HYBRID SYSTEM AND DISTRIBUTED GENERATION PLACEMENT FOR AN OPTIMAL MINIGRID RURAL ELECTRIFICATION: CASE STUDY IN MADAGASCAR

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ABSTRACT

This paper aims to design and analyze an energy system for rural electrification in order to find the optimal configuration of a mini-grid. Designing is not only to practise a best sizing of power demand in each village of the investigated site but it needs also to use some effective optimization methods for finding the best placement and capacity of the generators which should be implemented on the designed system. However, that system should be technically satisfying and economically attractive. That's why different types of generator are investigated, whether it is standalone Distributed Generation (DG) system or hybrid system that combines renewable energy with other energy source. Simulation and technical optimization are performed with Matlab software by using Genetic Algorithm (GA) combined with Newton Raphson load flow, while economical optimization is done under HOMER software. Application is carried out in a remote rural community of Antsahalava / Madagascar that have 19 villages and needs a daily consumption of 9.7 MWh/day and a total power demand of 2.4 MW.

Keyword: *optimal mini-grid, rural electrification, techno-economic optimization, hybrid system*, DG

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1. INTRODUCTION

According to the assessment of the World Bank [1] and the Global Energy Assessment [2] , 1.4 billion people around the world do not have access to electricity, and 84% of whom live in rural areas. It has been estimated that over 800 million rural inhabitants would lack electricity access in 2030 without the implementation of any new policies and measures to accelerate access to electricity. In Madagascar, 65.53% of the population live in rural areas [3]; but many of that remote rural areas are still unelectrified and national grid extension has been very slow. Electrification rate is low. It was around 5% as the estimation seen in [4], [7] and 6.1% according to the work of [5] and [6] in 2015. During the periodic survey of each households, only 15.4% of Malagasy households have electricity [3]. This survey indicated also a clear disparity in access to electricity in rural and urban areas. The enhancement of rural electrification is, then, one of the contributions to sustainable development.
Several power generators system has been observed in many isolated sites. System choice depends on the local energy sources whether it is renewable or not. As far as the electricity production at the rural areas concerned, renewable energy technologies are very suitable but cannot ensure the continuous power supply at the off-grid area. It is due to the intermittent nature of wind and photovoltaic. However, the using of stand-alone diesel generator system, which requires fuel supply and high maintenance, has disadvantages linked to noise, pollutant emission. It means that each of these technologies has limitations. Several solutions have been proposed for technical optimizations of mini-grid but most of them are not economically feasible [8]. The only efficient solution to face and optimize it, is the combination of these two technologies to form a hybrid system and must be implemented in a critical bus of the designed mini-grid. Besides, DG has many advantages over centralized power generation

including power losses reduction, voltage profile improvement and system stability improvement [9]. The optimal placement of DG is important to achieve the maximum benefits with energy efficiency enhancement.

In this work, we are designing an optimal mini-grid for a rural community of Antsahalava that contains 19 villages. Optimal design methodology for this rural mini-grid begins with data collection followed by power sizing. Identification of distribution line between each village to form an initial and near optimal configuration are done in our previous work [10] but at this paper we focus on finding the best placement and capacity of the generators. The generator might be a Distributed Generation (DG) or an hybrid system. Finding and optimizing generators placement are carried out under Genetic Algorithm (AG) and this simulation is conducted in MATLAB. Finally, a comparison of the costs of different configurations resulting different generators placement is done, and the least expensive configuration will be retained as a technical and economic solution for the mini-grid. We conclude the work with conclusions and perspectives that can be contributed in decision-making for the implementation of the new rural electrification project.

