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FCpowered RBS: Data Analysis And System Optimization

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Abstract

The previous works on the use of PEM Fuel Cell based power supply system for the operation of off-grid RBS (Radio Base Stations) sites showed a strong influence of system design parameters on the energy conversion performance. In this paper a perturbation of system design is performed through validated models to understand better the variability of performance over a full year operation. Results show that a ratio of energy produced by fossil over energy produced by renewables sources of 0.2 can be reached slightly increasing the photovoltaic plant size without affecting drastically the renewable exploitation. Moreover a positive Net Present Value can be achieved in comparison with the traditional diesel genset solution (from 260k€ to 350k€). The NPV value increases with the PV size and with a reduction of the battery size that leads to a steep reduction in the RES exploitation. Therefore, an optimum has to be sought as a compromise between the two aspects.

Keywords: PEM fuel cells; Alkaline electrolyzers; Radio base stations; Renewable sources; Off-grid Telecom Stations

1. Introduction

The key role of the Hybrid Renewable Energy Systems (HRESs) is highlighted in the de-carbonization scenario proposed in the European Energy Roadmap [1]. HRESs can be used for power supplying to off-grid Radio Base Stations (RBS). Recent studies [2,3] estimated that by 2020 there could be up to 400,000 off-grid RBS operating on renewable power in remote parts of the developing world. Different works have shown how the use of hydrogen and fuel cells for chemical energy storage and programmable and efficient energy production can be a competitive solution to standard diesel generators [4,5]. In particular, the integration of different renewable energy sources (such as Photovoltaic (PV) and wind) with short and long term energy storage (such as electric batteries and hydrogen) in a HRES is a clean and high efficiency energy generation solution for remote sites [6,7]. Due to their characteristics of high conversion efficiency, cheap maintenance costs [8], low noise and fast response [9], FCs are attractive as

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programmable power sources alternatively to Diesel gensets. Moreover, the intrinsic clean features of the hydrogen conversion process allow almost CO2-free operation.

HRES efficiency however depends on sub-components sizing depending on load profile and the control strategy [10]. Design optimization and control strategies indeed affect systems behavior [11–14]. The design process has been carried out in the project led by Ericsson Italia [15] and supported by the University of Rome Tor Vergata and the JRC, on a real scale. The design phase was reported in [10] and based on a benchmark cycle made of three representative days [10]. The procedure has been then further tested in [16], evaluating its effectiveness by extended experimental activities where effects due to the use of real equipment, real radiation profile and real control system on the performance of the HRES were taken into account.

In this paper, HRESs applied to RBS are further investigated through a full-year based numerical analysis. The aim is to improve the reliability of the model for design oriented applications introducing further details to test the real behavior of the system and to carry out a detailed analysis of the performance. Comments on the validity of the design process carried out in the previous papers have also been provided highlighting room for improvement and criticalities of the design process itself.

2. System layout and performance parameters

The characteristics of the HRES designed and realized in the FCpoweredRBS project are accurately described in [16]. Table 1 includes the main characteristics of the HRES subsystems, highlighting the three considered for the analysis.

Table 1 - Design characteristics of the 6 sites installed in Lazio (Central Italy) highlighted the sites used for the present study [16]

	Site #1 (Baschi)	**Site #2 (Fiano Romano)**	**Site #3 (Colle Turchina)**	**Site #4 (Sasso)**	**Site #5 (Campoleone)**	**Site #6 (Sonnino)**
PV system Power	5 kWp	5 kWp	3 kWp	5 kWp	2.5 kWp	5.5 kWp
Fuel cell Power and technology	1.7 kW Dantherm H_2 fed	1.7 kW Dantherm H_2 fed	1.7 kW Dantherm H_2 fed	1.7 kW Dantherm H_2 fed	1.7 kW Dantherm H_2 fed	2.5 kW Ballard Methanol fed
Lead-acid battery System capacity	640 Ah @ 48 V	640 Ah @ 48 V	380 Ah @ 48 V	640 Ah @ 48 V	320 Ah @ 48 V	640 Ah @ 48 V
Average Power of the RBS load	1.31 kW	1.28 kW	0.35 kW	0.72 kW	0.87 kW	0.65 kW

As highlighted in Table 1, sites #2, #5 and #6 have been selected for further investigation in this work, due to the following reasons:

- Site #2 – has been taken as a reference case for the RBS application, due to its average power absorption, PV peak power, FC power output and BESS capacitance;
- Site #5 – has been chosen in order to analyze the effects of subsystems sizing depending on scaling laws;
- Site #6 – has been chosen in order to evaluate methanol in place of H2 to fuel the FC.

