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ENERGY SUPPLY TIME IN AN ISLANDED GRID PORTION RE-ENERGIZED BY LOCAL RENEWABLE SOURCES

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ABSTRACT

When a portion of the low-voltage distribution network, typically a village, is disconnected from the upstream network, due to a fault or maintenance, it can be re-energized temporarily by the distribution system operator. Usually, if closing of a normally open tie-switch connected to a neighboring feeder is not possible, a diesel generator is conveyed to the islanded grid portion, and used towards temporary energy supply. This solution though can be costly, environmentally detrimental or not available. In this paper, an alternative solution towards temporary energy supply of a islanded grid is presented, relying instead only on local renewable sources, here photovoltaic sources, and a small battery. This work further improves decision-making, by providing valuable information to system operator. Given consumption and generation time-series data, the continuous supply of the islanded grid is estimated, depending on several parameters such as the starting time and the demand response scheme enforced.

INTRODUCTION

An alternative solution to using mobile diesel generators is investigated to reduce the carbon impact of the temporary supply for an islanded portion of the distribution grid, a procedure occurring after a fault or during a maintenance event. This alternative solution is based on using local renewable sources, here photovoltaic (PV) sources, and a small battery. Another advantage of this solution would be a faster re-energization, as there is no delay associated with transporting the diesel generator.

The question of transient stability regarding the type of inverter control used in this inverter-based island has been addressed in [1]. In this paper, the focus is on longer-term, energy-based considerations. Since PV is an intermittent source, it is tempting to include a battery to supply energy at night or low-irradiance times. Traditionally, the battery is sized using optimization algorithms that minimize selected indicators, economic and environmental, while having as the main objective to satisfy 100 % of the load. In [2, 3] state-of-the-art optimization algorithms and sizing criteria are reviewed. The authors of [2] also point out that some criteria are less often used, such as resilience and sustainability, defined as the long-term balance between environmental health, social equity, and economic vitality.

Indeed, those criteria are less prone to be mathematically modeled and incorporated into an optimization strategy. To correct this bias, the authors of [4] chose to analyze a subset of the partially optimal solutions in the search history of a multi-criteria algorithm and post-process them. This approach seems particularly adapted to the present case, and a similar perspective has been adopted in the following work.

As opposed to the traditional above-mentioned sizing studies, the objective of the present work is to determine, considering the generation and storage capacity already present in the microgrid, for how long the load could be supplied, or which percentage of the load could be supplied during a certain time. Indeed, the scenario under study is a temporary islanding scenario, in which aiming to supply 100 % of the load does not necessarily make sense, in the light of economic, environmental, and resilience indicators. Demonstrators proved that by using a large battery, an islanded portion of the distribution grid can be operated for a few hours. However, other levers than the size of the PV sources and batteries can be used to improve this temporary and constrained electricity supply. For instance, Demand Response (DR) programs can be enforced to first ensure a fair distribution of the limited energy resource, and second ensure a sustained but limited supply, meaning that black start shall be performed only once.

In [5], the goal of the authors is to maximize user satisfaction in a rural microgrid with a constrained generation capacity. Increasing the generation size however can be costly and not help to unforeseen low-generation conditions. Instead, a DR strategy is used: the load is divided into three categories based on their priority, and a central control sheds the excess load if the battery State of Charge (SoC) goes too low. In [6], the sizing of an Egyptian microgrid mainly based on PV and wind energy is studied. A biomass plant and connection to the grid are also available. The sizing algorithm is run multiple times with different percentages of participation in a price-based DR strategy, time-of-use strategy. The main takeaway of the study is that increasing the participation in the DR strategy, from 10 % to 30 %, increases the capacity of PV and wind sources, while the capacity of biomass, exchanges with the grid, costs, and CO₂ emissions decrease. This study is a good example of the

complementarity of sizing and DR studies.

The remainder of the paper is organized as follows: in section I, models used in this work are presented. Section II introduces the methodology, while different operating conditions and their effects are analyzed in sections III and IV.

