for its optimization. Wind power is a clean, renewable energy produced by the force of the wind on the blades of a propeller. Wind speed is thus characterized indirectly, on the one hand, according to Weibull's law, which makes it possible to determine the Weibull parameters that best correspond to the distribution function of the histogram of wind speed measurements at the site under consideration. The wind distribution function is expressed as [27, 17, 28]:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} exp\left[-\left(\frac{v}{c}\right)^{k}\right] \quad (18)$$

with

$$k = \left(\frac{\sigma}{\bar{v}}\right)^{-1.086} \quad (19)$$

$$c = \frac{\bar{v}}{\Gamma(1+\frac{1}{k})} \quad (20)$$

$$\Gamma(\alpha) = \int_0^{\infty} x^{(\alpha-1)} e^{-x} dx \quad (21)$$

The average power output is therefore:

$$\bar{P} = \int_0^{\infty} P(v).f(v)dv \quad (22)$$

Figure 1 shows the wind turbine's power output as a function of wind speed:

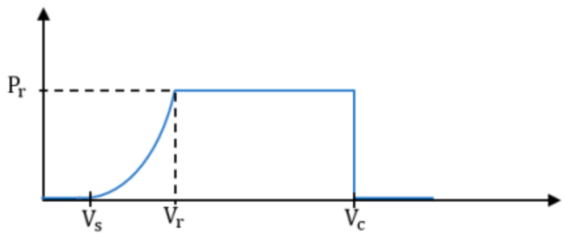

Figure 1*. Wind power distribution by speed.*

The variation in power as a function of wind speed is broken down as follows:

$$P(v) = \begin{cases} 0; v < Vs \\ p_1(v);\ Vs < v < Vr \\ Pr;\ Vr < v < Vc \\ 0; v > Vc \end{cases} \quad (23)$$

On the other hand, direct measurement of wind speed allows us to express the wind power of the site under consideration by the equation:

$$P_e(t) = \frac{1}{2} \times \rho_e \times S_w \times v^3(t) \times \eta_e \times X_e^d \quad (24)$$

2.4. Water Power

Hydropower is the electrical energy generated by water resources. Depending on the energy capacity to be produced, there are small-scale hydroelectric power plants with a maximum installed capacity of 30 MW or less, medium-scale hydroelectric power plants with a capacity of between 30 MW and 100 MW, and large-scale hydroelectric power plants with a capacity of over 100 MW [29]. Hydroelectricity production depends on the average flow of water (m3/s) over a period of time t; the difference in height between inlet and outlet (ht) in m, the acceleration due to gravity (g) in m/s2, the density of the water and the efficiency [18, 30, 21]. It is expressed by:

$$P_h(t) = \rho_h \times g \times Q \times h \times \eta_h \quad (25)$$

2.5. Biomass Power

Biogas production remains an essential opportunity for valorizing animal, vegetable, local, agricultural and other wastes. However, many countries are in the process of implementing the exploitation of this resource. Indeed, Asheal Mutungwazi et al. present the amount of biogas produced as a function of biodigester capacity installation in South Africa [31]. Moreover, according to Rafat Al Afif et al [32], there are no specific impacts of extreme events that could affect biomass power generation worldwide. The daily biogas volume was therefore expressed as a function of the methane volume by [33]:

$$V_{bio} = \frac{V_M}{0.01X_{CH4}} \quad (26)$$

$$V_M = \frac{c\times 0.01X_{CH4}\times Vm\times 0.01V_S\times 0.75\times M_{MSW}}{M_C} \quad (27)$$

It then follows that:

$$V_{bio} = \frac{c\times Vm\times 0.01V_S\times 0.75\times M_{MSW}}{M_C} \quad (28)$$

Electrical power output (in kW) is:

$$P_b = \frac{\eta_g\times V_M\times E_{CH4}}{\Delta t} \quad (29)$$

C. Togo's energy context

Togo is located in the northern hemisphere of West Africa, between the 6th and 11th parallels of north latitude and between the meridians 0 °30' and 1 °30' of east longitude. It does, however, have enormous potential for power supply. Existing production resources include thermal, solar, hydro and imported power.

Aside from the country's potential for renewable resources, it should be noted that most of Togo's electricity is generated by thermal power plants. Numerous diesel-powered units (both large and small) are also installed in the country, either in isolated networks or connected to the grid. Examples of large thermal power plants include: Lome B (11 MW); Lome seat (16 MW); Contour Global (99.7 MW); Tag Lome port (23 MW); Dapaong (1.9 MW); Kara (3.2 MW); Sokode (1 MW). Total production is ~ 158 MW. In view of all these non-renewable resource capacities, it is therefore necessary to carry out this study to assess the country's renewable natural resource potential, in order to make a significant contribution to their management.

In recent years, Togo has begun to promote the use of primary resources. Indeed, the country also has a number of photovoltaic mini-power plants to cover the needs of small villages. These were all completed between 2017 and 2018:

1) the Assoukoko mini-solar power plant with 250 kWp;
2) the Bavou mini-solar power plant with 150 kWp;
3) the Kountoum mini-solar power plant with 100 kWp;
4) the Takpapieni mini-solar power plant with 100 kWp.

In addition to these mini solar power plants, the country also has the Blitta solar power plant, with a capacity of 70 MW.

Togo has an interesting hydraulic potential, which is highly seasonal (seasons vary from region to region). The hydrographic system is made up of three main basins: the Volta basin, draining rivers to the north-west (approx. 26,700 km²); the Mono basin, draining rivers to the south-east (approx. 21,300 km²); and the Lake Togo basin (approx. 8,000 km²) [33]. The Nangbéto power plant was commissioned in 1987. It is the country's most powerful hydroelectric plant. In reality, however, it produces half for Togo and half for Benin. It is located on the Mono River, 210 km northeast of Lomé. Its installed capacity is 2 x 32.8 MW. After 25 years in operation, the plant is currently undergoing major rehabilitation. Numerous hydroelectric site projects have been launched and are currently being studied to make use of the available energy potential. At present, just under 70 MW of hydroelectric power is used throughout the country. There are two hydroelectric power plants on Togolese soil. The Nangbéto plant is the main source of hydroelectric power. A second small power station produces electricity at Kpimé.