The same dimensionless parameters studied in [17] and considered in [18-19], have been discussed with minor modifications. They are calculated referring to a year and can be divided in two main groups to characterize system design and to evaluate system performance.

2.1. Design parameters

2.1.1. PV plant size coefficient

The parameter Isize is defined as the ratio between the overall amount of energy available from the reference total sun radiation over the total energy demand over the year:

$$I_{size^{-1}} = \frac{E_{RES}}{E_{LOAD}} \tag{1}$$

2.1.2. FC size coefficient

The FC size is defined based on the ratio between its power output and the mean power at the load. This parameter measures the FC capability to supply power at the load.

$$FC_{size^{-1}} = \frac{P_{FC}}{\bar{P}_{LOAD}} \tag{2}$$

2.1.3. BESS size coefficient

The BESS size is defined as the ratio between the energy capacitance of the battery pack compared with the mean energy required at the load over one day. It is representative of the storage capability of the BESS over a daily cycle.

$$BESS_{size^{-1}} = \frac{E_{BESS_{1cycle}}}{\bar{E}_{LOAD}} = \frac{Ah \times V_{nom}}{\bar{E}_{LOAD}} \tag{3}$$

2.2. Performance parameters

2.2.1. System efficiency

The HRES global efficiency, η_{sys}, is defined as the ratio between the energy requested at the load, E_{Load}, and the sum of the PV energy input, E_{RES}, and the $H_2(m_{H2})$ fed at the FC from the 200bar bottles, that is supposed to be produced from fossil sources (E_{FES}):

$$\eta_{sys} = \frac{\left[E_{Load}^{PV-DIRECT} + E_{Load}^{PV-EB} + E_{Load}^{PV-elec-FC} + E_{Load}^{FES-FC}\right]}{E_{RES} + E_{FES}} = 1 + \frac{Isize}{1 + E_{FES}/E_{RES}} \tag{4}$$

2.2.2. Renewable (RES) vs fossil (FES) sources energy ratio

The ratio between the energy produced by fossil and renewable sources, which is representative of the renewable energy fraction, takes also implicitly into account the role of the BESS.

2.2.3. PV subsystem performance coefficient

This parameter takes into account the capability of the HRES to use RES local sources comparing the energy produced at the PV to supply the load with the reference energy theoretically obtainable by the PV subsystem. It is representative of both the time-phase between production and consumption, and of BESS and H2 storage features.

$$\Psi_{PV} = \frac{E_{Load}^{PV-DIRECT} + E_{Load}^{PV-EB} + E_{Load}^{PV-elec-FC}}{E_{RES}\eta_{PV}^{*}} \tag{5}$$

2.2.4. Costs parameters

Assessed economic parameters have been used for the investment analysis, and in particular the net present value (NPV) to be compared with a standard Diesel genset with a rental fee of 90€/day. Other costs are following: Standard batteries are quoted 1000 €/kWh, with 10000 cycles lifetime. Fuel have been costs at 0.8 €/Sm^3, with a LHV of 9.6 kWh/Sm^3, and a price of 0.0833 €/kWhe produced at the FC. The 1.2 kW PEM FC selected has 6000 h lifetime and capital costs of about 14000€ for FC considering the cabinet and stack replacement. Moreover, every FC shutdown has been assumed affecting lifetime by 3 steady hour operation time.

3. Control strategy and validation of the Matlab/Simulink model

The control strategy employed in the installed RBSs is based on the bus voltage and gives priority to RES, using FC as the latest priority source. It is explained with more detail in [17].

First, the numerical model has been validated against the real data collected at the three RBS sites studied over the year 2015. In particular, two different representative days for Fiano Romano (the best (Figure 1 - left) and the worst (Figure 1 - right) of September) are reported in Figure 1 to show the excellent agreement between the simulated and real power profiles over time. The capability of the battery charger controller to accurately capture the saturation of the BESS capacity is confirmed also in the comparison against the real data. The general shift in the FC shut-down for the simulated cases can be attributed to the effect of SoC initial conditions that is a minor issue toward the evaluation of energy consumptions over the year.

