An Islanded Microgrid Design : A Case Study

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***Abstract*—Mafate is a natural protected cirque in Reunion Island, where about 300 dwellings are settled. The locals suffer from a massive energy insecurity because Mafate is not connected to the main grid. Although stand-alone solar microgrid installations are the preferred solution, they cause significant costs. "Micro Réseau Mafate" is a research project funded mainly by the European Regional Development Fund aiming at proposing strategies for microgrid development. In this paper, an actual islanded microgrid in Mafate is under scrutiny. The objective of the study is to rightsize the actual microgrid design considering the actual energy demand and solar resource measured in-situ. A Levelized Cost of Energy analysis is carried out and energy demand increasing scenarios are considered.**

***Index Terms*—Hybrid power plant, solar power, conventional energy sources, batteries.**

Fig. 1. Drone photography of the case study microgrid.

I. Introduction

Global electricity consumption has drastically increased over the years. However, some areas are still highly affected by energy insecurity for various reasons such as topography, local authority regulations or remoteness. Each of these 3 common causes generates additional costs for electrification. Solar based microgrids are suitable for rural electrification, as primary energy transportation is costless. However, rural microgrid development requests a major capital investment, especially for a reliable energy storage system. To secure power supply, particularly during bad weather periods, microgrid designers tend to oversize installations. Although microgrid oversizing is a security guarantee, it leads to important extra costs. The case study is described in *Calogine et al.* [1], it is a 7 kWp solar microgrid supplying 3 actual residential houses in Mafate of Reunion Island (France). The dwellings seen in figure 1 are located at about 50 meters away from the power plant. A 140 kWh lead acid battery capacity is installed in-situ. The microgrid, designed by the SIDELEC [2], is operational since january 2019 and tested in the scope of the European project entitled "Micro Réseau Mafate", aiming at proposing strategies for microgrids development. The installation is fully monitored to obtain weather, solar production, energy storage and energy consumption data. A microgrid model is used to simulate various configurations.

To foresee an increase of the actual consumption, dummy loads are generated by adding individual appliance profiles to the measured loads. The sub-metered profiles are drawn from public databases and aggregated according to probabilistic models. Hybridizing the solar microgrid with a diesel generator (DG) is also under examination to secure the power supply and to lower initial costs. As we have a 3 years feedback on the microgrid operation through the collected data, a rightsizing is proposed in this work, to determine a more profitable power plant configuration. An analytical method [4] is applied to optimize the sizing against Levelized Cost of Energy (LCOE) and fuel consumption criteria. The process is carried out considering energy demand increase scenarios, and realistic configurations of the case study.

The paper is organized as follows, section II describes the actual microgrid in Mafate, section III presents the microgrid model and section IV the load increasing scenarios, finally section V contains the sizing results and discussions.

II. Case study microgrid

In this section, a feedback from the case study microgrid operation is given through the measured data. Actual aggregated energy demand and solar resources in-situ are described.

A. Load evaluation

A majority of Mafate inhabitants has a very rural lifestyle, with a low access to energy. On the case study site, before microgrids were installed, they used weak solar installation and DG requiring a regular fuel supply. Storing a high fuel quantity in Mafate is not possible to avoid fire incident, as it is an UNESCO protected site. Mafate is not accessible on foot, each significant supplying has to be made by helicopter, leading to extra costs. Furthermore, wood fire cooking is generally favoured by the locals. Consequently, the inhabitants are naturally accustomed to saving electrical energy. This behaviour is demonstrated by the energy demand data, as seen in figure 2. Indeed, the 3 dwellings consume far less energy, with

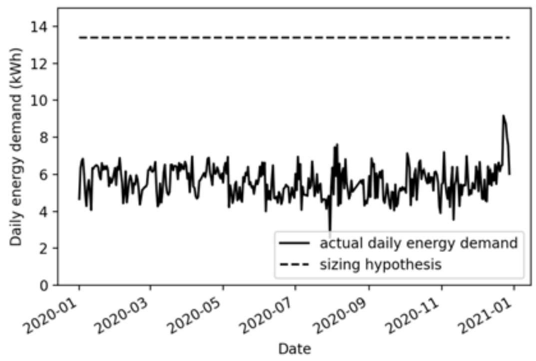

Fig. 2. Daily aggregated energy demand, in-situ measurement compared to sizing hypothesis.