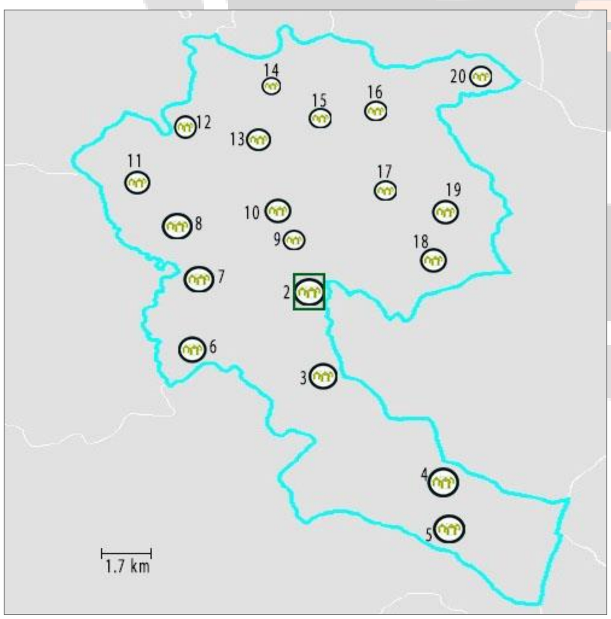
2 DESIGN AND SYSTEM CONFIGURATION

2-1 Optimization Criteria

As mentioned in our previous work [10] and in other work [11], designing a power distribution system must determine, as optimized as possible, the locations and characteristics of loads, the appropriate generator with its corresponding power source, the distribution voltages, and the distribution line configuration. This requires technical and economical optimization. Both these optimization methods are validated by finding power loss minimization and voltage profile improvement [17], according to the international standard limit as IEC Std. 50160 [12]. Power loss must under 6% of the capacity of the installed generator whereas voltage profile have to be comprised between 0.95 and 1.05 p.u.

2-2 Study area and Distribution line configuration

Geographical location of villages in this study area is presented in figure 1. This selected site is in rural municipality of Antsahalava district of Antanifotsy, province of Antananarivo/ Madagascar; whereas the one-line diagram for this area considered as the nearest optimal configuration during the previous work is illustrated in figure 2.



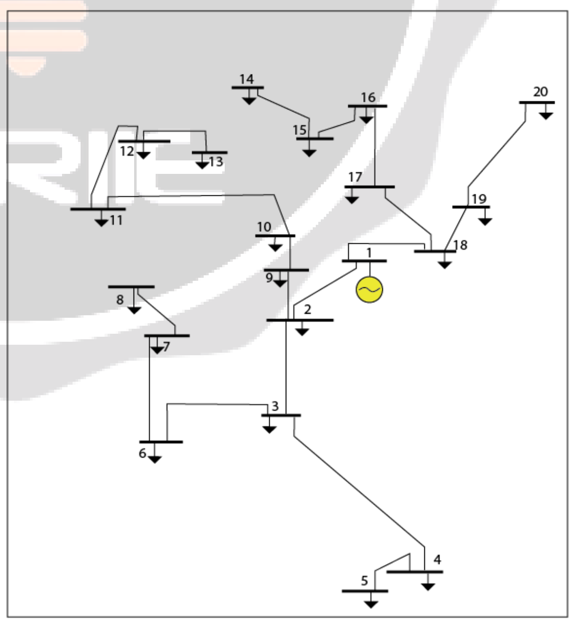


Fig 2: One-line diagram of the near optimal configuration

Data collection of this initial configuration are shown in table 1. Parameters chosen during this test configuration are:

-Medium Voltage : 5 kV
-Low Voltage : 230 V
-Power factor : 0.8

Table-1: Bus data of the initial configuration of the designed mini-grid

Bus (Village)	Bus type	V		Angle [rad]	Pd [kW]	Qd kVAR]	Pg [kW]	Qg [kVAR]
		[pu]	[kV]					
1	2	1	5	0	0	0	2520	1843
2	0	0.9646	4.823	0.5465	210.9	158.2	0	0
3	0	0.9449	4.724	0.8695	82.2	61.6	0	0
4	0	0.9338	4.669	1.0592	113.6	85.2	0	0
5	0	0.9326	4.663	1.0799	138.6	104	0	0
6	0	0.9346	4.673	1.0444	88.2	66.1	0	0
7	0	0.9275	4.6375	1.1661	130.4	97.8	0	0
8	0	0.9254	4.627	1.2032	62.1	46.6	0	0
9	0	0.9421	4.710	0.9096	142.2	106.7	0	0
10	0	0.9360	4.68	1.0105	201.1	150.8	0	0
11	0	0.9104	4.552	1.4476	199.3	149.4	0	0
12	0	0.9034	4.517	1.5718	158.7	119	0	0
13	0	0.9016	4.508	1.6027	60.4	45.3	0	0
14	0	0.9696	4.848	0.4910	61.4	46	0	0
15	0	0.9705	4.852	0.4757	133.6	100.2	0	0
16	0	0.9720	4.860	0.4511	102.4	76.8	0	0
17	0	0.9770	4.885	0.3687	99.2	74.4	0	0
18	0	0.9852	4.926	0.2355	144.4	108.3	0	0
19	0	0.9823	4.9115	0.2830	98.7	74	0	0
20	0	0.9748	4.874	0.4058	164.7	123.5	0	0
Total power					**2392**	**1794**	**2520**	**1844**
loss							**128**	**50**

*Bus Type: (2) slack-bus and generator bus (PV bus), (0) load bus (PQ)

2-3 Generators placement on the mini-grid

As far as this initial configuration of a mini-grid concerned, it is not the very optimal configuration but it is necessary for running optimization with another algorithm to find the best result of voltage stability and reach the minimum threshold of active loss. In this initial configuration with one generator installed at bus 1, even if active loss is 5.08% (less than 6%), almost of voltage profile are under 0.95 p.u, that means that the system is not stable.
However, many research that have done by [9],[13],[14], [18] emphasize that injecting an appropriate generator in critical bus is the one way to improve voltage profile and to reduce active loss. That's why, we are opting to use genetic Algorithm for best sizing generators into appropriate location. In this approach, an hybrid system must install on the slack bus and Distributed Generation is used as single energy system that should be implemented at critical bus. Electrical power generation systems consisting of two or more energy sources are known as hybrid system. It can consist of two renewable sources or combinations of renewable and conventional sources. For example, solar and wind energy can be combined together or with other renewable sources (hydro, geothermal, biomass, etc.), or with a diesel generator. Distributed Generation (DG) is simply defined as the decentralization of power plants by placing smaller generating units closer to a load bus.
Injection of DG in a network involves a transit of active and reactive powers which can increase or decrease of active losses. It depends on the type of DG to be injected into the grid. According to the study of D. Ramakrishna et Al. [13], DGs can be classified into three types as follows:
- **DG type 1**: This type of DG injects real power only. Power factor for this type of DG is 1. Solar PV system is an example of this type.
- **DG type 2**: It injects both real and reactive power into the system. $0<\cos\varphi<1$ and $Q_{DGi}=\tan\theta.P_{DGi}$. Example: Synchronous Generator, Wind turbine in PMSG model *(Permanent Magnet Synchronous Generator)*

- **DG type 3**: It is capable of injecting real power but consumes reactive power from the system. Power factor is given by: 0< cosφ < 1 but reactive power are calculated by $Q_{DG_i} = -(0.5 + 0.004 P_{DG_i}{}^2)$

Ex: Synchronous compensator, Wind Turbine based in DFIG model *(Doubly-Fed Induction Generator)*
Since our work does not focus on compensation or network reconfiguration, this DG type 3 is excluded.