The validation has also been performed over a full year confirming the excellent agreement also in terms of the total energy fluxes for the different subsystems, with small deviations within 4% (Figure 2). This confirms the robustness of the approach and the very good accuracy of each subsystem numerical model. The simulations were able to provide high accuracy in the energy splitting between fossil and renewables sources as confirmed by the Efes/Eres parameter. Also, the PV coefficient parameter ψ_{PV} has been accurately evaluated, confirming the reliability to capture both the

BESS behavior and the PV power production profiles.

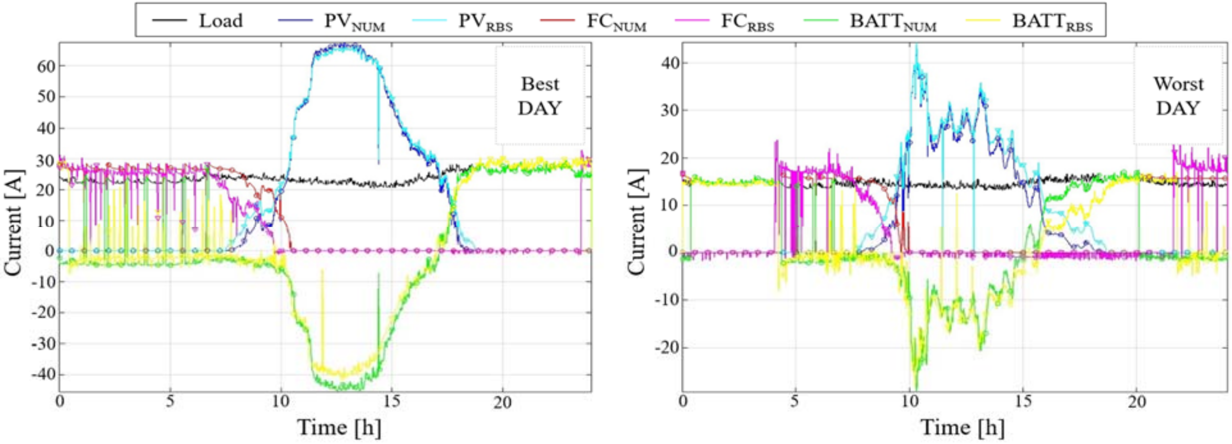

Figure 1 - Current profile over time from different components and to the load – comparison between real and simulated data for two different cases (best day – A (right) and worst day – B (left)).

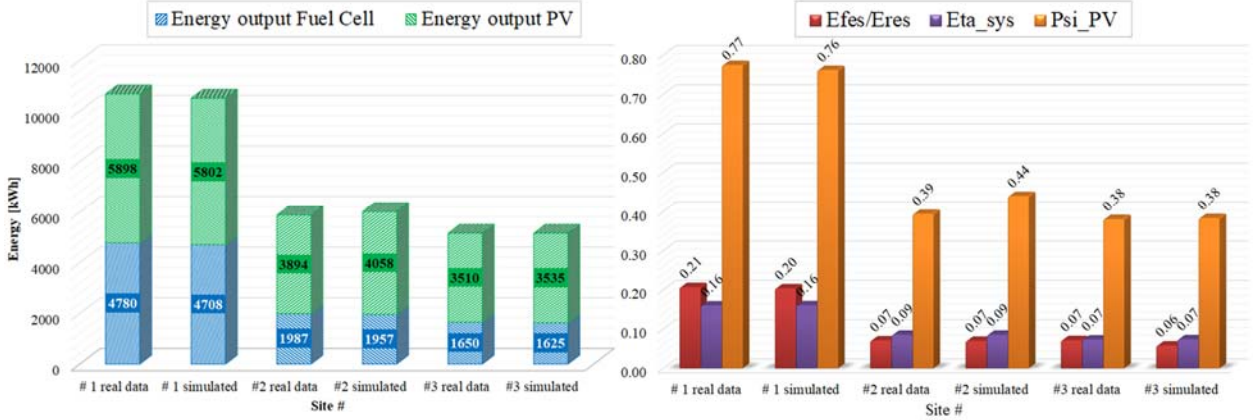

Figure 2 - Real and simulated energy output from Fuel Cell and PV for the sites tested (left) Comparison of the real and simulated performance parameters for the three sites analysed (right)

4. Numerical results

With the validated numerical model, 16 annual simulations have been set to evaluate the performances and the economic return of different configurations by varying PV power size and BESS capacitance in terms of number of batteries, considering a constant load (Fiano Romano). Details are provided in Table 2.