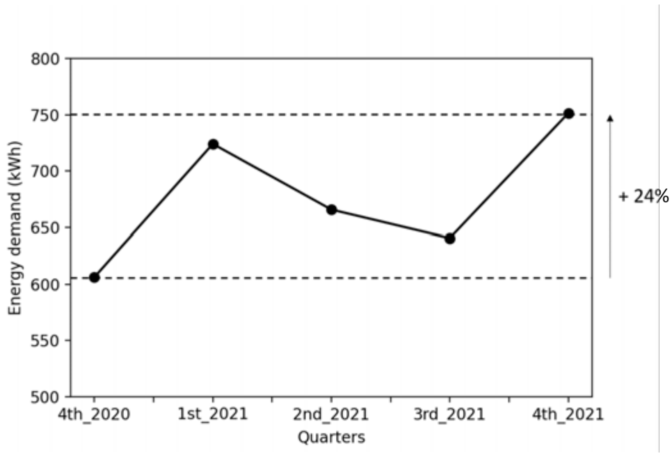

Fig. 3. Energy demand evolution on a quarterly basis. The bottom dashed line is the energy demand for the fourth quarter of 2020, while the top dashed line represents the energy demand for the fourth quarter of 2021.

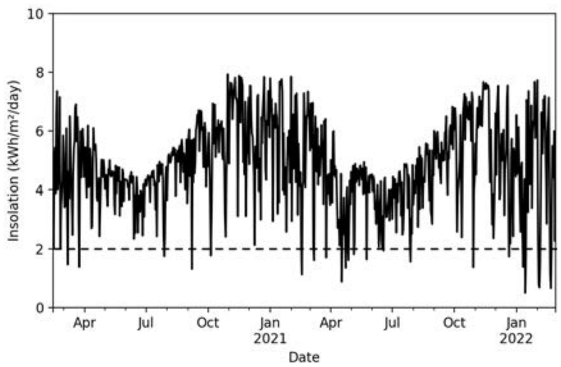

Fig. 4. Daily insolation received on a horizontal surface at the experimentation site in Mafate. The dashed line represents the threshold for considering a very low insolation level.

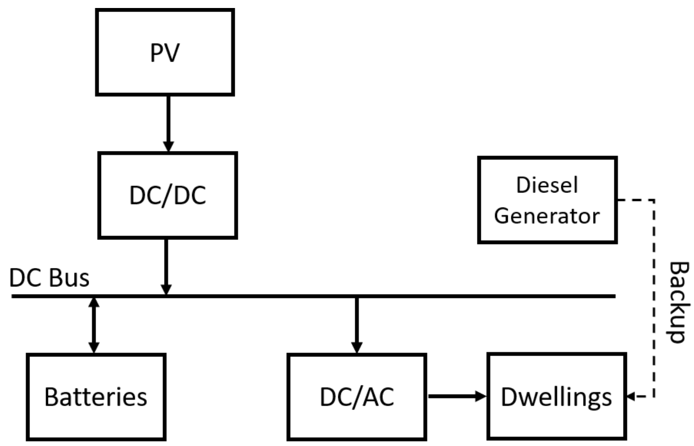

Fig. 5. The case study microgrid architecture.

an average difference of 7.80 kWh between sizing demand hypothesis and actual energy demand. Thus, the microgrid is at least 58.00% too oversized. However, oversizing is necessary to mitigate the uncertainties on demand increases. To evaluate the load increase, the energy consumption is determined on a quarterly basis. Figure 3 demonstrates a 24% load increase between the fourth quarter of 2020 and 2021.

B. Solar resource evaluation

Another source of uncertainty is the solar resource. Daily insolation is represented in figure 4, the seasonal cycle can be clearly seen. June to July is the peak winter period while January to December is the peak austral summer. During cloudy days and rainy days, insolation values decrease sharply reaching 2 kWh/m²/day. Even though low insolation days is at a first sight dispersed over time, in the beginning of February 2022 we had 3 very cloudy days (from the 3rd to the 5th of February) in a row during Batsirai cyclone. At the end of February, a second cyclone named Emnati struck Reunion Island, responsible for the three consecutive very low insolation days (from the 20th to the 22nd of February). Those two extreme climatic events are important to be considered for the microgrid rightsizing process.

