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Stochastic sizing of isolated rural mini-grids, including effects of fuel procurement and operational strategies

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ABSTRACT

The governments of developing countries struggle to guarantee the universal access to electricity on their territory and 1.2 billion people are still without any service, especially in remote areas. Hybrid mini-grids can be an effective solution since they exploit local renewable resources integrated with energy storage devices, reduce the use of fuel generators, and defer the construction of long and expensive grids until the growth of demand makes it profitable. Off-grid mini-grids are typically operated with simple load-following dispatching strategies, but predictive approaches can provide better performances, although at the expense of additional computational requirements. This paper investigates the benefits of using rolling-horizon dispatching strategies during the mini-grid design stage, also comparing how the optimal size of components is affected by several technical and economical parameters. Moreover, we propose the use of a stochastic sizing procedure that captures the uncertainties related to the load, to the renewable generation, and to the time required for the fuel procurement and delivery. A case study with real load data collected from an existing mini-grid placed in Habaswein, Kenya, is presented and discussed. The optimal sizing of some components turns out to be almost unaffected by the operational strategies, so their preliminary design can be simplified to avoid time-consuming simulations. Conversely, the optimal sizing of the diesel generator and of its fuel tank is strongly related to both the local economic parameters and the operational strategy of the mini-grid, which must be properly simulated.

1. Introduction

Nowadays, while industrialized countries have completed their electrification process, governments of developing countries are still struggling to provide a reliable access to electricity to around 2.2 billion people worldwide [1,2], of which 1.2 billion lacks any service [1]. Mini-grids are widely considered one of the most effective solutions to supply areas far from the grid or with weak infrastructure, since they can defer the construction of long and expensive grids until the growth of demand makes it profitable. In this context, planning tools are really helpful to identify the cheapest electrification option even at country scale [3,4].

International and national efforts are in particular promoting hybrid solutions that include renewable sources and energy storage [2,5,6], not only to comply with the COP21 guidelines and reduce local pollution, but also to reduce the project costs, the renewable sources being already competitive with fossil fuel technologies in many contexts [5]. Business and technical risks in mini-grid investments are still significant [7], although the huge potential market of USD 200 billion/year [5] is attracting not only non-governmental organizations, research institutions, and public investors, but also private companies.

Predictive operational strategies of resources can improve the efficient use of fuel-fired generators and reduce load shedding with respect to the traditional load-following procedures [8,9]. In addition, stochastic sizing methodologies are very promising tools in order to properly cope with the uncertainties related to load, renewable sources and fuel procurement, assuring a robust and reliable probabilistic design of the mini-grid, including the fuel tank capacity.

For these reasons, this paper proposes and analyzes a stochastic sizing technique that combines a probabilistic approach, an optimization tool and the simulation of a predictive operational

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Nomenclature

NPC	Net Present Cost of the mini-grid project
$CAPEX$	capital expenditures
$OPEX$	operational expenditures
S	number of Monte Carlo scenarios
N_L	lifetime of the project in years
T_r	time resolution
T_h	period of time between two consecutive redispatching procedure
T_o	time horizon of the MILP optimization
$C_{F,t}$	fuel cost ($)
$C_{C,t}$	cost of load curtailment ($)
$C_{M,t}$	maintenance cost ($)
$C_{RC,t}$	cost of RES curtailment ($)
C_{SS}	cost of the overuse of the battery ($)
$F_{D,t}$	fuel consumption (l)
$P_{C,t}$, $P_{RC,t}$	curtailment of the load and renewable energy sources (kW)
$P_{D,t}$, $z_{D,t}$	diesel generator power (kW) and its status (1: running, 0: off)
$P_{inv,t}$, $P_{B,t}$	inverter and battery power (kW)
$P_{L,t}$	load (kW)
$P_{PVAv,t}$	available renewable production (kW)
P_D^{max}, P_D^{min}	maximum and minimum diesel power (kW)
$V_{F,t}$	fuel available in the tank (l)
$E_{B,t}$	energy available in the battery (kWh)
E_B^{max}, E_B^{min}	maximum and minimum energy battery level (kWh)
P_{B+}^{max}, P_{B-}^{max}	maximum and minimum battery power (kW)
P_{inv+}^{max}, P_{inv-}^{max}	maximum and minimum inverter power (kW)
$c_{DS,i}$, $c_{DI,i}$	piecewise linearization of the fuel consumption (offset and slope)
c_{SS}	specific cost of the battery overuse ($/kWh)
η_I, η_B	efficiency of the inverter and battery (–)

strategy of resources including their intra-daily redispatching. The benefits obtained with respect to traditional load-following procedures are investigated and numerically discussed for an isolated system, also performing a wide sensitivity analysis of results when techno-economic local constraints and parameters change. Moreover, the optimal sizing of the fuel tank is explicitly considered into the design of the mini-grid, turning out to be particularly dependent on the average and variance of the time required for fuel delivery.