Biomass, although less developed in the country, is produced entirely from domestic resources. In 2018, the total biomass-based primary energy supply was 2972 ktoe, of which 99% (2940 ktoe) was wood energy, notably firewood and charcoal (DGE, 2019). The remainder is plant waste (26 ktoe). Among the few biodigester-based biomass resources for power generation is the methanization unit with a capacity of 50 to 80 m3 shown in the figure below. This unit produces usable energy, while the solid digestate produced after methanization is used to amend agricultural fields and for co-composting. Finally, liquid digestates are used to accelerate the maturation of agricultural waste (grass, corn waste, straw, etc.). It should be pointed out that the country does not yet produce bio-electricity on a national scale. The few existing units are for domestic and personal use. In fact, production is still in its infancy, and there are some 15 bio-digesters, but only 4 are operational and producing biogas and/or electricity, whereas biogas production deposits are very large and could be the subject of macro or micro-technology methanization facilities, depending on the abundance of deposits. These deposits are made up of: livestock and slaughterhouse waste (poultry droppings: 2,496 tonnes/year, goat manure: 2,976 tonnes/year, cow sludge: 8,100 tonnes/year, i.e. a total of 13,560 tonnes/year (DGE, 2019/ UL/WASCAL, 2019)); agricultural waste (farm residues: 93798 tonnes/year on average; and agricultural or agro-industrial processing waste: 696.45 tonnes/year on average) with very high methanogenic power, municipal waste, forestry waste.

In addition, no wind power systems have yet been installed in the country. Studies to analyze annual power availability could contribute to future decision-making.

Apart from these various primary and secondary resources, Togo is mainly an importer of electrical energy. It imports energy from neighboring countries such as Côte d'Ivoire, Ghana and Nigeria. Togo does, however, export a small amount of power to Burkina Faso.

The use of all natural energy resources is essential if we are to achieve energy independence through optimal exploitation of these resources.

2.6. Bibliographical Reviews

Optimizing the use of natural resources requires numerical optimization methods not only to minimize investment costs, but also to plan the management of these resources. These methods are based on mathematical formulations and numerical calculations. These include Newton's method, the simplex method and others.

In fact, several optimization methods for solving engineering problems have been studied. The work of a number of authors is mentioned here. In Chile, Gomez Sanchez et al [34] presented a paper entitled "A mathematical model for the optimization of renewable energies systems", in which they describe different mathematical optimization models based solely on solar and wind power. The CPLEX linear programming method is exploited.

In India, Md Mustafa Kamal et al [35] propose a grid-connected electrification system with an integrated model formed by the solar photovoltaic system, wind power and the battery. The proposed model is optimized using a differential algorithm to determine the optimal system configuration. This algorithm is compared with the genetic algorithm and particle swarm optimization. The results obtained in their article show better optimization with the differential algorithm.

In Cameroon, Divine Khan Ngwashi et al [36] worked on a study of optimized Congolese microgrid systems compared with gas, PV and battery. It was shown that PV and battery systems are more reliable. Homer software was used.

In Colombia, more precisely in the isolated community of Playa Potes, in the department of Choco a case study was undertaken by Juan Pablo Viteri et al [18], to test the optimization model for planning renewable stand-alone power systems is an Implicit Stochastic Optimization model. The results obtained suggested, as the best solution, an electrical system based on solar energy with capacities of 22 and 29 kWp, and battery storage of 74 and 93 kWh.

In Ethiopia, Getachew Bekele and Getnet Tadesse [19] carried out a feasibility study of a small hybrid hydro/PV/wind and diesel system for rural electrification. A battery system was not considered in this article. HOMER energy software is used for optimization and sensitivity analysis of the hybrid system.

Siddaiah et al. exploit the evolutionary approach of artificial intelligence on a solar-wind hybrid study.

In short, several studies have been carried out using methods [29] that are either deterministic (mixed integer programming, linear programming [37]...); stochastic (pareto optimization [35, 36], Langrage's method,...); and meta-heuristic (genetic algorithm [38, 39], neural networks, particle swam [40, 41], evolutionary algorithm [42, 43]).

Among all these different methods, there is the linear programming [44, 45] and mixed integer linear (PLNEM) solution method, which provides a suitable framework for obtaining high-quality solutions [46] with acceptable computational effort and good convergence properties. Indeed, this method has been used in the past to solve hybrid models of renewable energy systems. We can cite the work of Nagabhushana A. et al [47], who used the linear programming approach in Maltlab to solve the economic problem of hybrid systems (solar/battery/wind); of A. K. Akella et al. who used the LINDO linear solver for their solar/wind/biomass system optimization work [37]; Ruey-Hsun Liang [48], Wai Lip Theo et al. [49, 44, 46, 50, 51]. The ANFIS (Adaptive Neuro-Fuzzy Inference System) software, based on a neuro-fuzzy system, has been exploited [52]. Other works based on PLNEM are studied: L. Ferrer-Martí et al. [53], optimize the design of wind-PV hybrid systems, solving the issue of wind-PV generator location and microgrid design, taking into account point-of-consumption demand and energy potential; W. S. Ho et al. optimize a biomass/solar system for a smart-village in Malaysia for the use of these renewable resources [54].

The linear and mixed integer linear programming solution method is therefore widely used for HRES (Hybrid Renewable Energy Systems) and is characterized by good convergence [55, 56].

3. Materials and Methods

3.1. Material

Python, programming language version 3.10, was used. The optimization problem is formulated as an instance of mixed integer linear programming. The algorithm obtained in Python is then solved using the simplex method.

3.2. Method

3.2.1. General Formulation

Optimization consists in minimizing or maximizing the following function f(x) subject to defined constraints:

$$min/max: f(x) = [\, f_1(x), f_2(x), \dots f_n(x)] \quad (30)$$

Subject to:

$$h(x) \geq 0 \quad (31)$$

The proposed energy management model optimizes the efficient management of energy resources while minimizing energy costs.

3.2.2. Power Distribution System Model

Consider a global system made up of several subsystems with different energy resources (electricity grid, solar (PV), wind, hydro, etc.) and different unit energy costs. Supposing these systems are already installed, the aim of the work is to minimize the cost of penetrating these different resources into the electrical network, for efficient annual management of electrical energy production.

The design of the model thus defined, inspired by [57, 58], is shown in Figure 2.

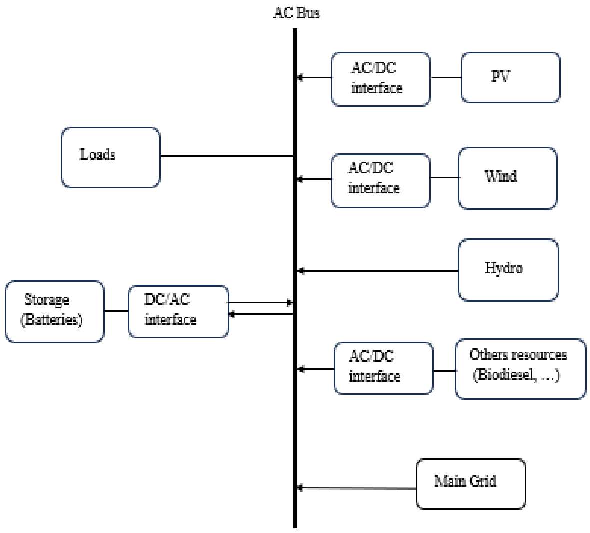

Figure 2. *Power grid model for efficient management of renewable resources.*

The case of Togo's renewable resources served as an application for the model developed in a Python programming language.