III. A MICROGRID MODEL

In this section, a microgrid model is presented. The model inputs are the weather data measured in-situ (irradiance and ambient temperature), and the real/dummy energy demand.

A. Microgrid architecture

The microgrid architecture is presented in figure 5. The energy demand is met by prioritizing the energy from the photovoltaic (PV) field. If there is a PV production surplus the battery is charged, while if there is not enough solar production, the battery is drawn. The DG works as a backup, whenever the battery is depleted.

Designers tend to limit the use of the DG because Mafate is a protected site where it is substantial to limit emitted pollution (noise pollution and greenhouse gas (GHG) emissions).

B. PV model

The PV model used is presented in *Guezgouz et al.* [6], the paramaters are adjusted according to the parameters of the PV panel used. PV output power is defined as :

$$E_{pv}(t) = \Delta t.N_{pv}.P_{pv}.f_{pv}.\frac{G(t)}{1000}.(1+K_t(T_c(t)-T_{ref})), \quad (1)$$

where Δt, f_{pv}, G, P_{pv}, N_{pv}, K_t are respectively the time step, the losses factor, the solar radiation, the PV panel power peak, the number of panels composing the solar field, and the temperature coefficient of the PV panel. T_c is the cell temperature, calculated as follow :

$$T_c(t) = T_{em}(t) + \frac{NOCT - 20}{800}.G(t), \quad (2)$$

T_{em} being the ambient temperature and $NOCT$ the nominal operating cell temperature.

C. Battery model

In this work an energy balanced battery model is used. It has been demonstrated in *Zhang et al.* [7], simplified battery model accuracy is not too far from a more detailed model. The battery model output are the State of Charge (SOC) and the depth of discharge (DOD) defined as :

$$SOC(t) = \frac{E_b(t)}{E_{bnom}} \times 100, \quad (3)$$

$$DOD(t) = 100 - SOC(t), \quad (4)$$

$E_b(t)$, E_{bnom}, respectively the energy capacity of the battery at time t and its nominal energy capacity. $E_b(t)$ is calculated according to the previous energy level with

$$E_b(t) = E_b(t-1) + (E_{pv}(t) - \frac{E_{load}(t)}{\eta_v}).\eta, \quad (5)$$

$$\eta = \begin{cases} \eta_c \text{ in charging mode} \\ \frac{1}{\eta_d} \text{ in discharge} \end{cases}, \quad (6)$$

η_v being the inverter efficiency and $E_{load}(t)$ the energy demand. For standalone microgrid design, battery lifetime is important to consider as it is generally the most expensive component. For our study, the simulated DOD for an average operating day is determined to estimate the battery lifetime with respect to the figure 6.

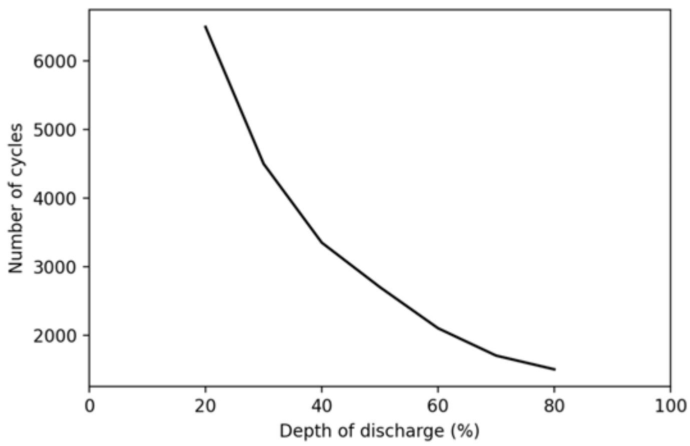

Fig. 6. Cycle number as function of the DOD at 25°C. The figure is given by the OPzS battery supplier in technical datasheets [5].

