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Comparative study of PV power plants for isolated sites based on battery storage

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ABSTRACT: This article analyses several configurations according to load plans for rural electrification. The contribution of this paper lies in the enhancement of the dimensioning of the part storage by electrochemical batteries for a photovoltaic solar hybrid system (PV)/DIESEL. Battery sizing approaches are proposed and put into competition. In order to carry out this comparative analysis, the use of the Multi-Criteria Decision Matrix or MDM was adopted as a methodological approach. The analysis makes it possible to choose the approach of precise dimensioning, adapted to a given site according to the criteria imposed by the consumers in relation to their priorities. It is important to analyze specific cases with specific conditions for the cases of rural areas in developing countries because each area has its own peculiarities in terms of needs, requirements and living conditions. This analysis highlights that the PV/DIESEL configuration is more beneficial with the battery fleet used to cover only the missing energy load while the Photovoltaic Generator (GPV) is low or even no production as at night. The Battery Park is dimensioned according to the total charge requested during the night when there is no sun. This reduces the number of batteries and implies a minimum expenditure in terms of financial cost. This configuration is very important for developing countries because the lack of financial means is a major obstacle. It is suitable for autonomous production systems based on photovoltaic solar in rural areas: case of Madagascar.

KEYWORDS: Solar Photovoltaic/Diesel Plant, Batteries, Multicriteria Decision Matrix, Hybrid System.

Nomenclature / Abbreviation

AFREC: African Energy Commission
E: Total energy to be covered [kWh]
E_b: Energy requirement for 24h [kWh]
E_c: Sum of energy requirement for 24h [kWh]
E_{cpic}: Ec peak in 24h [kWh]
E_m: Sum of energy missing for 24h [kWh]
EnR : Renewable Energy
E_p: Total energy to be produced by GPV [kWh]
f_N: Frequency of occurrence of N for 1 year with N number of dark days.
GE : Generator
GPV : Photovoltaic generator
IEPF : Institut de l'énergie et de l'environnement de la Francophonie
MDM : Multicriteria Decision Matrix
N_{bat}: Number of batteries
NPE: New Energy Politic
PRISME: International Program of Energy Management Support
PV: PhotoVoltaic

I. INTRODUCTION

Today, electrical energy is among the conditions of human survival. Globally, with only 35.5% of the electrified population, Africa has the lowest electrification rate in the world. This rate is estimated at 42.8% for South Asia, 89.2% for Latin America, 88.1% for East Asia and 91.8% for the Middle East [1-3].There are significant disparities between 93.6% electrified North Africa and sub-Saharan Africa where only 23.6% of households have access to electricity. In Sub-Saharan Africa, rural populations are the worst off because only 7.5% have access to electricity, of which the rural electrification rate is generally less than 5% [1-2]. Also, 11.3% of the electricity offered in Africa is wasted in production and transport compared to 9.2% in the world [3]. Africa has significant energy deficits while African countries have enormous potential in fossil and renewable energies. Indeed, the continent's resources are underexploited, or exported in raw form, or as mentioned above, wasted during extraction or transport. 21 out of 53 countries would be able to profitably exploit hydropower in Africa, but only 7% of this potential is exploited. The average daily solar radiation in Africa is between 5 and 7 kWh/m², on par with the Arabian Peninsula, northern Australia and northern Chile. However, Africa has only 1.3% of the world's photovoltaic capacity [3]. In the absence of a satisfactory supply, energy consumption per capita is very low in Africa, averaging 0.5 tons of oil equivalent per capita compared to 1.2 on the global average. For the generation of electricity in isolated sites, the use of renewable energy-based generators is the most suitable solution thanks to their increasingly attractive price and increasing reliability [4-5]. In the case of the Sahelian areas, photovoltaic solar panels are favored as the main bases of the electricity production system [4, 18]. In the literature, many authors suggest several solutions of combining sources in order to have optimal and efficient production systems in terms of energy and price [6-8, 13, 18].