3. METHODS AND MATERIALS

3-1 Genetic Algorithm method

Genetic Algorithm **(**GA) has the ability to deal with wide range of optimization objectives within continuous or discrete variables. The basic principle of GA is the maintenance of a population of solutions to a problem as encoded information individuals that evolve in time as encoded information individuals that evolve in time [15]. Generally, GA comprises three different phases of search: Phase 1: creating an initial population; phase 2: evaluating a fitness function; phase 3: producing a new population. A genetic search starts with a randomly generated initial population of which each individual (chromosome) is evaluated by means of a fitness function. Chromosome in this and subsequent generations are duplicated or eliminated according to their fitness values. Further generations are created by applying GA operators (selection, elitism, crossover, mutation). This eventually leads to a generation of high performing individuals. In our case, the chromosome represents a configuration of the grid characterized by the presence (or not) of generator at bus. This means that if the gene characterizing the chromosome is 1, a DG is to be installed on the bus and on the other hand if it is 0, the bus is like a load bus (no generator installed).
For example, the chromosome which represents the configuration of a distribution network composed by 10 buses and 2 generators installed at bus 1 and 5 is x= [1 0 0 0 0 1 0 0 0 0].
Determination of objective function is very important in this algorithm because it determines what function is to be minimized or to be maximized during the optimization and on what factors it is dependent. Then, all of the objectives function are evaluated in one function that called fitness function.
Our fitness function used to assess the optimality of a solution is: $F = \alpha_1 F_1 + \alpha_2 F_2 + \alpha_3 F_3$

Where F_1, F_2, F_3 are the objective function associated respectively to:
- difference between voltage profile average in cases with DG and in base case (without DG).
- difference between active power losses in cases without DG and with DG
- difference between reactive power losses in cases without DG and with DG

$$F_1 = VPA_{withDG} - VPA_{withoutDG} \;\; ; \; F_2 = L_{PwithoutDG} - L_{PwithDG} \;\; ; \; F_3 = L_{QwithoutDG} - L_{QwithDG}$$

$\alpha_1, \alpha_2, \alpha_3$ are the weights that express as follow:

$$\alpha_1 = \frac{k_1}{VPA_{withoutDG}}, \; \alpha_2 = \frac{k_2}{L_{P\,withoutDG}}, \; \alpha_3 = \frac{k_3}{L_{Q\,withoutDG}}$$

VPA means the voltage profile average of the *n* bus in the mini-grid, $VPA = \frac{\sum_{i=1}^{n} V_i}{n}$ [p.u]

k_1, k_2, k_3 : the emphasis factors or the coefficients of each objectives function
n: number of buses
L_P and L_Q are the total Active Power Loss and Reactive Power Loss of the system respectively. They are obtained from the result of load flow analysis by the Newton Raphson Method [10], [16].

3-2 Matlab and HOMER software

The applications of GA were developed using MATLAB R2105a environment whereas HOMER 3.11.2 has been employed to carry out the economical optimization of energy system. It is possible with this software to model hybrid systems that work in parallel with the electrical grid or in off-grid [19]. The purpose of this analysis is to assess the technical and economic viability of any different configurations, including all possible combinations of PV, wind turbines, diesel generators, and batteries and to determine the best configuration for electrical power production in each location.

4. RESULTS AND DISCUSSION

4-1 Simulation result through GA

In this step, simulation are focusing in identification of the bus that generators should be placed. Before optimization, the base configuration is characterized by the chromosome: x= [2 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0 0] where the gene characterize this chromosome at bus 1 (slack bus) is fixed as 2. It means that the hybrid energy system production is only placed at the slack bus. And DG should install in other bus. If gene=1, DG will be placed, if gene=0, no DG.