Table 2 – Matrix of subsystem design characteristics

	1	2	3	4
Number of Panels	12	16	20	24
BESS capacity [Ah]	160	320	480	640

A 4x4 matrix for each performance parameter has been setup to represent effects on HRES performance parameters. Looking at the energy provided by FES over RES ratio (Figure 3 - left), two immediate conclusions can be drawn:

- the point of minimum relative consumption of energy from FES corresponds to oversizing of both subsystems;
- the sensitivities to variations with respect to the sizing parameters are very different. In fact, keeping Isize constant and varying Bsize there are no great variations in the performance parameter. Keeping constant Bsize there are considerable variations in the consumption of FES.

One of the goals of the off-grid HRESs is to minimize Efes/Eres, and therefore, once a fixed threshold for the environmental Efes/Eres index is given as a design constraint, a region of possible designs can be defined. Within that region, the designs can be further characterized in terms of economic arguments (primarily system and operation costs), allowing for the choice of the optimal design through the dimensionless parameters.

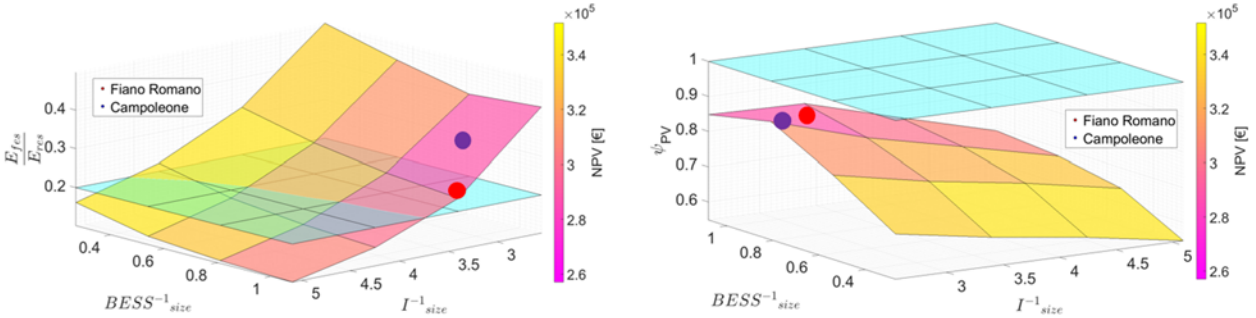

Figure 3 - Energy from FES over energy from RES (left) RES exploitation (right) – the two dots are representative of the performance of Fiano Romano and Campoleone (red and violet respectively)

Figure 3 (right) shows the effect of design parameters on the RES exploitation. The reference value of 1 is reported (case in which the photovoltaic energy is exploited entirely). An area of optimum is highlighted around the point of minimum PV size and maximum batteries size. On the other hand, if BESS capacitance is minimized and PV peak power is maximized, ψ_{PV} is minimum highlighting oversizing issues.

Figure 4 shows that the maximum value of the NPV, evaluated over 20 years, is obtained at the maximum sizing of the PV and minimum sizing of the BESS. This is due to the fact that the economic return depends on H2 consumption, as well as on the number of cycles of the BESS and operating hours of the FC. In fact, the amount of H2 bought is particularly low at the maximum point of the NPV, given the great excess of energy. The minimum of NPV is instead reached at the point of minimum energy excess, corresponding to the minimum amount of PV panels and maximum battery capacitance.

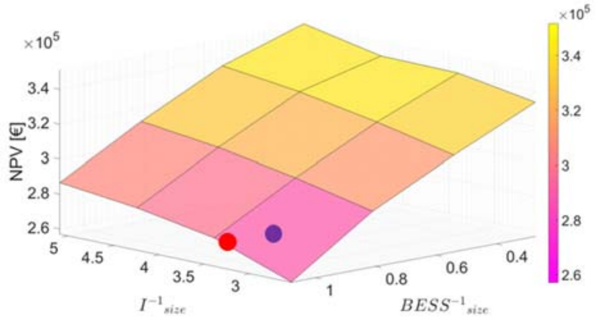

Figure 4 - Net Present Value – the two dots are representative of the performance of Fiano Romano and Campoleone (red and violet respectively)

Looking at the current sizing of Fiano Romano and Campoleone (red and violet dots in previous figures), it can be noted how the ratio of energy from FES over RES is closer to the target one, especially for the first one. It is particularly interesting that current sizing allows for a maximum exploitation of the renewable energy sources. However, from the economic point of view, this system lies in the area of minimum NPV, due to the quite high BESS capacitance highlighting the opportunity of optimization during the design process discussing the trade-off between environmental and economic aspects.