Despite their promising results, these solutions are widespread as we seek to obtain solutions that meet and suit the particularity of the rural areas of Madagascar, hence the purpose of this paper. Among many African countries, Madagascar is a victim of under-electrification while it is rich in renewable and even fossil energy resources. Indeed, the Country has multiple energy resources both fossil and renewable (hydraulics, wind, solar PV, marine, geothermal and biomass, oil, etc.), however, these energy sources are sub-exploited in relation to the needs of the population. Among the national potentials, to mention only the renewable types, the hydropower offers a potential of 7 800 MW distributed throughout the country. However, only about 350MW, or 2% of the total potential is exploited [6]. The average sunshine potential is estimated at 2000 kWh/m2/year for 2,800 hours per year [10]. For wind power, Madagascar has a large reservoir with average wind speeds estimated between 6 to 8m/s in the North and 6.25m/s in the South at 50m in height [9]. Agricultural biomass resources (rice bale, sugar cane) and organic and solid waste can also strengthen the recoverable sources in electricity production. Today, electricity production in Madagascar is provided by 66% hydro and thermal with 34% hydrocarbons [10]. According to the African Energy Commission (AFREC) database in 2017 [11], Madagascar's total electricity production increased from 780 to 2865GWh from 2000 to 2017. A sharp jump was observed between 2005 and 2012 as the evolution almost tripled. Similarly, for Renewable Energy, a positive development is observed but the slope is very low. Production almost doubled from 2000 to 2017, but the EnR penetration rate fell from 69% in 2000 to 41% in 2017 [11].

However, a revival of recourse to EnR has been felt since 2014, even if the progress remains rather weak. Moreover, in 2015, the electrification rate is only 15%, of which 4% at the rural level housing more than 66% of the population of Madagascar [10]. Faced with this chasm and seen the energy potential of Madagascar, with the New Energy Policy (NPE) 2015-2030, the State aims to increase the electrification rate to 70% including 17% in rural areas by 2030. With this vision, 80% of production will be from renewable energy sources. Fluctuations in load over annual, seasonal or daily periods are not necessarily correlated with resources. For isolated regions, the solution is certainly the coupling of several energy sources. But in any case, the storage system is unavoidable for Madagascar. Electrochemical batteries are still the most recommended as adequate on the basis of price/quality criteria [12]. The storage part is still a major problem [13]. The Battery Park must be well sized because it is the most expensive part of the system [13-14], the reduction of its cost is desired in priority, while maximizing the rate of satisfaction of the consumer. In this case, an effective design approach is necessary, hence the objective of this work. Its main contribution lies in the development of the dimensioning of the part stored by electrochemical batteries in a hybrid solar system PV/DIESEL in sustainable development logic [15]. In the sense of optimization, the load plan plays a crucial role for the size of the system, for which the cost is paramount. For this, five (05) types of consumption plan are put in competition with nine (09) possible cases identified. Of these, only one will be identified as the most optimal not only in terms of cost but also in terms of environmental impact by assessing the level of CO2 emitted. The latter will then be the subject of an in-depth analysis on the basis of the Multicriteria Decision Matrix (MDM) in order to allow a judicious choice corresponding to a specific need according to the criteria imposed and the priorities of consumers. As such, the assessment criteria refer to the situation of villagers in rural Madagascar [16, 17]. In this paper, the presentation of possible load plans is started first and is followed by the definition of evaluation criteria. The evaluation itself is then carried out and ends with the presentation of the results.

II. MATERIALS AND METHOD

Battery fleet operating modes : Storage systems such as batteries play a key role in a production system in remote locations. In this role, the operation of the Battery Park can be defined according to the need and priority for the desired consumption plan. For a PV/DIESEL/Battery configuration, by defining the Photovoltaic solar power plant as the main source of the system, it is the Batteries fleet and the Electro gene Group (GE) that play the various roles according to the proposed consumption plan. In this condition, the initial approach to the design of the battery fleet is based on the following relationship [19]:

$$C_{bat} = \frac{EN}{UD} \tag{1}$$

With,

C_{bat}: Battery Capacity [Ah]
E: Total amount of energy to be covered [Wh]
N: Number of days of autonomy [Days]
U: Battery voltage rating [V]
D: Allowable battery discharge depth [%]

For this case, five consumption plans are proposed with the defined battery fleet operation. They are grouped in Table 1. The sum of energy to be covered "E" is varied depending on the type of operation of the battery fleet. The size of the generator depends on the type of operating plan.

