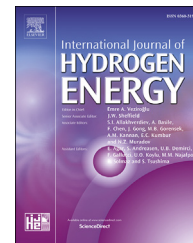


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# Optimal management of hydrogen storage in stochastic smart microgrid operation

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## ABSTRACT

This paper presents an energy management and reserve scheduling scheme in order to optimally operate a 17-bus Low Voltage (LV) grid-tied microgrid, powered by photovoltaics, a wind turbine and a Fuel Cell (FC) utilizing on site hydrogen production and storage. Since high Renewable Energy Resources (RES) penetration is assumed, the expected deviations due to their intermittency are accounted for by the reserve provision by the FC system, in order to deviate as little as possible from the scheduled energy demand injected by the upstream grid. All these are incorporated into the operating cost of the microgrid assuming penalization of unscheduled power injections from the grid. The intermittency of RES and load are incorporated in the model by assuming known probability density functions for the forecasting errors. Then, energy and reserve scheduling is performed utilizing the Harmony Search algorithm in order to minimize the expected operating costs of the examined system by optimal reserve and energy provision from the stored/generated hydrogen. For that purpose, hourly optimizations are performed for a given year to assess the value on-site hydrogen generation and FC technologies add to microgrid operation and Distributed Generation (DG) in general. The purpose is to prove the use of hydrogen storage systems in effective uncertainty balancing. The hydrogen storage system appears to effectively counter the intermittency of renewables in moderate penetration, reducing the uncertainty costs. In higher renewable penetrations, due to uncertainty being already accounted for by the storage, the benefits of the RES penetration are even greater.

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## Introduction

Microgrids (MG) are defined as localized entities consisting of Distributed Energy Resources (DER), thermal and electrical loads that have a common connection point to the upstream

grid [1]. They can operate in interconnected mode and, if needed, autonomously. The benefits arising from Distributed Generation (DG) technologies include localized energy consumption-production, thus distribution losses decrease considerably [2,3], greater penetration of smaller scale RES

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and less carbon intensive generation technologies [4] and all these elements are encompassed in the control framework of the MG which enables effective coordination with all the other active elements present in the system. These elements could be electric vehicles [5], flexible loads and storage units like batteries, flywheels, hydrogen storage etc [6]. As far as DER are concerned, there is a plethora of viable technologies used, from wind turbines and photovoltaics to micro turbines and, of course, fuel cells [7]. In this study, the latter will be utilized in conjunction to an electrolyzer that will produce hydrogen and store it in a tank, in order to be used for energy balancing or reserve provision purposes.

Hydrogen is attracting a lot of attention as a mean for pollutant and emission-free energy generation, with applications ranging from Distributed Generation to the automotive industry. A factor aiding in its growth is the evolution of the materials used and, of course, the declining cost per kilowatt. The role of transforming hydrogen into usable electrical energy is done by the FC. FCs consume pure hydrogen and convert the chemical energy stored, through an electro-chemical reaction, into water vapor, electricity and heat effectively producing zero emissions. The waste heat can be harnessed in order to satisfy thermal needs bringing the efficiency of the system to even higher levels [8]. The system itself consists of an array of individual cells, stacked upon one another that carry out the task mentioned above. The FC is classified differently depending on the materials used and has varying operating characteristics. The most promising and latest technology is that of Proton Exchange Membrane FCs (PEM FC) that allow greater current densities through them, operation at lower temperatures and at lower pressure [9]. Alternatives are the Alkaline (first used in Apollo space program) Phosphoric Acid, Molten Carbonate and Solid Oxide types. The hydrogen needed can be purchased by external sources or it can be produced on site. On site production has shown to be a cheaper alternative than purchasing the hydrogen from reforming plants [10]. For that purpose electrolyzers are utilized, which as their name suggests, uses electric current to electrolyze water, breaking it apart into hydrogen and oxygen which can be stored for use in various applications (DG, vehicles etc.). The two most common alternatives are Alkaline electrolyzers versus their PEM counterparts. An in depth analysis and review of the latter technology, comparison to already established ones and the improvements presented in recent works, can be found in Ref. [11]. In a similar fashion as the fuel cell, individual cells are stacked upon one another in order to produce the desired hydrogen output [12]. A comparison of the state of the art large scale electrolyzers can be found in Ref. [10] demonstrating how competitive on site generation is in larger scales. Hydrogen technologies in the form of fuel cells and hydrogen storage have found various applications in larger and distribution level applications. In Ref. [13] a hydrogen storage system is utilized in order to maximize the revenue of a wind farm from participation in the day ahead market. In Ref. [14] an alkaline electrolyzer is coupled with renewable resources in order to produce and store the maximum possible hydrogen. In Refs. [8,15,16] a hydrogen storage and fuel cell system is utilized along RES in order to meet the demand of a microgrid. As far as storage itself is concerned the most

common means are physical storage tanks [16] and utilization of metal hydride tanks [17].

This storage however, since it is going to be implemented in the context of a MG, means that it should be coordinated effectively with all the other units and controllable loads present in the network, in order to meet the operators' objectives. Such objectives can be cost minimization, higher reliability, reduction of Green House Gas (GHG) emissions or provision of services to the grid. In order for that to be achieved, an energy management framework must be established and act as the backbone of the MG control architecture. Due to the plethora of parameters involved in MG operation along with the uncertainties they bear, various approaches have been applied to economic operation of such systems, especially when storage is involved. In Ref. [18] battery storage scheduling is achieved utilizing a fuzzy logic expert system. In Ref. [19] 2m + 1 estimate method is utilized along a heuristic approach named Charge System Search to solve the optimal operation of a MG including FCs and hydrogen storage. In Ref. [20] an isolated hydrogen based microgrid, incorporating PVs is managed by the Model Predictive Control approach. By the same method, a smart building is regulated to meet heat and electricity needs utilizing a PEMFC and electrolyzer system [21]. Finally, in Ref. [22] hydrogen storage is coordinated with batteries and a FC to ensure reliable operation of a laboratory scale MG.

In this paper, the examined LV MG incorporates two kinds of DER. Initially, two RES units and specifically a PV array and a small Wind Turbine (WT) are considered. To supplement their generation a PEMFC unit is present for energy balancing services and the needed hydrogen is produced on site by an alkaline electrolyzer and is being stored in a steel tank. In performing the daily scheduling of the system, the Harmony Search (HS) algorithm is incorporated to manage the hourly hydrogen production for the day, decide on the storage levels kept for each hour so as to account for generation and load uncertainties and, of course, minimize operating costs. The use of a method such as Harmony Search, was necessary due to the high dimensionality of the problem as well as its stochastic nature. As mentioned above, the management scheme performs hourly scheduling for the next day based on present forecasting of prices and RES generation and assuming known forecasting error distributions. The problem is simulated for a whole year to assess the benefits of hydrogen storage on energy balancing in smaller scales. Matlab environment is used for the aforementioned simulation.

## Theory and formulation

### Fuel cells

FCs act as a converter of chemical energy stored in the fuel used to Direct Current (DC) electricity. They consist of individual cells that are stacked upon one another to produce the required power output. The cell voltage can be described as:

$$V_{FC} = OCV - V_{act} - R_{ohm} \quad (1)$$

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