IV. Load increase scenarios

Each Mafate dwelling connected to the case study microgrid has a far lower energy demand than the average dwelling in Reunion Island due to their rural lifestyle. However, the figure 3 hints an eventual load augmentation for the future. There are several possible causes for energy demand increasing, two reasons are considered, load augmentation due to the use of more electrical appliances and load increasing due to connection of more dwellings to the microgrid. We note L_j^k the load profile with j additional appliances and k connected dwellings. The applied load increasing process is defined as :

$$L_n^m = \sum_{j=0}^{n} a_j + \sum_{k=0}^{m} d_k, (m, n) \in \mathbb{N}^2, \quad (7)$$

a_j is the j^{th} appliance sub-meter power profile, a_0 is the always-off signal, i.e a constant function equal to 0 W. d_k is the individual profile of the k^{th} dwelling, d_0 is the always-off signal. We note n and m respectively the number of added appliances and the number of dwellings connected to the power plant.

A. Additional appliances

With the microgrid, dwellers are more confident to consume energy, thus a likely scenario would be that the inhabitants will purchase and use more appliance types to ease their daily life. Between 2019 and 2021, dwellers used mainly fridge, freezer, television set, phone charger and lighting. For simulations, sub-meter load profiles are added incrementally to the aggregated load to evaluate the microgrid capabilities to meet higher loads due to the use of more electrical appliances. To construct the a_j time-series in equation (7), an operating profile of the appliance to add is extracted from the Dataport public dataset [8]. Chunk extracted are repeatedly added to an "always-off" signal, a_0, according to a realistic normal distribution of the hours of use for each specific appliance.

B. Additional dwellers

For profitability purpose, the microgrid operators intend to connect more dwellings to the power plant. Up to $m = 3$ in equation 7, the measured data are considered. To create a fictive load for an additional dweller, i.e when $m > 3$, an actual measured individual load, randomly chosen between the 3 monitored dwellers, is shuffled by day. The day shuffling allows to avoid biased power peak after aggregation. Choosing

TABLE I
LIST OF THE ADDED APPLIANCES WITH THEIR NORMAL DISTRIBUTION DEFINITIONS, $N(\mu, \sigma^2)$ IS THE NORMAL DISTRIBUTION DEFINITION OF THE APPLIANCE WHERE μ AND σ ARE RESPECTIVELY THE MEAN HOUR OF USE AND THE STANDARD DEVIATION. THE OCCURRENCE IS THE NUMBER TIMES OF USE OF EACH APPLIANCE BY THE 3 INITIAL DWELLINGS.

Appliances	Mean power (W)	Occurrence	$N(\mu, \sigma^2)$
Washing machine (wm)	136	370	$(18, 4^2)$
Electrical oven (ov)	1558	85	$(18, 4^2)$
Microwave (mw)	1007	300	$(9, 3^2)$
Dish washer (dw)	549	150	$(21, 3^2)$

TABLE II
CONSIDERED LOAD SCENARIOS

id	Load	Energy (kWh/year)	Additional appliances
0	L_0^3	2067	-
1	L_1^3	2128	wm
2	L_2^3	2221	wm - ov
3	L_3^3	2234	wm - ov - mw
4	L_4^3	2359	wm - ov - mw - dw
5	L_0^4	2773	-
6	L_0^5	4045	-
7	L_0^6	5120	-
8	L_0^7	6253	-
9	L_0^8	7318	-
10	L_0^9	8484	-
11	L_0^{10}	9182	-

a load base between the 3 monitored dwellings allows to retain local consumption behaviours.

V. EXPERIMENTATION AND RESULTS

A. Microgrid configurations

For the present work, 4 configurations are under examination :

- configuration 1 (C1) : 7 kWp solar field, and a 140 kWh energy storage,
- configuration 2 (C2) : 7 kWp solar field, and a 70 kWh energy storage,
- configuration 3 (C3) : 3.5 kWp solar field, and a 140 kWh energy storage,
- configuration 4 (C4) : 3.5 kWp solar field, and a 70 kWh energy storage.

For each configuration, a 3 kVA DG is used if backup is required. The solar field for the initial configuration, C1, is composed of two solar panel arrays, each array has its own MPPT charge regulator. Therefore, halving the total solar field is equivalent to stopping one of the arrays. A same logic is applied to the batteries, as in C1 there are two battery banks connected in parallel where each battery bank is composed of 24 serially mounted cells of 2 V each. Consequently, cutting one of the battery fleet would keep the DC bus voltage at 48 V. Adding more solar panels and more batteries to the C1 configuration are not viable options as it would require more lands to be purchased.