Table 2 shows the results of optimization, according to the numbers of injected DGs into the mini-grid

Table -2: Results of GA simulation

	N_{DG} =2				N_{DG}=3				N_{DG} =4			
Bus	**V [kV]**	**V [pu]**	**Bus type**	**Pg [kW]**	**V [kV]**	**V [pu]**	**Bus type**	**Pg [kW]**	**V [kV]**	**V [pu]**	**Bus type**	**Pg [kW]**
1	5.00	1	2	**1773.7**	5.00	1	2	**1483**	5.00	1	2	**1207.4**
2	4.95	0.991	0	0	4.95	0.991	0	0	4.96	0.993	0	0
3	4.90	0.981	0	0	4.90	0.981	0	0	4.95	0.991	0	0
4	4.91	0.982	0	0	4.91	0.982	0	0	4.96	0.993	0	0
5	4.91	0.984	1	**278.8**	4.92	0.984	1	**278.8**	4.97	0.994	1	**278.8**
6	4.86	0.973	0	0	4.86	0.973	0	0	4.95	0.990	0	0
7	4.83	0.967	0	0	4.83	0.967	0	0	4.96	0.993	1	**262.4**
8	4.83	0.960	0	0	4.83	0.97	0	0	4.96	0.992	0	-0
9	4.90	0.982	0	0	4.90	0.982	0	0	4.92	0.984	0	-0
10	4.89	0.979	0	0	4.89	0.980	0	0	4.91	0.983	0	0
11	4.89	0.979	1	**400.2**	4.89	0.979	1	**400.2**	4.91	0.982	1	**400.2**
12	4.87	0.975	0	0	4.87	0.975	0	0	4.88	0.978	0	0
13	4.87	0.975	0	0	4.87	0.974	0	0	4.88	0.977	0	0
14	4.77	0.955	0	0	4.89	0.980	0	0	4.89	0.980	0	0
15	4.77	0.956	0	0	4.90	0.980	1	**268.8**	4.90	0.981	1	**268.8**
16	4.79	0.958	0	0	4.89	0.979	0	0	4.89	0.979	0	0
17	4.82	0.965	0	0	4.90	0.980	0	0	4.90	0.980	0	0
18	4.87	0.975	0	0	4.92	0.984	0	0	4.92	0.984	0	0
19	4.86	0.972	0	0	4.90	0.981	0	0	4.90	0.981	0	0
20	4.82	0.965	0	0	4.86	0.973	0	0	4.86	0.973	0	0
PTM (pu)	**0.974**				**0.979**				**0.986**			
Active power total (kW)				**2452.7**				**2430.8**				**2417.6**
Active loss (kW)				**60.58**				**38.7**				**25.45**

Parameters chosen during the simulation are:

- Population size : Npop= 80,
- Max of generation : maxgen = 100,
- Crossover probability Pc = 0.85,
- Mutation probability Pm = 0.06,
- length of chromosome (Nbit)= 20
- Coefficients of objective function: k1= 10, k2=70, k3=20