Table 1 : List of Proposed Approaches to Battery Fleet Operations

Consumption plan		**Function of the battery fleet**	**Design basis calculation method**	**Conditions**
PC_1 : Approach_1	The battery park is used to cover the amount of energy requested for 24h. The GE is the backup system during dark days or main system failure.	Dimensioned in relation to $\mathbf{E_c}$; Ensures $\mathbf{E_m}$ rescued by GE when necessary.	Design of the GPV : $E_p = \frac{E_b}{k}$ Sizing of the battery fleet : $C_{bat} = \frac{EN}{UD}$ Sizing of the generator set : depending on N, f_N	$E_b = E_c$ $E = E_c$
PC_2 : Approach_2	The battery park is used to recover excess energy produced during the day. GE covers the lack of energy beyond the PV Generator (GPV) and Battery Park.	Dimensioned relative to $\mathbf{E_s}$; Ensures $\mathbf{E_m}$ supplemented by the GE.		$E_b = E_c$ $E = E_s$
PC_3 : Approach_3	The battery fleet is used to cover the missing energy while the GPV is low or even no production. GE is the backup.	Dimensioned relative to $\mathbf{E_m}$; Ensures $\mathbf{E_m}$ completed by GE if necessary.		$E_b = E_c$ $E = E_m$
PC_4 : Approach_4	GPV is the main source, GE is the second source. The battery park will serve as a buffer source ensuring the consumption during the switching time between the first two sources.	Dimensioned relative to $\mathbf{E_{cpic}}$; Only provides charge during PV to GE switch. The GE provides the full of $\mathbf{E_m}$.		$E_b = E_c$ $E = E_{cpic}$
PC_5 : Approach_5	The battery park is the secondary source after the GPV, it ensures the storage of all the amount of energy produced. GE is purely backup.	Dimensioned relative to $\mathbf{E_p}$; Ensures $\mathbf{E_m}$ rescued of the GE.		$E_b = E_{cj}$; $E = E_p$

These approaches have been estimated based on examples of the realities of isolated sites and the energy needs of rural areas in Madagascar [20].

Methodological approach : The approach taken in this contribution is based on the MOP, which allows several options to be evaluated in situations where all possibilities seem plausible. To do this, the approach consists of the following 5 steps [22-23]:
Identify the objective of the approach and the type of decision;

List possible solutions;

Develop the list of criteria to be considered;

Evaluate each of the solutions against each of the criteria;

Weight judgments to design the best rated solution.

In order to be able to assess the design basis approaches, you have to do the conventional design basis. First, you have to have the production system dimensioned. Therefore, a real case of a site was chosen and is the subject of the next section.

Site PV/Diesel Plant Sizing : The design of a system cannot be started without the power balance of the electricity consumption required, which is dimensioned in relation to the available resources [21]. For this, a real case of a village is observed. Below are the curves representing the daily energy requirement and the potential of the site in terms of sun of the case of the village of Ivovona located in the rural commune of Ramena, Antsiranana-Madagascar of latitude -12°13'60.00" South and longitude 49°20'59.99"- East.

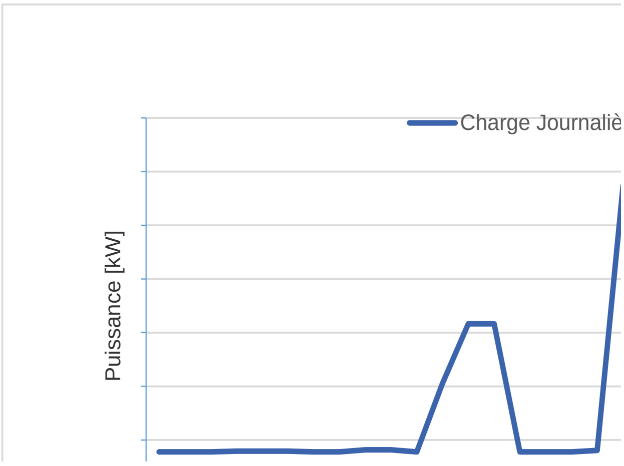

Figure 1. Charge curve of Ivovona – Ramena-Madagascar

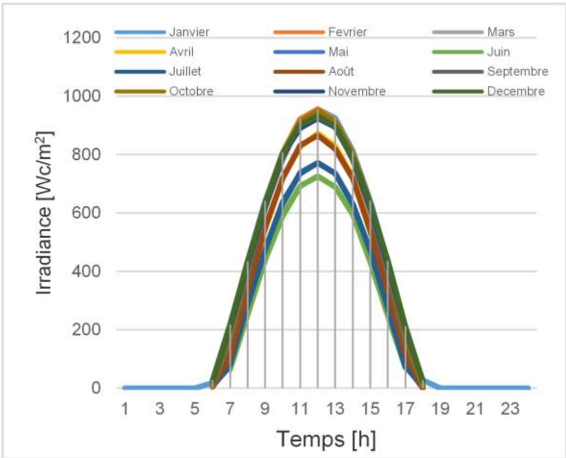

Figure 2. Direct solar potential – Ivovona

For the design, the characteristics of the equipment used are grouped in Table 2.