3.2.3. Problem Formulation: Optimal Management of Renewable Resources in the Network

In reality, the aim is to satisfy electrical loads at any given moment, based on the exploitation of existing primary resources, in order to minimize external energy dependency in the power grid.

The aim is therefore to reduce loads on the power grid by optimally combining the various non-homogeneously distributed and intermittent natural resources over the course of a year. The problem is then formulated as the following optimization problem:

Objective function:

$$min: f(t) \quad (32)$$

$$f(t) = \sum_{i=1}^{6} \sum \sum \alpha_i c_i P_i \quad (33)$$

Subject to:

$$\sum_{i=1}^{5} \sum \alpha_i P_i = \alpha_6 P_{bat} + P_l \quad (34)$$

$$\alpha_i = \begin{Bmatrix} 1 \; if \; the \; resource \; is \; available \\ 0 \; if \; not \end{Bmatrix} \quad (35)$$

$$i = \begin{cases} 1, solar\ (s) \\ 2, wind\ (e) \\ 3, hydraulic\ (h) \\ 4, biomass\ (bio) \\ 5, grid\ (r) \\ 6, battery\ (bat) \end{cases} \quad (36)$$

$$\begin{bmatrix} P_s^{min}(t) \\ P_e^{min}(t) \\ P_h^{min}(t) \\ P_{bio}^{min}(t) \\ P_{bat}^{min}(t) \\ soct^{min}(t) \end{bmatrix} \leq \begin{bmatrix} P_s(t) \\ P_e(t) \\ P_h(t) \\ P_{bio}(t) \\ P_{bat}(t) \\ soct(t) \end{bmatrix} \leq \begin{bmatrix} P_s^{max}(t) \\ P_e^{max}(t) \\ P_h^{max}(t) \\ P_{bio}^{max}(t) \\ P_{bat}^{max}(t) \\ soct^{max}(t) \end{bmatrix} \quad (37)$$

$$P_r(t) \geq 0 \quad (38)$$

for

$$P_s(t) = \eta \times \varepsilon \times S \times I(t) \times (1 - k\Delta t) \times X_s^d$$

$$P_e(t) = \frac{1}{2} \times \rho_e \times S_w \times v^3(t) \times \eta_e \times X_e^d$$

$$P_h(t) = \rho_h \times g \times Q \times h \times \eta_h \times X_h^d$$

$$P_{bio}(t) = \frac{\eta_g \times V_M \times E_{CH4}}{\Delta t} \times 1000$$

$$soct(t+1) = soct(t) + \frac{p_{bat}(t) \times \Delta t}{N_{bat} \times C_{bat} \times V_{bat}} \eta_{bat}$$

$$soct^{max}(t) \geq \tau \times E_{bat}^{limit}$$

$$soct^{min}(t) \leq \tau' \times E_{bat}^{limit}$$

$$E_{bat}^{limit} = p_{bat}(t) \times \Delta t$$

$$\tau, \tau' < 1$$

$$p_{bat}(t) = P_s(t) - \frac{P_{charge}(t)}{\eta_{onduleur}}$$

$$P_{bat}^{min}(t) = N_{bat}\, min\{0,\ C_{bat} \times V_{bat} \times (soct^{min} - soct(t))/\Delta t\}$$

$$P_{bat}^{max}(t) = N_{bat}\, max\{0,\ C_{bat} \times V_{bat} \times (soct^{max} - soct(t))/\Delta t\}$$

under

$$I(t) = I_0(t)(a + b\frac{n}{N})$$

$$I_0(t) = \frac{24 \times 3600 \times G_{SC}}{\pi}\left(1 + 0.033 \times \cos(\frac{360 \times n_d}{365})\right) \times\times \left(cos\emptyset cos\delta sin\omega_s + \frac{\pi\omega_s}{180} sin\emptyset sin\delta\right)$$

$$\delta = 23.45 sin\left(360\frac{248+n_d}{365}\right)$$

$$\omega_s = cos^{-1}(-tan\emptyset tan\delta)$$

a= 0.33; b=0.43; $G_{sc} = \frac{1367W}{m^2}$

with

$$\Delta t = T_c - T_{c,ref}$$

and

$$v(z) = v(z_r)\frac{\ln\left(\frac{z}{z_0}\right)}{ln\left(\frac{z_r}{z}\right)}$$

$$V_M = \frac{c\times 0.01X_{CH4}\times Vm\times 0.01V_S\times 0.75\times M_{MSW}}{M_C}$$

$$c = \frac{0.375g\ de\ carbone}{g\ de\ solide\ volatile}$$

$$Vm = 22.4L$$

$$M_C = 12g/mol$$

$$\eta_g = 0.04$$

$$E_{CH4} = 10\ kWh/m^3$$

The results obtained on the basis of the technical and economic parameters, are largely inspired by the CAPEX costs presented by Juan Pablo Viteri et al. [18].

The detailed flowchart for solving the optimization problem is shown in Figure 3.

In this flowchart, the efficient management of renewable resources in the electrical network (taking into account the annual variation in electrical loads), depends on the period T defined in 12 months of the year (T = 12) and therefore, as a function of each month t.