B. Simulations

LCOE has been used and calculated in several works on microgrid sizing, such in [9] and [10]. This economic metric is useful to compare energy system configurations based on each subsystem features. We use the LCOE for configuration comparison. We suppose a 25 lifetime years for the PV panels, the battery lifetime depends on its DOD as indicated in figure 6. Project lifetime is supposed to be 25 years for the simulation. A DG is used only when the battery is depleted. When backup is required, we suppose a 30% higher maintenance cost. For the DG operation, the fuel price is supposed to be slightly higher than usual prices due to helicopter deliveries. Simulations are processed on MATLAB/SIMULINK. The 4 different microgrid configurations are simulated according to 11 load scenarios, see Table II.

C. Results

The actual configuration C1 with the actual load, L_0^3, has a very high LCOE, between 0.12 and 0.16 €/kWh more than the actual energy price in Reunion Island, which is considerable. Simulation and real operation of the microgrid show C1 with L_0^3 load does not need DG backup, see figure 8. Figure 7 demonstrates the LCOE results. From scenario 0 to scenario 4, for which only appliance profiles are added to the aggregated load, we see a slight decrease for each configuration. From scenario 5, new dwellings are connected to the power plant making the decrease more substantial. Indeed, increasing the load demand, thus increasing the produced energy, reduces the LCOE value. For grid operators to aim at a profitability, they have to connect new end-users to the actual microgrid. From scenario 6, with load L_0^5, the energy cost becomes interesting regardless of the configuration. However, increasing the energy demand weakens the power plant. As seen on figure 8, from load scenario 9, C1 needs an auxiliary DG. C1 and C2 keep reasonable DG energy needs, even with 10 dwellings, L_0^{10}, where about respectively 60 and 110 L of fuel per year are required. For those last configurations, the DG is activated only for the lasting bad weather periods. Hence, C1 and C2 does not need a too frequent fuel deliveries.

After scenario 6, fossil fuel requirements for C3 and C4 increase drastically, contrary to C2 and C1. The last two have a higher solar energy collection capability, which is very important for the case of Mafate. Indeed, the afternoons are often cloudy, so the most of the solar energy collection has to be made in a short period in the morning otherwise the battery is deeply discharged and slowly charged, shortening its lifespan. That makes C3 and C4 less resilient to load increasing. C3 is then the most unfavourable configuration as it has a higher LCOE than C4 with an equal conventional source need.

C2 gives an interesting trade-off between LCOE and fuel requirements. Up to 6 end-users, the C2 power plant is capable to operate without a DG at 0.11 €/kWh cost, slightly under the local average energy price. C2 can reach an even more interesting LCOE value (0.07 €/kWh) at a low fuel consumption (110 L/year) for 10 dwellers connected (scenario 11).