I- MODELS

Generation

The energy in the microgrid is exclusively produced by roof-top PV panels. The following paragraphs describe the PV module selected, the irradiation data used, and the selection of four representative days.

PV module

A polycrystalline PV module of 245 Wp and 1.63 m² has been selected.

Irradiation data

Irradiation and meteorological data have been retrieved from the Sodapro website [7], for a location in Grenoble, France. From those data, the output of the PV panel has been calculated using the following equations:

$$P_{panel} = \frac{P_{gi}}{P_{STC}} * P_{panel}^{STC} * [(T - T_{STC}) * \delta_{panel} + 1] \quad (1)$$

$$T = T_{amb} + (T_{NOCT} - 20) * \frac{P_{gi}}{P_{NOCT}} \quad (2)$$

where P_{panel} is the output panel power in W, P_{gi} is the global irradiation in W/m², P_{STC} and T_{STC} are the irradiation and temperature in Standard Test Conditions (STC) in W and °C, P_{panel}^{STC} is the peak power of the panel under STC in W, δ_{panel} is the temperature coefficient of the module in °C⁻¹, T_{amb} is the ambient temperature in °C, P_{NOCT} and T_{NOCT} are the irradiation and temperature under Normal Operating Cell Temperature (NOCT) conditions in W and °C. The time step of the generated profiles is the minute.

Representative days

Four representative days have been selected to represent a variety of use cases. In this paper, all results have been obtained using the sunny summer representative day.

Consumption

In the presented work, it was necessary to have a time-wise detailed, low-aggregated, realistic, and alterable set of consumption profiles. The needed precision, ease of use, access to local data, and the time available made that we decided to build a residential load profile generator from scratch, using Matlab (Version 9.12.0, R2022b), rather than using one from the state of art. Other residential load profile generators exist in the literature: one developed by

the Center for Renewable Energy Systems Technology (CREST) of Loughborough University, which is available online [8], and another by the University of Twente, which also allows to add DR strategies to the profiles [9]. Other load profile generators could be found in the literature, but most of them were not open-source. The reasons for developing a residential load model were the in-depth knowledge of the model required to properly apply DR strategies, the use of a time step of our choice, the ease of integration of the model in the developed code, and the choice of the output format.

The load profile developed includes the following electric equipment: lights, oven, stove, internet box, fridge, washing machine, dishwasher, ventilation, TV, informatics equipment, electric heater, electric domestic water boiler, other (air-dryer, rice-cooker, etc.). For each piece of equipment, the following information is provided:

- the proportion of households using it;
- the window of time during which it can be used;
- a random starting time within this window of time;
- a consumption pattern: it is either extracted from real-life measurements (e.g. dishwasher cycle) or determined using a given power and duration of use (e.g. lights). Real-life measurements were retrieved from [10].

The parameters of the load profile were adjusted considering standard daily energy consumption data, and elementary characteristics of standard aggregated load profiles (height and time of the consumption peak, baseline consumption value, etc.) made available by the main French DSO, Enedis, on their Open Data [11]. The time step of the generated profiles is the minute.

For repeatability, in the following work, unless stated differently, instead of generating random new consumption profiles for each graph, a fixed set of profiles has been used. A sample of 30 households is used unless stated differently.

II- METHODOLOGY

The estimation of the supply time on the island requires an Energy Management System (EMS) algorithm and a minimal set of assumptions. At the beginning of the algorithm, a starting time, a PV capacity, a battery capacity, and weather conditions selected. The battery is considered half-charged to start the simulation with the same potential up and downward. Then, for each time step, the EMS is implemented in the form of general rules:

- if there is surplus energy produced, it is stored in the battery. If the battery is full, the production is curtailed;