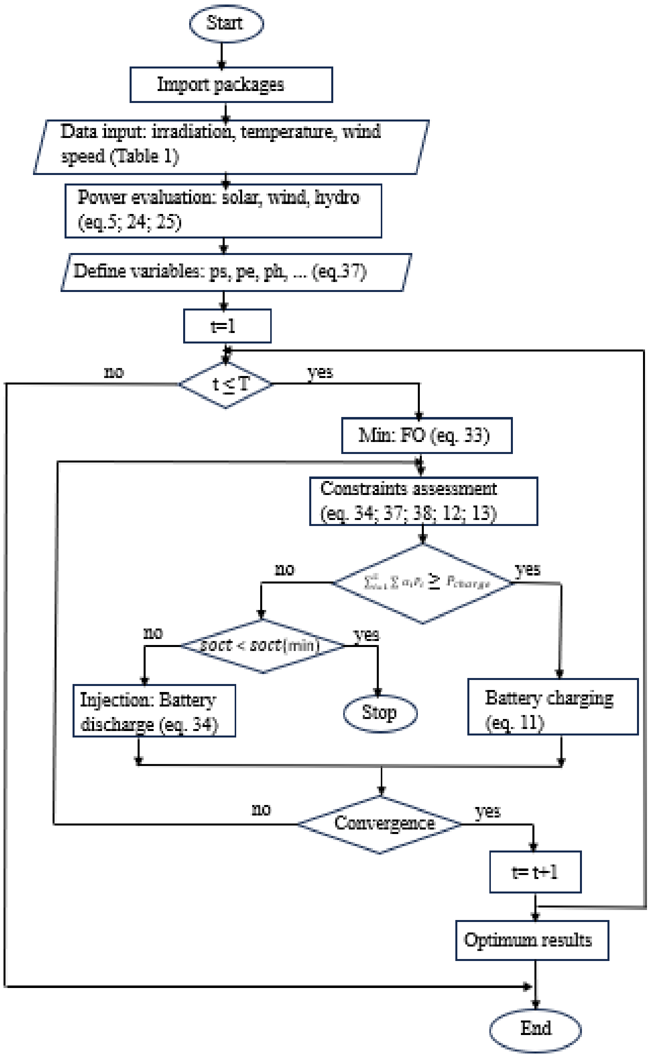

Figure 3. *Flow chart for efficient management of renewable resources in the grid. Eq mean equation.*

3.2.4. Data

For the data, only average and annual variations in the various energy resources of South-Togo are presented, as this area accounts for 95% of the country's electrical loads.

Statistical analyses of the data presented are based on the minimum value of the data used, the maximum value (max), the mean ($\bar{X}$), the standard deviation (σ):

$$min = min(x_i)\ ;\ max = max(x_i): i = 1, \dots .N \tag{39}$$

$$\bar{X} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{40}$$

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{X})^2} \tag{41}$$

Statistical data on energy resources in South Togo are shown in Table 1.

Table 1. Statistical data on energy resources in South Togo.

Month	Solar radiation (W/m²)				Temperature (degree)				Relative humidity (%)				Wind speed (m/s)			
	min	max	$\bar{X}$	σ	min	max	$\bar{X}$	σ	min	max	$\bar{X}$	σ	min	max	$\bar{X}$	σ
J	85.46	115.71	99.01	5.87	26.12	28.41	27.59	0.59	60.56	85.62	75.25	6.92	2.04	4.45	3.27	0.68
F	85.98	113.63	103.63	6.95	27.58	28.57	28.05	0.23	69.75	85.19	80.92	2.97	2.21	5.17	3.94	0.76
M	84.98	122.43	108.85	9.69	27.83	28.96	28.38	0.23	78.44	86.31	81.99	1.89	3.99	6.11	4.78	0.57
A	109.64	137.14	127.32	7.0	26.95	28.38	27.67	0.46	78.31	88.31	83.72	2.35	1.86	5.49	3.7	0.91
M	108.89	132.91	126.36	4.72	26.49	28.11	27.41	0.41	76.19	88.62	85.21	2.59	1.91	4.47	3.41	0.56
J	112.42	128.5	121.95	3.63	25.09	27.42	26.25	0.73	79.0	92.88	87.34	3.28	1.9	5.6	3.69	0.85
J	117.48	129.11	123.56	2.93	24.44	25.9	25.10	0.36	82.19	90.81	87.35	2.33	3.42	6.55	5.06	0.66
A	117.97	134.07	127.02	3.74	23.64	25.35	24.34	0.46	82.62	92.31	87.89	2.0	2.4	7.82	5.29	1.36
S	125.77	140.23	134.24	3.19	24.95	25.87	25.45	0.24	82.88	91.5	87.28	2.18	3.26	6.55	4.85	0.88
O	113.06	133.61	125.49	4.72	25.17	27.4	26.32	0.63	84.62	90.69	87.60	1.55	2.16	5.55	3.19	0.89
N	106.05	122.58	114.64	4.22	26.64	27.83	27.24	0.3	79.44	87.0	83.24	1.78	1.65	4.77	3.03	0.71
D	90.72	111.33	103.36	4.46	25.9	27.8	27.01	0.35	61.62	86.62	78.24	6.64	1.62	4.3	2.94	0.61

J=January; F= February;...; D= December.

The various results obtained on the annual availability of renewable resources and those for optimization are presented.

4. Results

4.1. Results of Annual Availability of Average Renewable Natural Resources in Togo

Annual assessment of the various natural resources is necessary for better planning of electrical power generation.

Figures 4 and 5 show solar radiation and temperature respectively.

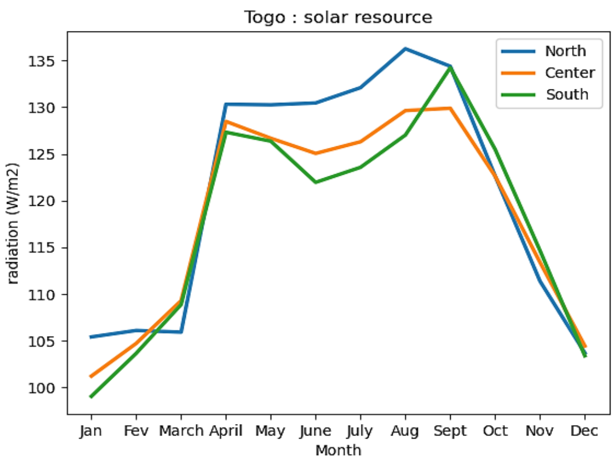

Figure 4. Solar radiation.

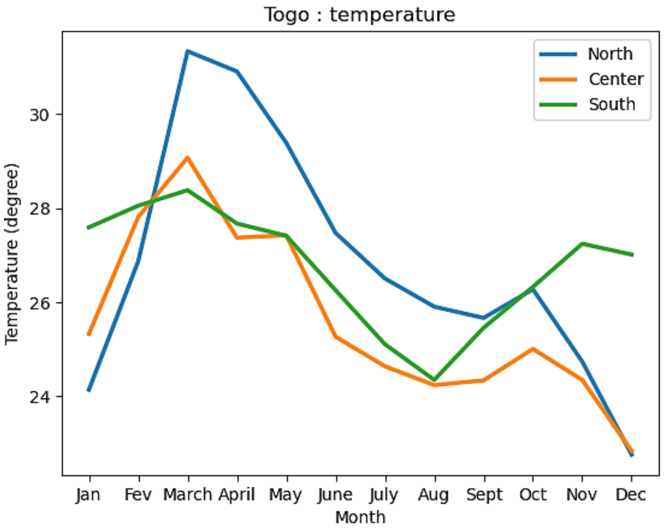

Figure 5. Temperature.