5. Conclusions

A numerical model for the simulation of HPS has been validated against the real data collected at the Fiano Romano RBS site over the year 2015. The validation has been performed over daily simulations and over the full year confirming the excellent agreement with small deviations within 4%.

Looking at the effects of PV and BESS sizing on the ratio of the primary fossil energy and the renewable quota, it is worth noting that a plateau can be obtained moving towards larger systems confirming positive environmental effects. The following synthetic conclusions can be also drawn:

- Once a fixed threshold for the environmental Efes/Eres index is given as a design constraint, a region of reasonable designs can be assigned.
- Within that region, designs can be further characterized in terms of economical arguments (primarily system and operation costs), allowing for the choice of the optimal design in terms of dimensionless parameters.
- An optimum region has been found for the RES exploitation parameters at high BESS capacity and low PV power (up to 90% of the PV subsystem parameter).
- The optimum in terms of economic index lies at high PV size and low BESS capacitance.

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6. References

[1] Energy Roadmap 2050. ISBN 978-92-79-21798-2 doi:10.2833/10759
[2] A.M. Aris et al. Sustainable power supply solutions for off-grid base stations Energies, 8, 2015 pp. 10904-10941
[3] K. Kusakana, H.J. Vermaak Hybrid renewable power systems for mobile telephony base stations in developing countries Renew Energy, 51 (2013), pp. 419-425
[4] D. Bezmalinovic, F. Barbir, I. Tolj Techno-economic analysis of PEM fuel cells role in photovoltaic-based systems for the remote base stations Int J Hydrogen Energy, 38 (2013), pp. 417-425
[5] G. Upreti, et al. Impacts of the American Recovery and Reinvestment Act and the Investment Tax Credit on the North American non-automotive PEM fuel cell industry Int J Hydrogen Energy, 41 (2016), pp. 3664-3675
[6] G. Piro, et al. Hetnets powered by renewable energy sources: sustainable next-generation cellular networks Internet Comput IEEE, 17 (2013), pp. 32-39
[7] C. Han, et al. Green radio: radio techniques to enable energy-efficient wireless networks IEEE (2011)
[8] A. Feshke, et al. The Global Footprint of Mobile Communications: the ecological and economic perspective Commun Mag IEEE, 49 (2011), pp. 55-62
[9] P. Bajpai, V. Dash Hybrid renewable energy systems for power generation in stand-alone applications: a review Renew Sust Energy Rev (2012), pp. 2926-2939
[10] G. Bruni, et al. Fuel cell based power systems to supply power to telecom stations Int J Hydrogen Energy, 39 (2014), pp. 21767-21777
[11] Lorenzo Bartolucci, et al., Renewable source penetration and microgrids: Effects of MILP – Based control strategies, Energy, Volume 152, 2018, Pages 416-426, https://doi.org/10.1016/j.energy.2018.03.145.
[12] G. Bruni, et al. Control strategy influence on the efficiency of a hybrid photovoltaic-battery-fuel cell system distributed generation system for domestic applications Energy Procedia, 45 (2014), pp. 237-246
[13] P. Petruschke, et al. A hybrid approach for the efficient synthesis of renewable energy systems Appl Energy, 135 (2014), pp. 625-633
[14] O. Erdnic, M. Uzunoglu Optimum design of hybrid renewable energy systems: overview of different approaches Renew Sust Energy Rev, 16 (2012), pp. 1412-1425
[15] http://www.ericsson.com/it
[16] S. Cordiner, et al. Fuel cell based Hybrid Renewable Energy Systems for off-grid telecom stations: Data analysis from on field demonstration tests, APEN, Volume 192, 2017, Pages 508-518
[17] G. Bruni, et al. Domestic distributed power generation: Effect of sizing and energy management strategy on the environmental efficiency of a photovoltaic-battery-fuel cell system, Energy, Volume 77, 2014, Pages 133-143,
[18] Lorenzo Bartolucci, et al., Hybrid renewable energy systems for renewable integration in microgrids: Influence of sizing on performance, Energy, Volume 152, 2018, Pages 744-758, https://doi.org/10.1016/j.energy.2018.03.165.