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Storage Solutions for Renewable Production in Household Sector

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Abstract

The penetration of renewable sources, particularly wind and solar, into the grid has been increasing in recent years. As a consequence, there have been serious concerns over reliable and safety operation of power systems. One possible solution, to improve grid stability, is to integrate energy storage devices into power system network: storing energy produced in periods of low demand to later use, ensuring full exploitation of intermittent available sources. Focusing on stand-alone photovoltaic (PV) energy system, energy storage is needed with the purpose of ensuring continuous power flow, to minimize or, if anything, to neglect electrical grid supply.

A comprehensive study on a hybrid stand-alone photovoltaic power system using two different energy storage technologies has been performed. This study examines the feasibility of replacing electricity provided by the grid with hybrid system to meet household demand. This paper is a part of an experimental and a theoretical study which is currently under development at University of Bologna. A test facility is under construction, at the University of Bologna, for the experimental characterization of the cogenerative performance of small scale hybrid power systems, composed of micro-CHP systems of different technologies : a Micro Rankine Cycles (MRC), a Proton Exchange Membrane Fuel Cells (PEM-FC), a battery, an electrolyzer and a heat recovery subsystem. The test set-up is also integrated with an external load simulator, in order to generate variable load profiles.

This paper presents the theoretical results of the performance simulations developed considering an hybrid system consisting on a photovoltaic array (PV), electrochemical batteries (B) and electrolyzer (HY) with a H_2 tank and a Proton Exchange Membrane Fuel Cell (PEM-FC) stack, in case of a household electrical demand. The performance of this system have been evaluated by the use of a calculation code, in-house developed by University of Bologna; future activities will be the tuning of the software with the experimental results, in order to realize a code able to define the correct size of each sub-system, ones the load profile of the utility is known or estimated.

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1. Calculation Methodology

The simulated system components are presented in Figure 1. The hybrid system uses solar energy as the primary electric power production source; the surplus of energy can be stored in batteries or in hydrogen production through water electrolysis, later transformed by the fuel cell (PEM-FC) into electric

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power. The system can also exchange electricity with the electrical network, if the utility demand is higher than the produced electricity or in case the electricity storable capacity is not enough in comparison with the production.

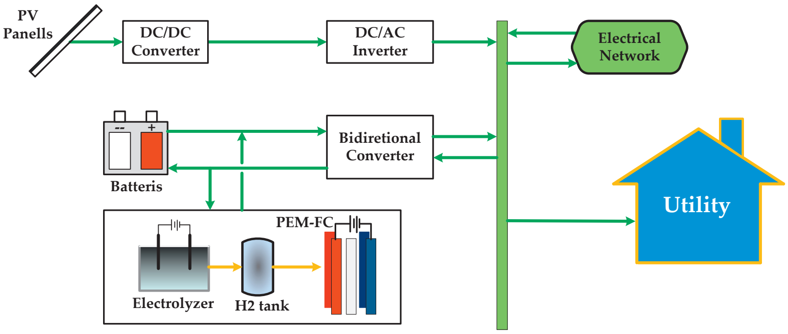


Figure 1 hybrid PV/B/PEM-FC power system configuration.

In order to estimate the performance of the hybrid system, a calculation code has been developed in Excel VBA environment. The in-house developed code is a mixed numerical-empirical tool, based on a lumped model approach. Each system component is considered as a black box, with a reduced number of key parameters, simulated with characteristic performance curves. These curves are obtained, when available, from experiments, or from physical modeling equations. The main input of the model are: (*i*) the user demand time profiles, (*ii*) the operating boundary conditions (ambient conditions, geographical position, etc.), (*iii*) the regulation strategy and the (*iv*) components parameters. The main output of the model are efficiency values for each component and for the whole system. The model can be used also to define the optimal sizing of subsystem components for a given electrical and thermal profile of the utility.