Table 2 : Characteristics of the equipment required

Module PV		**Batterie**		**Groupe Electrogene Diesel**	
Power (Pcu)	430 [Wc]	Tension	12 [V]	Nominal Power	15 [kVA]
Voltage	24 [V]	Capacité pour C20 et C25°C	220 [Ah]	Voltage	220 /230 [V]
Dimensions	1956 × 992 × 40 [mm]			Autonomy	+ 12 heures in continue
				Current	28 [A]
Cost	245 [Euros]	Unit cost	530,4 [Euros]	Cost	7 440 [Euros]

The results are of sizing of the solar panel sizing are presented in Table 3.

Table 3 : Result of the sizing of the solar power plant PV

Identification	Values	Unit
Daily requirement	86,78	kWh/j
Energy to produce	133,50	kWh
GPV peak power	26,70	kWc
Number of PV solars panels needed	63	

PV/diesel power plant battery fleet sizing : Based on Table 3, using the actual site solar irradiance values for a year, the estimated site deliverability is presented on the following curve:

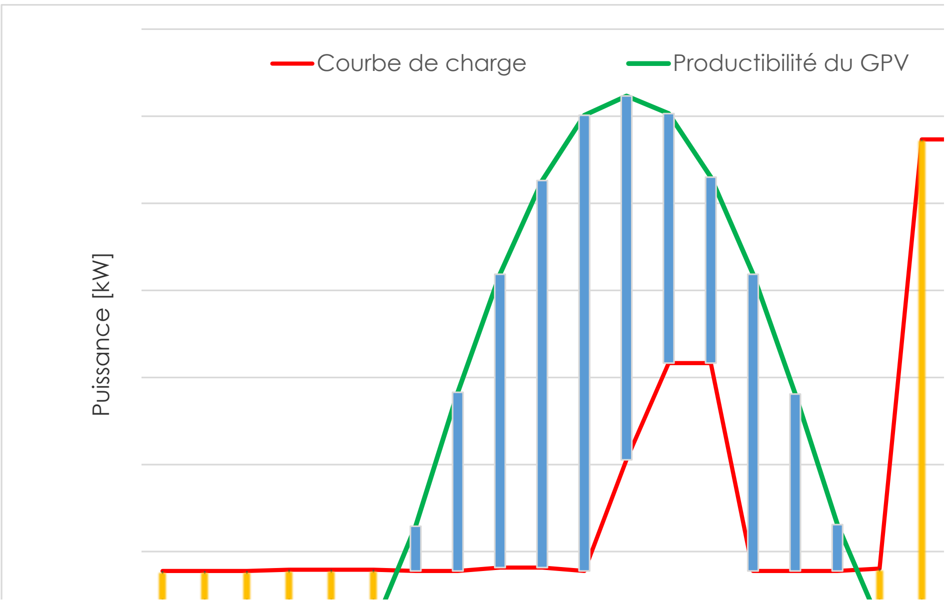

Figure 1 : Site Solar Deliverability

Figure 3 shows the deliverability in terms of solar energy of the Ivovona site in January 2022. The total energy produced in a day from 06h to 17h is 91.50kWh, while from 01h to 23h, the total energy requirement is 86.78kWh. The power plant can meet the demand but the production is only in the day while the charge is left from the day to night, the battery park is so to provide and also a GE backup system.

The following table (Table 4) shows the size of the battery fleet [19] and the EW according to each size range.