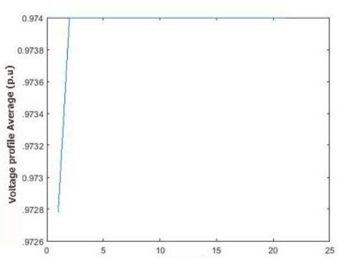


Fig 3: Voltage profile for N_{DG}=2

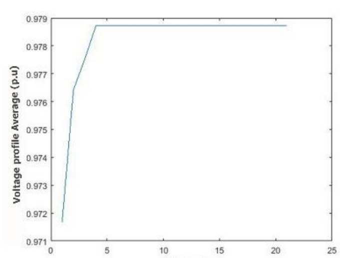


Fig 4: Voltage profile for N_{DG}=3

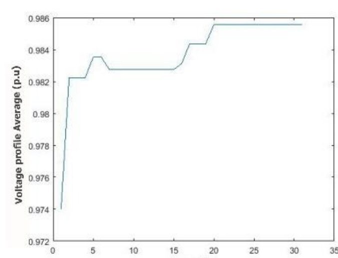


Fig 5: Voltage profile for N_{DG}=4

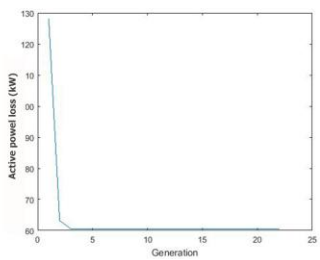


Fig 6: Power loss for N_{DG}=2

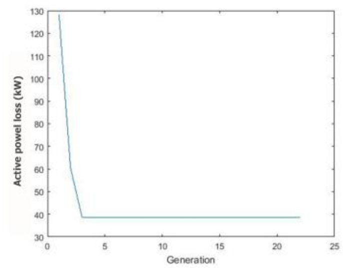


Fig 7: Power loss for N_{DG}=3

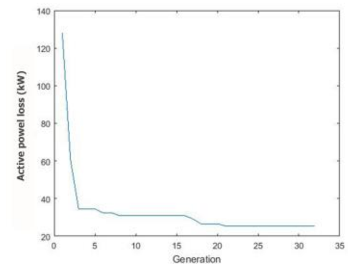


Fig 8: Power loss for N_{DG}=4

According to the tests carried out with GA (after optimization), as shown in table 2 and illustrated in figure 3 to 8; the convergence and the number of iterations and the robustness of the genetic algorithm are very satisfying. The best chromosome solution for each different configuration of different DG injection is corresponding to the column of bus type. So,

-Chromosome for N_{DG} = 2, x_optim = [2 0 0 0 1 0 0 0 0 0 1 0 0 0 0 0 0 0 0 0],
-Chromosome for N_{DG} = 3, x_optim = [2 0 0 0 1 0 0 0 0 0 1 0 0 0 1 0 0 0 0 0],
-Chromosome for N_{DG} = 4, x_optim = [2 0 0 0 1 0 1 0 0 0 1 0 0 0 1 0 0 0 0 0]

The first case with the injection of the two (02) DG indicates a maximum power loss of 60.58kW among the other two cases, its voltage profile average of 0.974 p.u is lower than that of the other two cases: 0.978 pu for the case of 3 DG and 0.986 pu for the case of 4 DG.

By taking the case of injecting the three (03) DG into three different buses, few iterations are enough to converge to an optimal solution. We observe that the DG are to be injected at bus 5, 11 and 15 with respective active power of 278.8kW, 400.2kW and 268.8kW. Power loss is 38.71kW.

With the injection of the four (04) DGs, the GA find the optimal chromosome, in the 21st iteration. In this case, the algorithm found that the fourth DG should be placed at bus 7 with a power of 262.4kW.

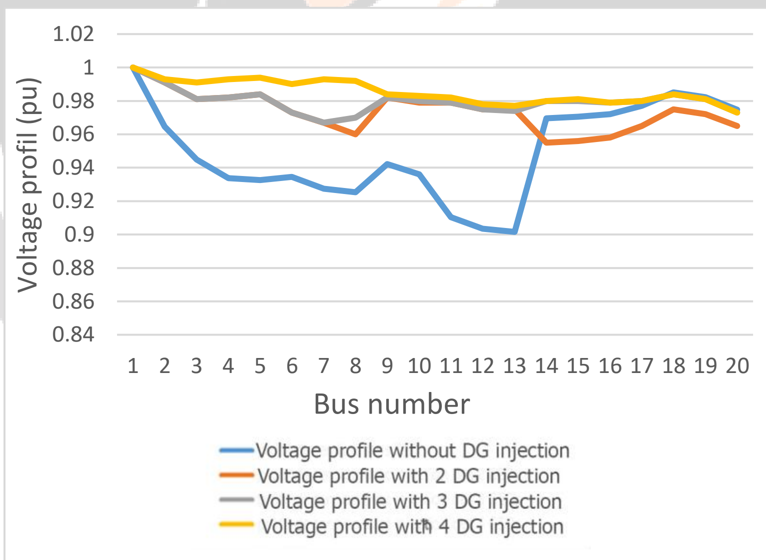


Fig 9: Voltage profile of different configuration

After comparing these different results, the configuration with 3 DG and 4 DG injection have voltage profile similarity; also the active power losses are all under the acceptable value (<5%) but the latter differs with the presence of one generator placed at bus 7 and have capacity of 262.4 kW. It shows that the configuration is technically optimized but economically, it is not attractive. For this reason we are opting of the configuration that injects 3 DG. At this step, full economic optimization is not yet fulfilled, and types of DG to be injected are also not identified.