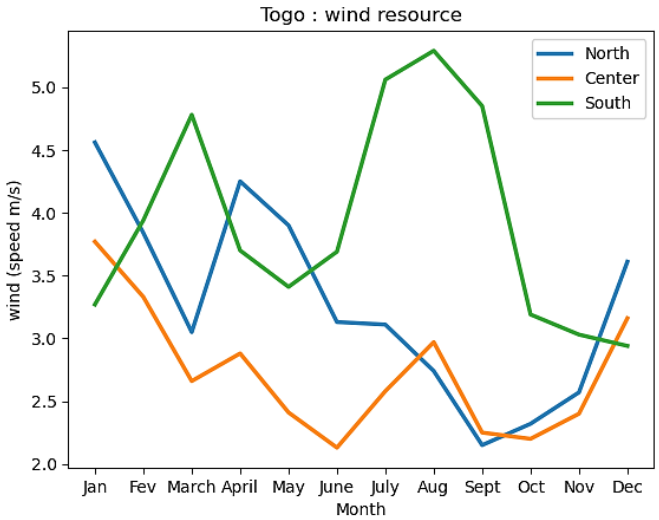

Figure 7. Wind resource.

Figure 4 shows solar power as a function of month. According to the months, solar power is highest from April to August. However, the temperature curve shows a higher perceived temperature in March and April, and a lower one in August and September.

The correlation between solar radiation and temperature is shown in figure 6:

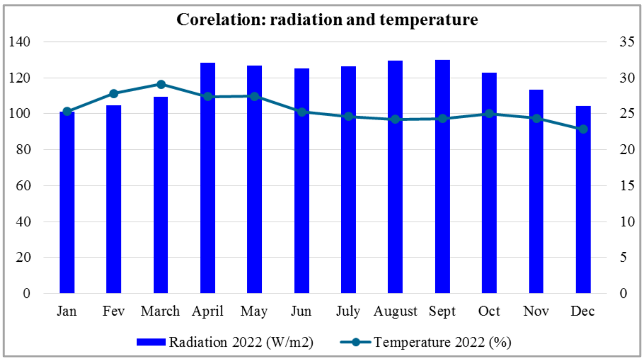

Figure 6. Radiation and temperature correlation.

From this figure, temperature and solar radiation show a proportionality. The higher the temperature, the lower the solar radiation; and the lower the temperature, the higher the radiation. The temperature varies from over 20 degrees to 30 degrees Celsius with solar power ranging from 100 to 130 W/m^2. This relationship makes it possible to evaluate the performance of photovoltaic solar panels operating under these conditions of temperature and solar irradiation.

Other renewable resources are shown in Figure 7:

Figure 7 shows Togo's wind resource. This resource is highly variable. This variation can be observed throughout the year. Wind speed varies only slightly from April to June. On the other hand, wind speed varies considerably from March and July to September, reaching a maximum speed of over 5 m/s in August. The power distribution as a function of wind turbine speed is shown in Figure 8:

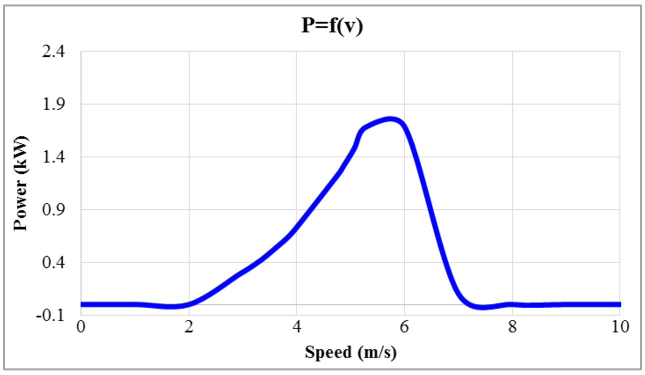

Figure 8. Power curve of a wind turbine.

The output power distribution required for a wind turbine and available, is given as follows:

$$P(v) = \begin{cases} 0;\, v < 2\, m/s \\ p(v);\ 2 < v < 5\, m/s \\ \sim 1.8;\ 5 < v < 6\, m/s \\ 0;\, v > 6 m/s \end{cases}$$

In Togo, the maximum power for a wind turbine unit is around 1.8 kW at an altitude of 10 m.

The hydraulic resource as a function of relative humidity is shown in figure 9.

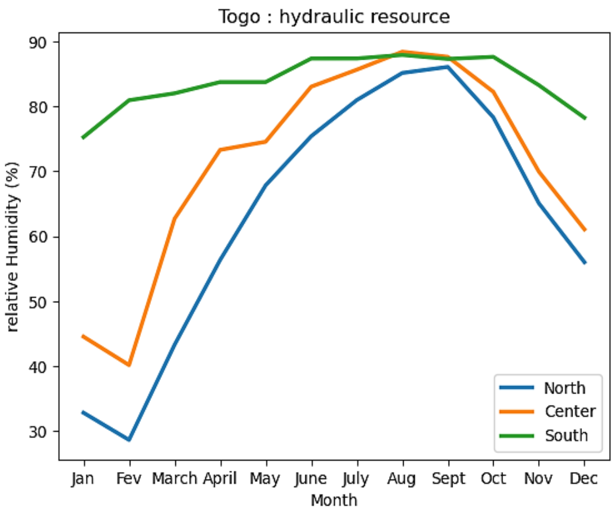

Figure 9. Water resources.

The most favorable and important annual water resource is that of June, July, August and September for all three regions, with humidity levels of over 85%. Although this humidity is higher in the South than in the other regions, it is also high in October in the South. The estimated capacity, taking into account the maximum existing capacity and the representativeness of the hydraulic resource, is shown in figure 10.

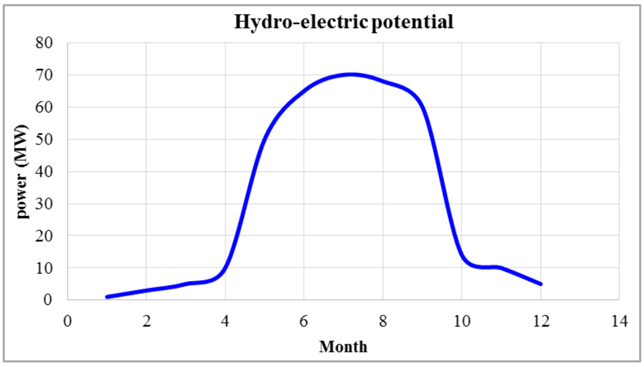

Figure 10. Example of hydropower potential.

In fact, this representation is an illustration of the annual availability of the relative humidity of the hydraulic resource, taking into account the total production capacity of existing hydroelectric power plant units.

An analysis of the results over three consecutive years is presented. This analysis enables conclusions to be drawn on the annual variation of each energy resource, which is necessary for decision-making in the optimal management of these resources.

4.2. Results of Comparative Studies of Average Annual Variations in Renewable Resources: The Case of Central Togo

In order to study the annual variations of the various renewable resources, a comparative study was carried out. Figures 11, 12, 13 and 14 show these studies.