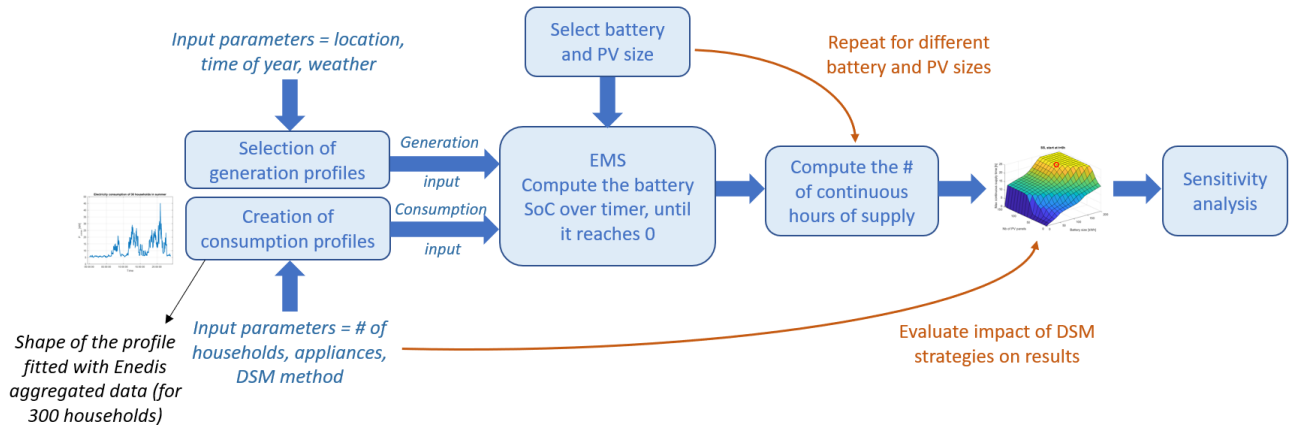


Figure 1: Methodology for the analysis of the continuous supply time in the islanded grid

- if there is an energy deficit, energy is provided by the battery. An efficiency of 95 % is considered for the battery. If the battery is empty and the load cannot be supplied, the algorithm stops and records the number of continuous hours during which the load could have been supplied. This value will be called the continuous supply time (CST).

The general methodology is illustrated in Figure 1.

III- SUPPLY TIME

In this section, different sizing options are investigated. This section is written without considering any requirement or standard from the distribution system operator (DSO), which means that all the sizing solutions are systematically considered, evaluated, and displayed. It is for the DSO to use those results as a decision tool by applying their criteria. In this work, the performance of a given re-energization solution is evaluated by computing the maximum CST before the battery is empty. Indeed, the most difficult step of the re-energization process is the black start; it is therefore interesting for the DSO to avoid black-starting the grid again and again, and rather maintain the grid alive as long as possible after the black start.

First, an arbitrary but realistic quantity of PV panels has been set to four panels per household, hence a total of 31.9 kWp of installed capacity for the whole microgrid. Operation both with or without storage is considered. Figure 2 illustrates the battery SoC for different battery capacities ranging from 0 (no battery) to 200 kWh, which is equivalent to the battery capacity of four Zoé electric cars [12]. It has been drawn for a “sunny summer (SS)” weather, starting at 10 a.m. Then, if the battery is small, it is quickly full and part of the production needs to be curtailed. After eight hours of supply, at 6 p.m., the SoC of the battery starts to decline for all battery capacities. Depending on the battery size, it is possible or not to supply the grid throughout the night. The simulation is stopped after 24 hours of supply, note that the SoC after 24 hours of supply is lower than the initial SoC, meaning that the same generation/consumption scenario cannot be cycled over several days.

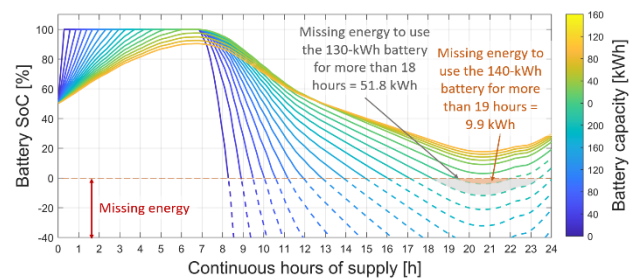


Figure 2: Battery SoC evolution with different battery sizes, four PV/household, sunny summer weather conditions, start time 10 a.m.