Table 4 : Battery and GE Fleet Sizing Result

				Capacité du parc batteries C_{bat}	Nombre des batteries (Nbat)	Energie produite annuelle par le GPV	Energie à couvrir par le GE [par an]	Durée de fonctionnement du GE [Par an]	Quantité de Gasoil nécessaire par an	Taux d'insatisfaction	Coût total (PV_Bat_GE)	CO_2
Approach	Example	N		[Ah]		[kWh]	[kWh]	[h]	[litres]	%	Euros	[tonnes]
Approche_1	Cas_1-1	N = 3	C_{bat} (Ec)	27 118	124	29 022	3 043,85	288	304	0,14	85 821,68	5 949,85
	Cas_1-2	N = 1	C_{bat} (Ec)	9 040	42	29 022	3 009,14	336	301	0,17	41 986,22	5 949,84
Approche_2	Cas_2-1	N = 3	C_{bat} (Es)	30 900	141	29 022	3 130,63	312	313	0,16	94 989,60	5 960,10
	Cas_2-2	N = 1	C_{bat} (Es)	10 300	48	29 022	3 338,89	358	334	0,18	45 468,57	5 960,16
Approche_3	Cas_3-1	N = 3	C_{bat} (Em)	17 943	82	29 022	3 131,50	312,24	313	0,16	63 596,56	5 960,10
	Cas_3-2	N = 1	C_{bat} (Em)	5 981	27	29 022	3 278,15	340,35	323	0,17	34 565,66	5 960,14
Approche_4	Cas_4	N = 1	C_{bat} (E_{cpic})	797	4	10 635	22 099,87	4 121	2 210	0,11	39 399,40	9,35
Approche_5	Cas_5-1	N = 3	C_{bat} (Ep)	41 719	190	28 969	2 904,14	249,36	291	0,14	120 813,28	5 949,81
	Cas_5-2	N = 1	C_{bat} (Ep)	13 907	64	28 969	3 222,61	323,04	323	0,16	53 960,33	5 949,90

The next step focuses on the evaluation of these approaches, in order to identify the one that will be ideal for the specific case, according to the criteria imposed by the consumer.

Evaluation of each approach according to the MDM

Identification of the objective of the approach and the type of decision : This is the first step in determining the decision to be made. It is a question of choosing the approach corresponding to the need and interest of the consumer.

List of possible solutions : These are the design basis approaches to be evaluated. The task at hand is to assess the approaches presented in Table 1.

List of criteria to be taken into account : Several elements of comparison are proposed in the literature. The criteria are very variable according to the needs and the desired levels of precision. As part of this work, all the criteria identified as relevant to the choice and based on MDM are: the Capacity of the battery park (Cbat), the

Number of batteries needed (Nbat), the Energy produced by the GPV (Egpv), the Energy to be covered by the GE (Ege), the Operating Time of the GE (Dfge), the Volume of fuels needed (Qté_c), the Dissatisfaction Rate (Insat), the Cost (Co), the amount of CO2 released (Qt_CO2).Before judging the approaches against the criteria, the following table groups the criteria values for each possible case.

Table 5 : List of criteria for comparison of approaches

	Cbat	**Nbat**	**Egpv**	**Ege**	**Dfge**	**Qté_c**	**Insat**	**Co**	**Qté_CO_2**
	[Ah]		**[kWh]**	**[kWh]**	**[h]**	**[litres]**	**[%]**	**[Euros]**	**[tonnes]**
Cas_1-1	27 117,50	124	29 021,54	3 043,85	288,00	304	0,14	85 821,68	5 949,85
Cas_1-2	9 039,17	42	29 021,54	3 009,14	336,00	301	0,17	41 986,22	5 949,84
Cas_2-1	30 900,81	141	29 021,54	3 130,63	312,00	313	0,16	94 989,60	5 960,10
Cas_2-2	10 300,27	48	29 021,54	3 338,89	357,50	334	0,18	45 468,57	5 960,16
Cas_3-1	17 942,81	82	29 021,54	3 131,50	312,24	313	0,16	63 596,56	5 960,10
Cas_3-2	5 980,94	27	29 021,54	3 278,15	340,35	328	0,17	34 565,66	5 960,14
Cas_4	796,32	4	10 634,23	22 099,87	4 121,00	2 210	0,11	39 399,40	9,35
Cas_5-1	41 719,23	190	28 968,16	2 904,14	249,36	290	0,14	120 813,28	5 949,81
Cas_5-2	13 906,41	64	28 968,16	3 222,61	323,04	322	0,16	53 960,33	5 949,90

Evaluation of each solution with respect to the criteria : In order to assess each case, it is mandatory to rate the criteria on a single scale. For this, a maximum rating is 1 and the minimum is 0. The interval step is 0.1 and therefore there are 10 possible assignable notes. Table 5 groups the values of each case according to each criterion. With these values, the maximum value for each criterion is divided by 10 (total number of possible scores to be assigned) and the value equivalent to the interval step (0.1) is obtained. Therefore, this value is the reference when assigning scores for all cases against each criterion.