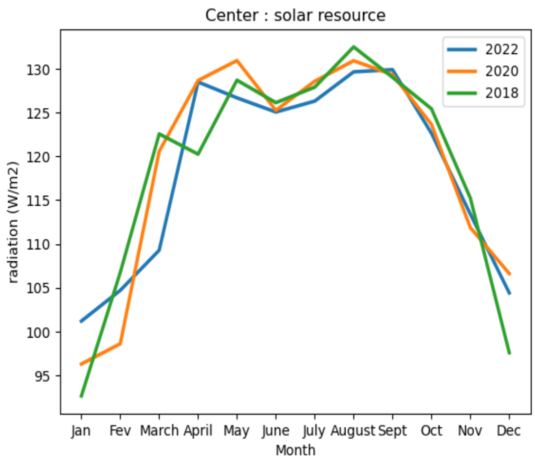

Figure 11. Solar radiation per year.

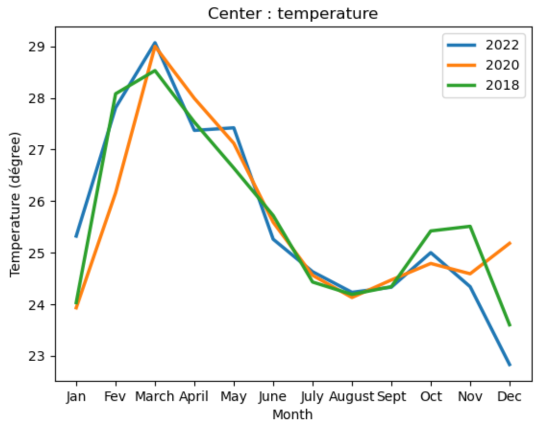

Figure 12. Temperature per year.

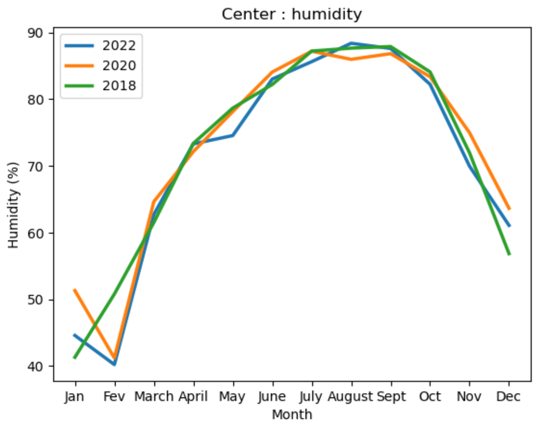

Figure 13. Hydraulic resource per year.

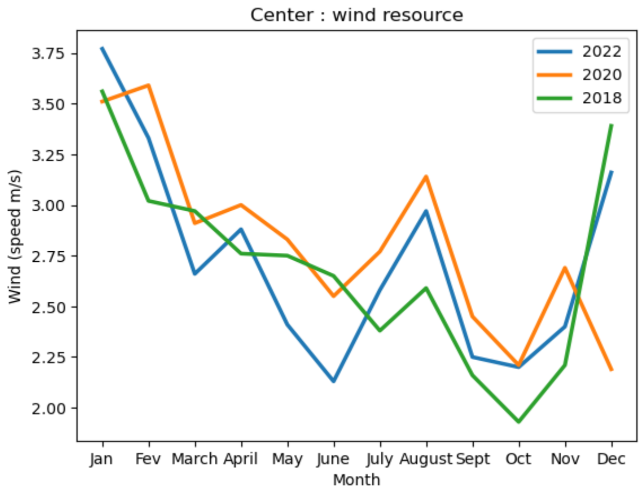

Figure 14. Wind resource per year.

From the various curves obtained, we can observe a generally similar trend for each renewable resource. This information is in fact a contribution to the country's annual resource planning.

4.3. Results of Optimal Simulations of the Annual Optimal Management of Renewable Resources in the Power Grid

4.3.1. Simulation of 1 kW Resource Availability

The various intermittent energy potentials are presented for a capacity of around 1 kW. Only solar, wind and hydro potential is shown. Indeed, according to Rafat Al Afif et al [32], there are no specific impacts of extreme events that could affect biomass power generation, so biomass power generation is possible at any desired time. Thus, in our results, the coefficient α_4 linked to biomass is 0. This resource can be equivalent to the corresponding optimized energy in the grid. Figure 15 below shows these potentialities.

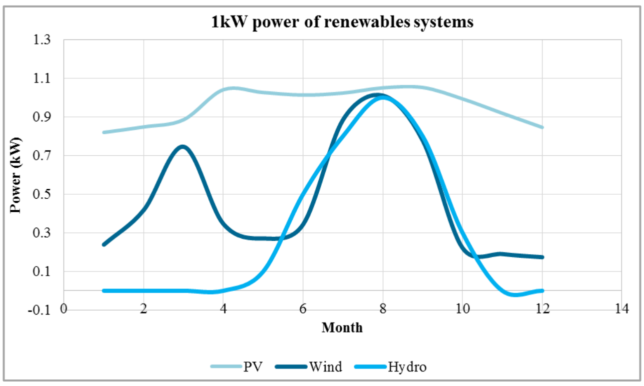

Figure 15. Energy potential of renewable resources.

This figure shows the uneven annual distribution of Togo's potential energy mix. This uneven distribution calls for an optimal combination of these resources. Optimal management of these resources is only possible with optimal management optimization models; hence this study.

4.3.2. Simulation Results for Optimal Load Management Using Renewable Resources

Managing resources optimally in relation to electrical loads means satisfying these loads temporally in relation to resource availability. To do this, we carried out a special study on Togo. Figure 16 shows Togo's loads in 2021, with a capacity of 195 MW.

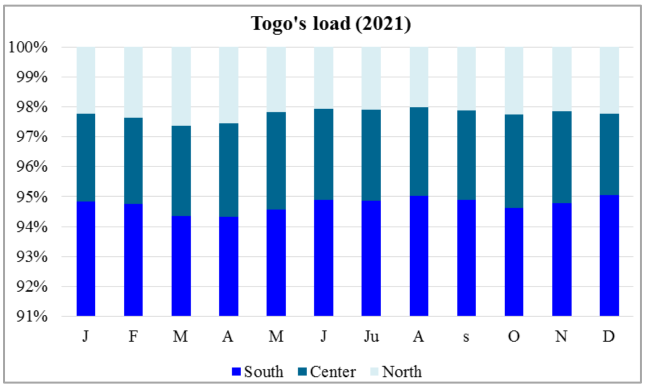

Figure 16. Electricity loads in Togo in 2021.