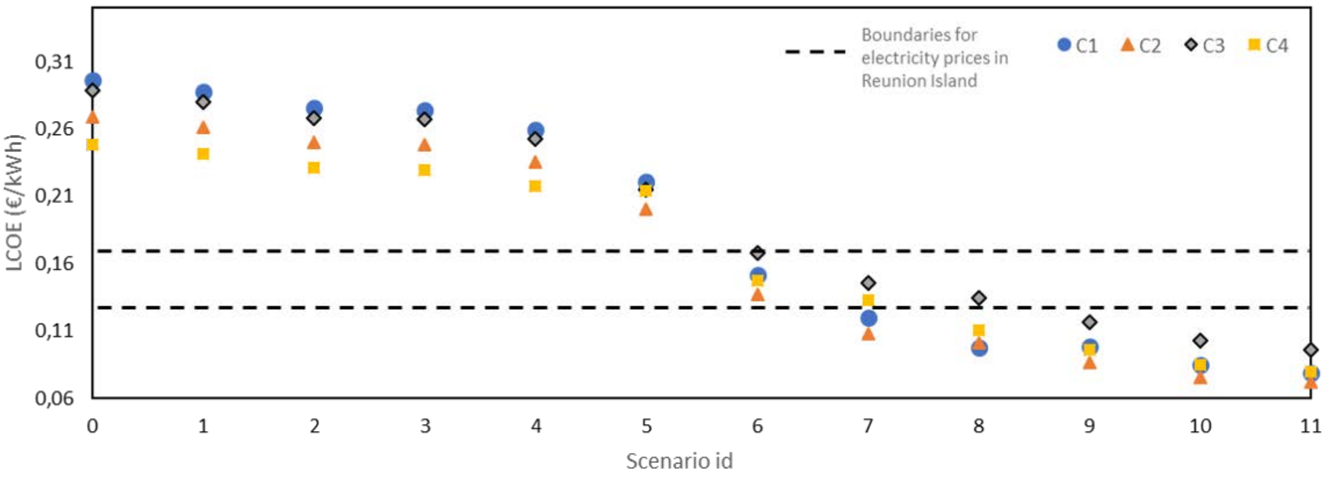

Fig. 7. LCOE values for each load scenario. Energy prices are obtained from the local grid operator [3].

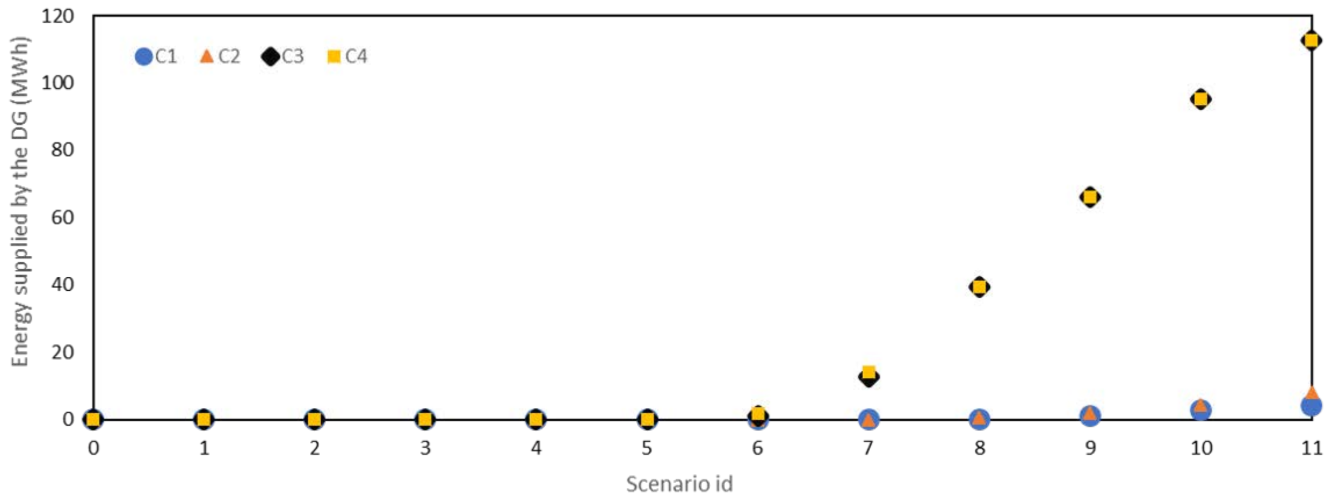

Fig. 8. Energy to be supplied by the DG for the 25 years simulation.

VI. Conclusion

The present work broaches the case of Mafate. The high surrounding relief makes it an off-grid area. To meet the local energy demand, solar microgrids are designed. Our case study is on a microgrid in Mafate powering 3 actual residential buildings. In this paper, the case study configuration is rightsized to reduce the LCOE and the DG use. Simulation results demonstrate more dwellings have to be connected to the installation to reach a more profitable microgrid operation. Batteries are the more expensive among the subsystems, halving battery capacity allows an average 9.00% LCOE decreasing, with an interesting resilience to load increasing, it can support until 6 dwellings connected without any backup needed. Our results show that hybrid systems are more resilient, with the use of a backup generator more than 10 dwellings can be powered with an affordable energy cost. Although fossil fuels have high impact on the environment, an economical and limited usage of conventional sources decreases energy storage investment costs, thus contributes to limit GHG emissions from electrochemical battery manufacture and transportation. For future investigations, it is worth wondering to what extent this GHG reduction compensates for the environmental impact of the DG operation.

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