More in details, a PEM-FC with an electrical power output equal to 4.40 kW, an electrical and thermal efficiency equal to 0.366 and 0.376 respectively has been chosen according to the experimental operating points which have been previously collected on a low-temperature PEM-FC stack [1, 2]; in particular, tests had been made at full load and various part-load settings, by regulating the internal anode side dead-end valve, in order to optimize part-load electric efficiency. A peak in efficiency was observed for an output power level close but lower than the peak power. The performance profiles are in line with other PEM-FC systems and can be assumed as representative of typical FC systems.

The performance calculation of the electrolyzer, has been carried out considering the Faraday efficiency (η_F) according to [3]. The trends of Faraday efficiency as function of cell current and the relation between cell current and voltage have been estimated according to the available literature. For what regards, the design efficiency of electrolyzer a value equal to 0.54 was selected [1].

The PV panels performance calculation is carried out by means of a routine which is able to estimate (considering an entire year of operation – 8760 hours) the position of the sun, the direct and diffused radiation components incident on a horizontal surface, the direct, diffused and reflected radiation components incident on a PV array for a given tilt and azimuth. This routine uses as input the latitude and the longitude (given the location), the hour of the day and day of the year. The PV produced power and efficiency are estimated as function of radiant incident power; more details about the adopted physical-mathematical model can be found in an Authors' previous work [4]. For this study a tilt angle equal to 35° with south facing orientation and the solar radiation of Bologna were considered as boundary conditions of photovoltaic conversion.

Batteries behaviour is performed considering non-dimensional curves related to main parameters (i.e. maximum power in charging mode or in discharging mode, battery voltage, etc.) as function of the state of charge (SOC). Once the battery storable energy is defined, the main parameters can be estimated by means of curve which were obtained by interpolating the main characteristics of a wide range of batteries available in the market [5].

In order to study the performance of the systems in case of residential buildings, the electrical and thermal load of a household has been estimated for an entire year. The electrical load curve is the result of the overlap of the various appliances which, in average, can be found in an Italian house; lighting, computer sites, cold and hot appliances, cleaning appliances, and audiovisual sites, were considered; also the stand-by mode (if present) was taken into account for the estimation of the electrical load curve. More details on the household load profile can be found in [6]. In this study the yearly required electrical energy is equal to 3200 kWh [6].

2. Results and discussion

For this study, two cases were taken into account: CASE#1 in which the electrical demand of the utility is covered by PV arrays, batteries as storage system and by the connection with the electrical network, and CASE#2 in which as storage system an electrolyzer with an H_2 tank and a PEM-FC is introduced (instead of batteries). A parametric analysis has been carried out by varying the design PV electrical power peak (i.e. the PV surface area) and the maximum value of electrical energy storable into the battery (CASE#1) or the maximum thermal energy (estimated as mass of H_2 multiplied by LHV) which can be recovered into the H_2 tank (CASE#2). The simulation were developed on hourly basis for a whole year of operation.

In order to understand the behaviour of the analyzed cases on the respect of the exchange of energy with the electrical network, a performance index called *Network Dependence Degree* (*NDD*) can be introduced. With reference to Figure 2, *NDD* can be defined as follows:

$$NDD = \frac{1}{2} \cdot \ 1 - \frac{EE_{SC}}{EE_{PR}} + \frac{EE_{PU}}{EE_{UT}}$$

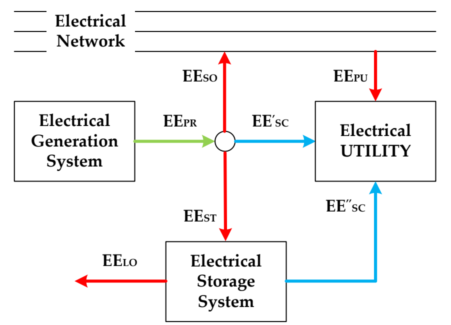
On the basis of the expression given above, it can be observed that:

- *NDD* = 1 means that all the demand of the utility is satisfied with the electricity from the network (i.e. $EE_{PU} = EE_{UT}$ and EE_{SC}=0);
- *NDD* = 0 implies that (*i*) all the utility energy demand is satisfied by the generator and also that (*ii*) all the produced electrical energy is given to the utility (i.e. EE_{PU} = 0, EE_{SO} = 0 and $EE_{SC} = EE_{PR} = EE_{UT}$);
- 0 < *NDD* < 1, indicates that (*i*) not all the production is used for the utility (EE_{SC}/EE_{PR} < 1) and/or that (*ii*) a fraction of the utility demand derives from the network (EE_{SC}/EE_{PR} > 0).