According to the figure, the southern region accounts for almost 95% of total national loads. To simplify this study, we will focus only on the major loads, i.e. those in South Togo. Figures 17 and 18 shows the different modelling results:

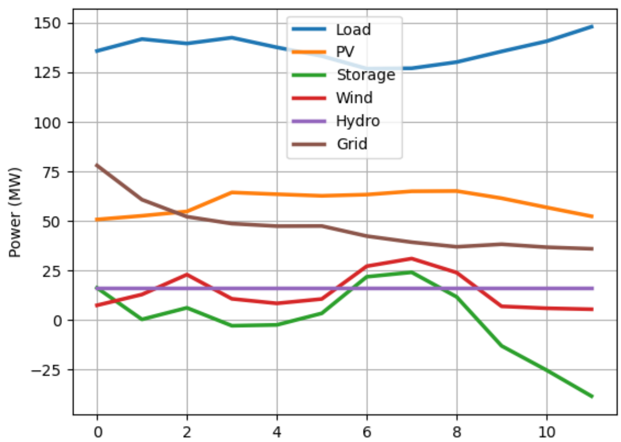

Figure 17. Optimal management of renewable resources: the case of South Togo.

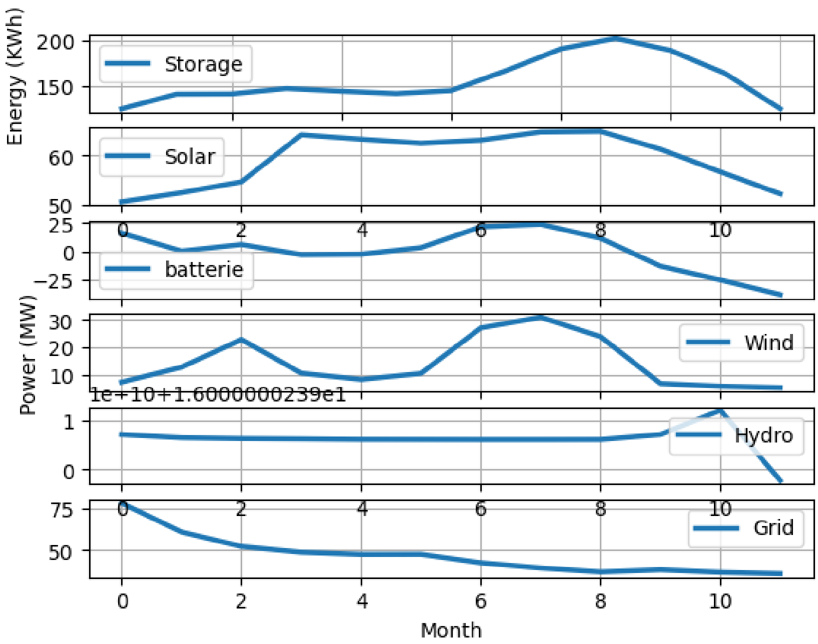

Figure 18. Simulations obtained from different renewable resources.

Table 2. Results of optimized simulation values.

Months/Systems (MW)	Objectif function (USD)	Power (PV)	Power (battery)	soct	Power (wind)	Power (hydro)	Power (grid/biodiesel)
January	30185.83538337	50.59000008	16.10261946	125	7.29182268	16.00000024	77.83012655
February	7493.38819407	52.45000009	0.18756169	141.10261946	12.75503066	16.00000024	60.5957174
March	14110.53651495	54.63500014	6.03352181	141.29018115	22.77595159	16.00000024	52.00590985
April	1939.29014263	64.24000011	-3.01186196	147.32370296	10.56326108	16.00000024	48.5061267
May	2325.72339825	63.33500011	-2.59584265	144.311841	8.26905688	16.00000024	47.23730382
June	9928.80617995	62.52500011	3.24511764	141.71599834	10.47784432	16.00000024	47.30122336
July	33336.46911887	63.15000008	21.6853283	144.96111598	27.01745224	16.00000024	42.21034946
August	35930.21093907	64.82000005	23.94968835	166.6464443	30.87165114	16.00000024	39.13168472
September	19519.14402523	64.94500008	11.54444071	190.59613265	23.79129369	16.00000024	36.80903221
October	-12515.95181863	61.3100001	-13.18540703	202.14057336	6.76962939	16.00000024	38.10488874
November	-28607.64232167	56.6950001	-25.41975695	188.95516633	5.80123862	16.00000024	36.60008109
December	-45760.70763742	52.2000001	-38.53540938	163.53540938	5.29949926	16.00000024	35.80671332

5. Discussion

On the one hand, the various results obtained and presented enable us to make a scientific contribution to the optimal management of renewable energy sources in the network required for decision-making. Indeed, in the context of the global energy mix, it has been shown on the one hand, that the heavy exploitation of fossil resources, constitutes enormous concerns in terms of environmental pollution. Hence the need to develop renewable energy resources. On the other hand, the intermittent nature of these renewable energy resources means that they need to be combined for optimized management of electrical loads. The case of Togo has made it possible to highlight its various resources for better management. This study was therefore based on an optimal management study of energies such as solar, wind and hydraulic power, with a grid storage system.

In fact, the uneven distribution of resources shows, firstly, that solar production is highest in the months from April to September, at 127 W/m^2, in contrary to the months from January to April, at 105 W/m^2 on average. As this distribution is a function of both irradiation and temperature, the higher the temperature, the lower the performance of solar photovoltaic modules, since a rise in temperature would lead to temperature gradients and, consequently, to recombination: all of which would contribute to a reduction in cell performance. What's more, the lower the temperature required to produce or generate energy, the better the solar cells' performance. During hot periods (with high temperatures), such as January to April of the year, it would therefore be wiser to favor cooling systems integrated into photovoltaic solar panels. For this resource, the months from April to September are more representative, with a high potential.

The country's annual wind power distribution is also presented. This distribution shows a lower potential in the center of the country and a lower potential in the north. Although low, there is considerable potential in the south of the country. As the power produced is linked to wind speed, the lower the wind speed, the less this resource can be exploited. For Togo, this resource reaches a maximum power of around 5 kW in August. However, wind power's potential can be used as an alternative resource in energy mix systems. With the development of suitable wind turbine technologies [57, 58], it could be possible to exploit this wind resource for small- and/or large-scale applications.

As for the hydraulic resource, since hydraulic potential is linked to the seasonal period, possibly to the rainy period, it has been shown that the most favorable period for generating more hydroelectric potential is the period from June to September.

Biomass potential is not represented, as this resource is not necessarily linked to climatic events, so there would be no specific impacts of extreme events that could affect its production. Nevertheless, an assessment of a specific field case could enable its integration into the local energy mix.