4-2 Choice of generators type in its best location placement

Table 3 indicates first economic results of different energy power system injecting only at slack bus (bus 1). At this case, no DG are injected at critical bus. But table 4 shows the results with DG consideration.

Table -3: Comparison of different energy power system injecting only at slack bus

	Capacity of the generator (kW)			Produ-ctible (MWh/an)	Investis-ment cost ($)	Operation and maintenance cost /year ($)
	Unity	number	Total Capacity			
Standalone Photovoltaic power system						
PV cells	275 Wc	10131	2786 kWc	3737	8 335 036	111 400
Standalone windturbine power system						
Windturbine	500 kW	5	2500 kW	455	7 500 000	210 000
Standalone Diesel Generator						
XHZY-500GF	500 kW	6	3000 kW	7755	270 000	2 644 200
Hybrid system (results by using HOMER)						
PV	300 Wc	3466	1040 kWc	1979	3 120 000	41 600
Windturbine	500 kW	1	500 kW	91,557	1 500 000	42 000
Diesel Generator	1000 kW	1	1000 kW	2585	80 000	681 400
Total cost of hybrid system					4 700 000	765 000

Table -4: Comparison of different configuration with 3 DG placement at bus 5, 11 and 15

	Generator Capacity (kW)	Configu-ration 1	Productible (MWh/year)	Cost ($)	Configu-ration 2	Productible (MWh/year)	Cost ($)
Bus 1	1 000 500 (Hybrid system)	**PV** (Sunrise) **Diesel generator** (Kholer)	1 899.953 315.370	3 157 000 600 000	**PV**(Sunrise) **Diesel generator** (Kholer)	1 899.953 315.370	3 157 000 600 000
Bus 5	280	**PV** (Sunrise)	375.585	880 000	**GD**((Kholer)	759.856	336 000
Bus 11	400	**GD** (Kholer)	916.788	480 000	**PV** (Sunrise)	529.200	1 256 000
Bus 15	270	**WT**(Vergnet)	45.155	1 630 000	**WT**(Vergnet)	45.155	1 630 000
TOTAL	**2450**		**3552.851**	**5 280 000**		**3549.534**	**5 349 000**

According to this table, configuration 1 represents a reliable and profitable solution because it produces energies of 3,552.8MWh / year; that is sufficiently covers the annual demand of 3,551MWh / year for the rural municipality. In addition, its total investment cost of $ 5 280 000 is lower than that of configuration 2 which is $ 5 349000. Therefore, configuration 1 is retained as optimal configuration.

4-3 Final design of the mini-grid

To validate an optimal single-line diagram of the network, Comparative results of different energy power system configuration as shown in table 5 is very important.

Table -5 : Comparative table between results from different energy power system

	Power demand [kW]	installed Capacity [kW]	Active loss [kW]	Annual consumption [MWh/year]	Productible [MWh/year]	Total cost [$]	LCO (year n=1) [$/kWh]
Standalone PV power system	2 392	2 786	394	3 551	3 737	8 446 436	2.260
Hybrid system placed only at bus 1	2 392	2 540	undefined	3 551	4 656	5 465 000	1.173

Standalone Diesel Generator	2 392	2 520	128	3 551	3 851	-	-
Hybrid system placed at bus 1 With 3 DG installed at bus 5,11,15	2 392	2 430	38.7	3 551	3 552.8	5 280 000	1.486

As we observe in this table, only the last row shows the optimal techno-economic result. Consequently, the final design of the mini-grid proposed to be the optimal configuration for this selected site of Antsahalava, taking into account all the data and hypotheses of generators placement, are shown in this last figure (figure10).