To put the cases on the same assessment size, the extremums of the scores are assigned and presented in Table 6.

Table 6 : Criteria classification by rating and interval

Paramètres	Cbat	Nbat	Egpv	Epe	Dfge	Qté_c	Insat	Co	Qté_CO_2	Notes
	[Ah]		**[kWh]**	**[kWh]**	**[h]**	**[litres]**	**[%]**	**[Euros]**	**[tonnes]**	**[Ah]**
Valeur minimale	0	0	0	0	0	0	0	0	0	0,1
Valeur maximale	41 7120	190,37	29 022	22 100	4 121	2 210	0,18	120 814	5 961	1
Pas d'intervalle	4 172	19,04	2 903	2 210	413	221	0,02	12 082	597	0,1

To judge the approaches, scores between 0-1 of the criteria values for each approach have been assigned and the result is grouped into the following table:

Table 7 : Assignment of marks to each criterion

Criteria	Coef.	Cas_1-1	Cas_1-2	Cas_2-1	Cas_2-2	Cas_3-1	Cas_3-2	Cas_4	Cas_5-1	Cas_5-2
Cbat	0,04	0,4	0,8	0,6	0,8	0,6	0,9	1	0,8	0,8
Nbat	0,04	0,4	0,8	0,6	0,8	0,6	0,8	0,9	0,1	0,7

Egpv	0,05	1	1	1	1	1	1	0,3	0,9	0,9
Ege	0,05	0,8	0,9	0,8	0,8	0,8	0,8	0,1	0,9	0,8
Dfge	0,04	0,9	0,9	0,9	0,9	0,9	0,9	0,1	0,9	0,9
Qté_c	0,08	0,8	0,8	0,8	0,8	0,8	0,8	0,1	0,8	0,8
Insat	0,2	0,3	0,2	0,2	0,1	0,2	0,2	0,5	0,3	0,2
Co	0,4	0,3	0,7	0,2	0,6	0,5	0,7	0,7	0,0	0,6
Qté_CO_2	0,1	0,1	0,1	0	0	0	0	1	0,1	0,1

For the evaluation, a weighting coefficient is assigned to each criterion according to their level of importance in relation to the final requirements. The sum of all coefficients must be equal to one. In the case of Ivovona, rural area of Madagascar, the factors considered the most important and considered as key factors are: cost, dissatisfaction rate and environmental impact by the amount of CO_2 released.

Weighting of judgments to design the solution with the best ratings : Since some criteria are assessed on a decreasing basis while others are assessed on a progressive basis, scores are first assigned before weighting. The weighting coefficients of which are fixed according to the priorities of the waste.

Finally, the final choice is made by the following relationship:

$$Choix = \sum_{j=1}^{Nc} \alpha_j C_j \qquad (2)$$

With: Nc=9 is the number of criteria
α_j : Coefficient defined for each evaluation criterion with "j" the criteria numbering.
C_j : Value or score assigned to a case for each criterion, with "j" numbering of the assessment criteria.
By associating this relation (2) with the various cases identified, the final formula is written as follows.

$$Choix = \underset{m=1}{\overset{Ncas}{Max}} \left\{ \sum_{j=1}^{Nc} \left(\alpha_j C_{jm} \right) \right\} \qquad (3)$$

With:
Ncas=9 is the number of cases.
Max: Maximum
m : numbering of identified cases.
C_{jm} : Value or score assigned to a case for each criterion, with "j" numbering of assessment criteria and "m" numbering of identified cases.

After weighting the scores against the coefficient, the results are summarized in the following table:

Table 8 : Weighting of the scores for each criterion

Critères	Cas_1-1	Cas_1-2	Cas_2-1	Cas_2-2	Cas_3-1	Cas_3-2	Cas_4	Cas_5-1	Cas_5-2
Cbat	0,01	0,03	0,01	0,03	0,02	0,03	0,04	0,03	0,03
Nbat	0,02	0,03	0,02	0,03	0,02	0,03	0,04	0,00	0,03
Egpv	0,05	0,05	0,05	0,05	0,05	0,05	0,02	0,05	0,05
Epe	0,04	0,05	0,04	0,04	0,04	0,04	0,01	0,05	0,04
dge	0,04	0,04	0,04	0,04	0,04	0,04	0,00	0,04	0,04
Qté_c	0,06	0,06	0,06	0,06	0,06	0,06	0,01	0,06	0,06
Insat	0,06	0,04	0,04	0,02	0,04	0,04	0,10	0,06	0,04
Co	0,12	0,26	0,09	0,25	0,19	0,29	0,27	0,00	0,22
Qté_CO2	0,01	0,01	0,00	0,00	0,00	0,00	0,10	0,01	0,01
Sum of ponderations	0,4058	0,5693	0,34987	0,5215	0,4662	0,5818	0,5767	0,2941	0,5144

The final assessment is made by adding the weights.

III. RESULTS AND DISCUSSIONS

Based on the weighting in Table 8, the result is presented in the following figure:

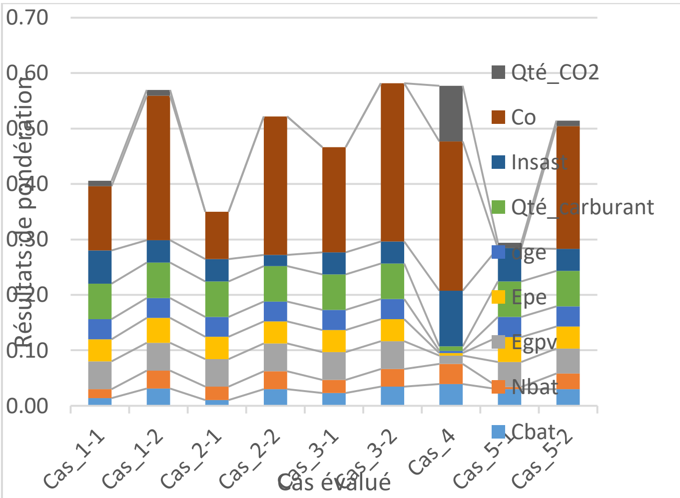

Figure 4: Results of weights by key factors

According to this figure, the results of the choices are:

Table 9 : Evaluation of each sizing approach of the battery park for a PV/Diesel solar power plant

	Choice								
Rang	1	8	3	4	5	6	7	8	9
Possible Case	Cas_3-2	Cas_4	Cas_1-2	Cas_2-2	Cas_5-2	Cas_3-1	Cas_1-1	Cas_2-1	Cas_5-1

Thus in the case of Ivovona, the approach 3 (Cas_3-2) meets the interests and priorities of consumers according to the imposed coefficients. In this caseCas_3-2, the cost is really minimal compared to other cases. It amounts to 50% of the average costs of other cases. Also, it offers an average dissatisfaction rate compared to others which amounts to 0.17% of the need. In this case, the number of batteries used is only 34% of the average compared to the number of batteries needed in other cases. In addition, the duration of operation of the generator is reduced compared to that of other cases which is 46% of the average. Although it has multiple advantages on these criteria, unfortunately, the environmental impact is higher compared to the amount of CO2 released which is 5 960 tons/ year or 113% of the average for all cases. This will lead to other impacts that remain to be defined if it is the criterion considered important and key factor according to consumers and place of installation [17].

IV. CONCLUSION

This contribution relates the determination of the sizing approach of batteries to be integrated into a solar photovoltaic production system with Generator Diesel. Batteries are very expansive, a reduction in its number in use is necessary. By comparing five approaches, a difference in the number of battery is observed and necessarily generates a variation in cost. This is significant in terms of investment which is the key factor regarding the case of the rural area of Madagascar. This cost reduction should neither reduce consumer satisfaction nor increase the environmental impact. In this sense, in this work, the proposed approaches could be put in competition by specifying some criteria judged among the key factors and which are classified according to their importances and prioritizations through coefficients attributed according to the developers.

The MDM methodological approach is the basis of comparative analyses and aims to put into perspective an original approach that can support developers of rural electrification for which, no universal solution is yet identified. Thus, the results obtained could contribute to the optimization of the battery-based storage system in the solar photovoltaic production system, which will have a direct impact on energy efficiency. In terms of perspective, the next step of this work is to evaluate the approaches to the sizing of the battery fleet in other production systems such as wind power plants, PV/Wind system and others. This is in order to be able to achieve a standardized approach allowing for the optimal size of the battery park of multisource systems.

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