Optimal management of all these different resources has made it possible to optimize their use throughout the year. The results show a composition of maximum load satisfaction, with 39% from grid compared with 8% from hydro, 10% from wind, 12% from batteries systems and 31% from photovoltaic systems. The simulation produced a storage requirement for energy management estimated at 220 kWh, with an optimal annual value for the cost objective function of around 67885.10212 USD. According to the results obtained, the months of January to April require a minimum energy storage system, due to the average availability of all resources. But from April to June, given the low potential of the wind resource, the storage system will have to inject energy into the overall system due to the storage carried out in previous months, in order to balance electrical loads. From June to September, the high availability of resources generates significant energy storage, which will eventually be used to help manage high loads in November and December. Imported loads due into the power grid are then considerably reduced by exploiting existing natural resources. This considerable reduction is then optimally managed by offsetting these natural resources throughout the year. This study is one scenario, among many others, that can be used to optimize the management of the power system. For example studies on microgrid installation methods have been carried out: in these studies, a microgrid was dimensioned [59]. Other studies have shown the planning of these microgrids [60].

6. Conclusions

Optimal management of natural energy resources, especially renewable ones, is essential for optimal planning of energy demand. This study has therefore presented a scientific approach to better manage and optimally plan existing renewable resources. The case of Togo was studied to highlight the management of these resources. Initial results showed that the country has enormous renewable energy potential, but that it is unevenly distributed across the country and throughout the year. This uneven distribution led to the development of an optimal resource management model, with an explicit resolution method based on integer linear and mixed linear programming, solved in the Python programming language. In the second stage, the results showed the availability of resources and their annual management, as a function of the demand for electrical loads. The results show a composition of maximum load satisfaction, with 39% from grid compared with 8% from hydro, 10% from wind, 12% from batteries systems and 31% from photovoltaic systems.

In conclusion, the results obtained are satisfactory and highly conclusive, having enabled us to optimally simulate the management of Togo's renewable energy resources. This study has therefore enabled us to develop an energy management model required for energy planning. The model will be used to solve the specific problems to which it will be called upon, and is a decision-making tool.

Abbreviations

I	Photodiode Current
I_{ph}	Photocurrent
I_0	Saturation Current
q	Load
V	Voltage
R_s	Serial Resistor
A	Ideality Factor
K	Boltzmann's Constant
T	Temperature
R_{sh}	Shunt Resistor
I_{0d}	Diffusion Current
I_{0g}	Generation Current
$I(t)$	Variable Current
n_p	Number of Cells in Parallel
n_s	Number of Cells in Series

$P(t)$	Variable Power
$P_s(t)$	Variable Solar Power
τ, τ'	Charging (80%) and Discharging (20%) Rates
η	Efficiency
ε	Performance Ratio
S	Area
Δt	Temperature Differential
X_s^d	Decision Variable
T_c	Cell Temperature
$T_{c,ref}$	Reference Temperature
$soct(t+1)$	Battery Storage at t+1
$soct(t)$	Battery Storage at Time t
$p_{bat}(t)$	Battery Power
N_{bat}	Number of Batteries
C_{bat}	Battery Capacity
V_{bat}	Battery Voltage
η_{bat}	Battery Efficiency
$f(v)$	Probability Density
c	Scaling Factor
v	Wind Speed
k	Shape Factor
σ	Ecart Type
FO	Fonction Objectif
$\bar{v}$	Moyenne Vitesse
Γ	Gamma Function
$\bar{P}$	Average Power
P	Power
$P_e(t)$	Wind Power
ρ_e	Air Density
S_w	Area Swept by the Wind Turbine
η_e	Wind Power Efficiency
X_e^d	Wind Turbine Decision Variable
$P_h(t)$	Hydroelectric Power
ρ_h	Water Density
g	Acceleration
Q	water flow rate
h	Head of Water
η_h	Hydroelectric Efficiency
V_{bio}	Volume of Biogas
V_M	Methane Volume
c	Constant Biogas Production
Vm	Molecular Volume
X_{CH4}	Methane Fraction in Generated Biogas
M_{MSW}	Organic Waste Mass
M_C	Carbon Molar Mass
P_b	Biogas Capacity
η_g	Gas Yield
E_{CH4}	Constant Methane Energy
$f(t)$	objective function
α_i	Binary Coefficient
c_i	Cost
P_i	Energy Production
i	Index
$\emptyset$	Latitude of the Location
δ	Declination Angle
ω_s	Angle
n_d	Day's Number
G_{sc}	Solar Constant
a	Regression Coefficient
b	Regression Coefficient
n	Number of Hours of Sunlight
N	Maximum Daily Sunshine
$\bar{X}$	Average
x	Variable
σ	Standard Deviation
Pr	Power in the Grid
Pl	Power of Load

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Kwami Senam Sedzro: Methodology, Validation

Takouda Pidéname: Methodology, Validation

Lare Yendoubé: Methodology, Supervision, Validation

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Conflicts of Interest

The authors declare no conflicts of interest.

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Biography

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Kwami Senam Sedzro earned a bachelor and a Master of Science degrees in Electrical Engineering from University of Lome in Lome, Togo (West Africa). He obtained a Master of Engineering degree in Energy Systems Engineering and holds a Doctor of Philosophy (PhD) degree in Electrical Engineering form Lehigh University in Bethlehem, Pennsylvania (USA). Sedzro is a Senior Member of the Institute of Electrical and Electronics Engineers, and an alumnus of the prestigious Fulbright Scholars hip program.

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Lare Yendoubé, Ph.D., is a leading academic in the field of physics with a robust focus on sustainable energy technologies and materials science. With a doctorate from the « University de Lomé » carried out alternately with the University of Nantes, France, his scholarly pursuit centers on the development and characterization of materials for renewable energy applications, particularly photovoltaics and energy storage systems. Currently, as a Full Professor at Université de Lomé, he is instrumental in steering research on materials and optoelectronics, with a significant emphasis on thin films and their utility in enhancing solar cell efficiencies. His role as the Chair of both the UNESCO Chair on Renewable Energies and the Master's Program in Materials and Energies underscores his dedication to advancing educational and research initiatives that address critical issues in energy sustainability. Professor Lare's research portfolio encompasses a broad spectrum, from the fundamental physics of materials to innovative applications in energy systems, focusing on the impact of nanotechnologies in transforming energy infrastructures to be more efficient and less reliant on non-renewable resources. His extensive publication record in top-tier scientific journals reflects his commitment to high-impact research. Beyond academia, Professor Lare actively engages in significant public service efforts, advocating for sustainable energy solutions and technology-driven policies to mitigate energy challenges in Togo and the broader region. His leadership in overseeing doctoral and master's research further cements his legacy as a mentor and leader, preparing the next generation of scientists and engineers to continue pushing the boundaries of what is possible in energy science and technology.