Important information is the maximum CST for each battery capacity, that is, the time at which the SoC reaches zero. A summary of the maximum CST for each battery capacity and PV capacity is illustrated in Figure 3. In this plot, the PV capacity was varied between zero and five panels per household. Starting from a given combination of PV and battery capacity, the figure illustrates, if associated with a metric, such as cost or carbon impact, which choice, as increasing the size of PV or battery, will be more efficient in increasing the maximum CST.

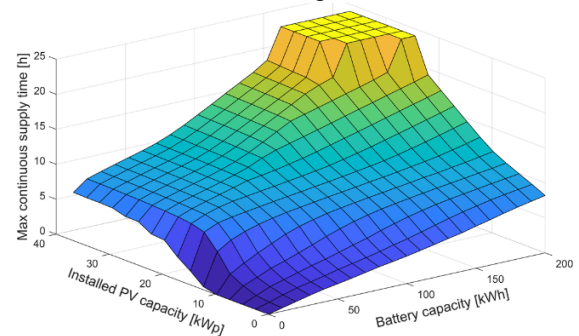


Figure 3: 3D plot of the continuous supply time depending on the PV and battery capacities, start time 10 a.m.

The information in Figure 2 is valuable, as they indicate to the DSO how much undersized a battery is, and therefore, if the use of DR could make it practicable to still rely on this battery. This idea is modeled, and presented in the next section.

The event that disconnects the portion of the distribution

is stochastic. Still, generally, for logistical reasons, outages happening at night lead to longer repair times, which can easily be understood. Therefore, it is important to analyze how the starting time of the islanded operation can impact the continuous hours of supply that can be provided to the islanded portion.

The impact of the start time on the maximum CST is illustrated in Figure 4. From those tests, one can see that the starting time for the re-energization has a great influence on the CST. For the same battery capacity, the CST will be higher if the re-energization starts in the morning. This can easily be understood because the morning is the time when batteries can be charged for future use. Therefore, in the case of an event occurring in the evening, it could be more advantageous to wait until the next morning to re-energize the microgrid, rather than start in the evening, stop at night, and start again in the late morning.

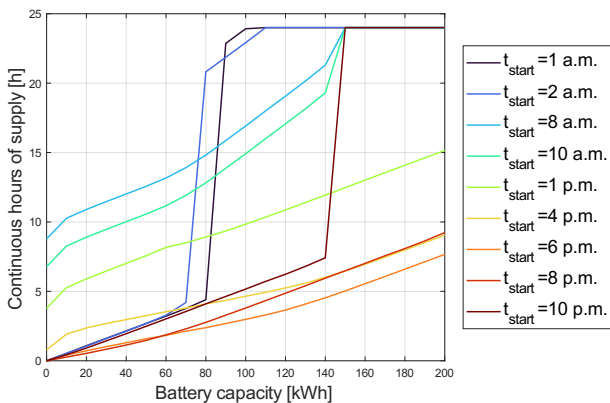


Figure 4: Continuous hours of supply according to the battery capacity and start time, 4 PV/household

IV- DEMAND RESPONSE

Considering Figure 2, the SoC value can be modeled with a negative value, assuming that power can be delivered to the grid. On this graph, the DSO can see how much energy is missing to allow a continuous operation of the grid, without having to stop and black start a second time. Once the missing energy is computed, the effort needed to not consume this energy can be estimated. One way to enforce those efforts is to use DR strategies, which involve altering electricity consumption patterns. It allows end-users to adjust their load to match supply variations. DR is a category of Demand Side Management (DSM), which refers to a set of strategies and practices aimed at optimizing energy consumption on the consumer side. It involves actively managing energy usage to achieve various objectives, such as cost reduction, load balancing, and environmental sustainability. Using DR strategies is also a way to include customers in grid resilience [13].