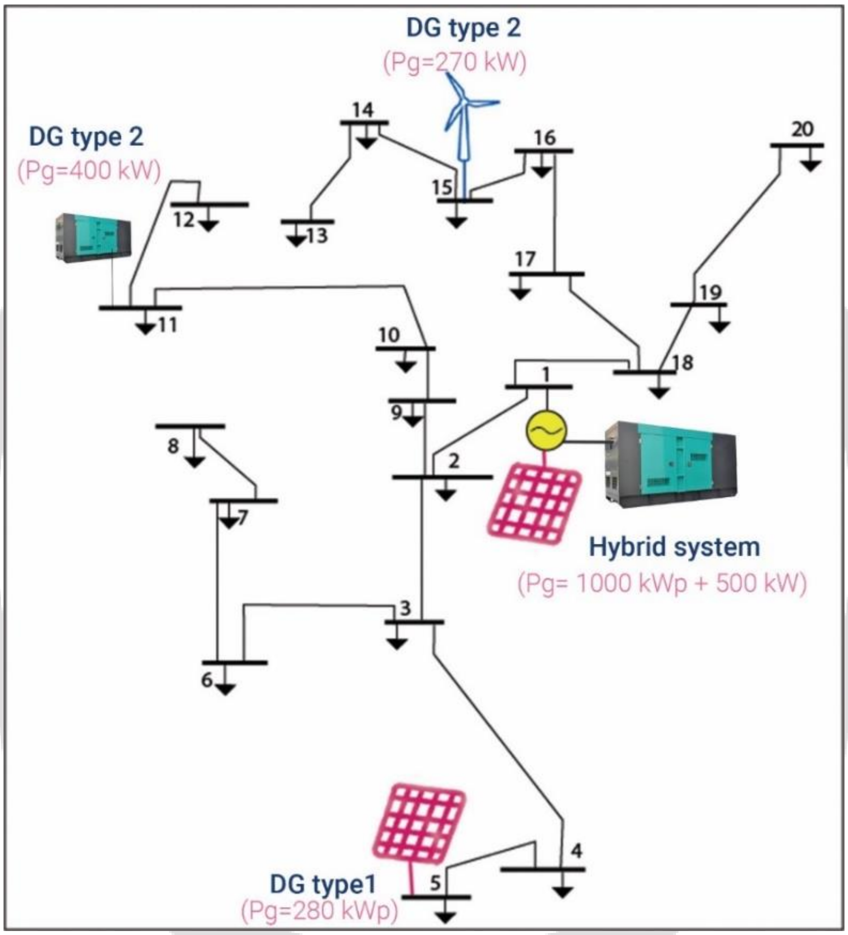


Fig 10: The proposed best placement of hybrid PV/diesel system and DGs for an optimal mini-grid

Thus, the optimal result is to install a hybrid system (1000 kWp PV with 500 kW Diesel Generator) at the Slack-bus, and to inject three more generators at bus 5, 11 and 15 with capacity of 280 kW PV, 400 kW DG and 270 kW wind turbine respectively. With this configuration, power losses in the mini-grid are minimum and bus voltages profile are the best.

5. CONCLUSION

The effectiveness of the proposed method to design and optimize an optimal mini-grid through generators placement is demonstrated in this work, through the example case of the selected site. It is hard not to be daunted by the scale of the problem of providing new energy system to the world's rural population. The rural electrification using hybrid renewable energy system within DG injected at buses has been introduced as a reliable solution. The analysis and results of this remote area show that the designed system can be economically and environmentally attractive. The system could be a good solution for rural area electrification because of the reliability and cost effectiveness of the system. We can say that a study to electrify a rural commune with an optimal design must be adjusted the production and distribution systems according to site demand. This study must also take into account the technical and socio-economical aspects.

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