2. Problem formulation

2.1. Uncertainties in sizing methodologies

The literature regarding the optimal sizing of power systems under uncertainties is very rich, especially for hybrid systems with multiple energy sources, isolated or linked to the national grid [10–14]. Typical methodologies iteratively simulate the operation of the system, testing several combinations of the size of the components [15,8,16–18] in order to find the design that minimizes total system costs, also including reliability aspects and other socio-economic indicators [19,16].

Conventional commercial software usually optimizes only a single deterministic scenario of load and renewable generation [17], while the scientific literature is recently proposing several approaches to make decisions under uncertainty, which means taking into account many possible profiles of load and renewable generation. Authors in [20] applied for instance a chance-constrained method to size and locate distributed energy sources, assuming that load flows can exceed the maximum capability of feeders according to a probability density function assessed by simulating multiple scenarios of load, distributed generation, and energy price. According to the approach suggested in [18], the best design of an isolated system can be obtained by deterministically optimizing the size of its component in several independent scenarios of load and renewable generation, previously drawn by a Monte Carlo procedure; the final best design is then obtained by analyzing the statistical properties of occurrence of the different scenarios. A similar approach is also proposed in [21], where the point estimate method is applied to an interconnected system, or in [22], in relation to an isolated system. Authors in [11] proposed a stochastic approach based on NSGA-II method to size a hybrid system able to meet the thermal demand under uncertainties in solar and wind production; the outcome is the Pareto front between the economic value of the energy-not-served and the investment costs. The study [17] details a robust approach by using multiple scenarios to size rural systems in developing countries, but robustness seems to lead to rather conservative results. Conversely, papers [23,12,15,8] propose to approximate the stochastic objective function of the problem into a weighted sum of the deterministic objective functions of single scenarios. This allows estimating the operational costs, the maintenance fees, and the energy-not-served under different conditions of load or renewable production, by weighting the outcomes of the different scenarios with their probability to occur. More in detail, authors in [15,8] firstly proposed to use this methodology to size also the fuel tank and the fuel logistics. The study in [15], based on a Particle Swarm Optimization (PSO) method to best select size scenarios to be investigated, was improved in [8], where the same authors included a rolling-horizon dispatching strategy of the batteries and of the diesel generator. The results were compared to the ones obtained by implementing a conventional load-following operating procedure, but the validity of this comparison were limited to a single techno-economic scenario, tuned for a possible mini-grid to be installed in Uganda. A wide sensitivity analysis is instead required to verify, generalize and enforce this comparison, moreover using realistic data collected from the field, as performed in the present paper. This enabled achieving additional results and fine-tuning design criteria, as discussed in the next sections.

The simulations carried out by the optimization techniques usually cover a time horizon long enough to capture the periodicities of both the load and renewable sources, which means at least an entire year [15,22,18,17]. A horizon of multiple years enables evaluating the degradation of the components [24], but the longer the time span, the higher the necessary computational time [8,25]; thus, model simplifications are required, such as in [25] where the entire year was sampled in a few representative weeks. For yearly simulations, the available renewable production is often estimated by using Typical Meteorological Year (TMY) data [24] that incorporate the random behaviour of renewable generation [26]. Nevertheless, many authors [15,8,22,18] proposed synthetic methods to draw realistic yearly profiles of the available renewable production [27–29]; synthetic approaches are useful for stochastic sizing, since enabling to analyze many realistic years, as in [12,15,22,18].

2.2. Fuel tank sizing

According to our literature analysis, papers referring to "tank sizing" in mini-grids focus on sizing hydrogen [30] or water tanks [31], while the ones citing the fuel tanks only focus on large power plants, e.g. in [32]. The optimization of the size of the fuel tank is usually not included into the sizing procedure of the whole mini-grid, probably because of the implicit assumption that the operator always assures that the tank is being properly refilled. However, recent papers [8,15] suggested that the distribution function of the