To assess the impact of the customers' behavior on the sizing of the components, different DR strategies are modeled. They have been selected considering both classical analysis on DR, and the capabilities of the Linky smart meter [14], implemented in France. It is important to

note that in this work, it is assumed that, if no DR strategy is enforced, the behavior of the customers regarding their electrical consumption remains the same in islanded mode as it would have been without incident on the grid. This assumption would be true if the islanded grid was immediately re-energized after the outage; otherwise, in the case where customers had to wait sometime before being reconnected, the consumption profile will be modified as they catch up the delayed consumption.

The proposed DR strategies are summarized in Table 1. In real-life, the implementation of each of those strategies raises technical challenges. For Strategy B, the classification of the loads according to their priority is done downstream of the meter, hence it is out of the area of activity of the DSO. For Strategy C1, sending a real-time signal to lower the switching power of the smart meter is challenging. Power Line Communication (PLC), the communication technology used by French smart meters, is not necessarily adapted for fast communication. Strategy D requires knowing the contact details of all the customers included in the islanded grid portion and assuming their responsiveness.

Table 1: Demand response strategies

Strategy	Description
A	No DR action is undertaken. The consumption remains as it would have been without incident.
B	Appliances in each household are plugged into different ports (1 for high-priority and 2 for secondary), both connected to the smart meter. When Strategy B is applied, only Canal 1 is activated.
C1	The load limiting capacity of each smart meter (usually 3, 6, or 9 kVA) is lowered. No consumption shifting is considered, only peak shaving.
C2	The load limiting capacity of each smart meter is lowered. 100 % of the consumption is shifted to a later random time. The total energy consumption remains the same.
D	Customers are incentivized to consume less (e.g. by SMS). Their level of effort is one of the parameters of the model.

In Figure 5, the CST of the island is shown under different DR strategies. From the graph, it stands out that Strategy D is the most effective; however, this observation should be considered carefully as the effect of Strategy D is largely dependent on the chosen parameters (mainly the willingness of the users to respond). Instead, an interesting outcome is that DR strategies are useless if the battery is either under or over-sized, while they are the most effective in increasing the CST when the size of the battery lies in between those extremes.

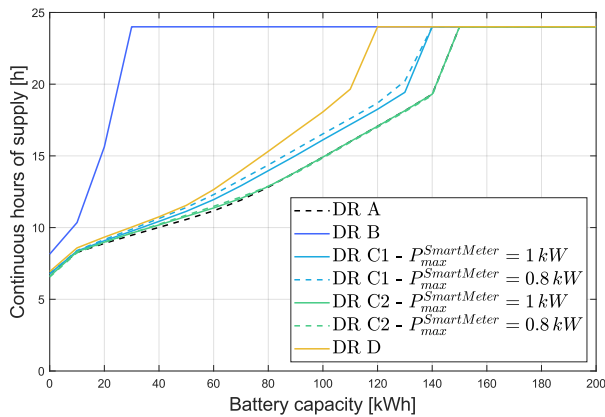


Figure 5: Effect of the different DR strategies on maximum continuous supply time, 30 households, P_{max} (SmartMeter)=1 kW, four panels per household, starting at 10 a.m.

CONCLUSION

This paper provides the DSOs with a multi-criteria and systematic assessment of what can be achieved regarding the temporary re-energization of a portion of the distribution grid that has been disconnected from the main grid, with parametric local resources. Those insights are supported by visual representations of the intermediate computation steps, to provide a clear picture of the ranges of possible re-energization as a function of the different system parameters. First, the focus was given to the continuous supply time, which is highly dependent on the starting time. This should be considered to avoid having to black start the islanded grid multiple times during the day. Second, the effect of a set of demand response strategies was analyzed regarding the continuous supply time. Those strategies were found to be effective only if the battery is not under nor oversized.

After this open-loop analysis, it is then the responsibility of the DSO to choose which criteria should be applied to select a particular solution, among the several ones that could be of interest, like maximizing customer satisfaction or supply time or minimizing the carbon emissions. Further research will focus on assessing the carbon impact of different design choices.

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