It should be noted that *NDD* furnishes values higher than zero also if it results EE_{PU} = 0 and EE_{SO} = 0 (i.e. no energy exchange with the network); this occurs when losses are present in the conversion chain of the storage system (EE_{LO} > 0).

The results of simulations, for the two analyzed cases, are briefly presented in Figure 3 which show the trend of *NDD* as function of maximum electrical energy and maximum storable thermal power respectively in the battery (CASE#1) and into the H_2 tank (CASE#2), for a variable design peak electrical power of the PV panels (ranging from 1 kW_p to 5 kW_p).

It can be observed from Figure 3, that been equal the amount of maximum storable energy and the peak electrical power of PV panels, the value of NDD is lower in CASE#1 in comparison with CASE#2. This mainly depends on the differences between the efficiency of the conversion chain (defined as the ratio EE''_{SC}/EE_{ST}) of the storage system used in the two cases; an efficiency value equal to about 90% occurs with the use of battery and equal to 20% (0.54×0.37) with electrolyzer and PEM-FC. Further, it can be observed that all the analyzed cases show an asymptotic trend of *NDD*; this allows defining the optimal value of storage system size for a given value of PV design electrical peak power.



EE_{PR}	total produced electrical energy
EE_{SO}	produced electrical energy towards the network
EE_{ST}	produced electrical energy to the storage system
EE'_{SC}	produced electrical energy to the utility
EE''_{SC}	produced electrical energy from the storage system to the utility
EE_{SC}	Total fraction of produced electrical energy consumed by utility $EE_{SC} = EE'_{SC} + EE''_{SC}$
EE_{LO}	fraction of the stored electrical energy not used for the utility and/or lost due to the efficiency of the storage $EE_{ST} = EE'_{LO} + EE''_{SC}$
EE_{PU}	electrical energy from the network
EE_{UT}	utility electrical energy demand $EE_U = EE_{PU} + EE'_{SC} + EE''_{SC}$

Figure 2 scheme for NDD calculation of an electrical generator with a storage system

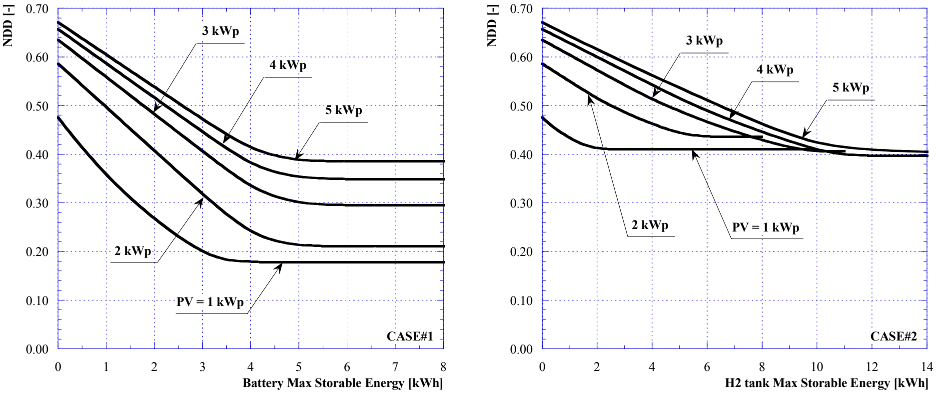


Figure 3 *NDD* as function of battery (CASE#1) and H_2 tank (CASE#2) maximum storable energy as function of PV panels peak electrical power .

3. Concluding remarks

This study presents the comparison between two storage technologies integrated with a non programmable renewable source (photovoltaic). The study was conducted with reference to a domestic utility conducting a parametric analysis in order to find the design of the hardware which allows the grid independency. The performance of the analyzed systems were evaluated by introducing a novel index which is able to take into account both the amount of electrical energy exchanged with the network and the efficiency of the adopted storage technology.

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