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Experimental analysis of photovoltaic integration with a proton exchange membrane electrolysis system for power-to-gas

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ABSTRACT

A proton exchange membrane electrolyzer is integrated with a photovoltaic system using Maximum Power Point Tracking (MPPT) power electronics systems in several configurations to evaluate the extent to which the system can respond to the dynamics of photovoltaic power. Both direct current from the solar photovoltaics (DC) and alternating current rectified to DC from the grid (AC) configurations are evaluated and the overall efficiency and dynamic hydrogen production capabilities are assessed. Performance characteristics as a function of weather (winter vs. summer; cloudy vs. sunny) and as a function of operating conditions (e.g., ambient temperature, stack temperature) are evaluated. The direct DC configuration was found to provide the highest energy transfer efficiency from electrical power to hydrogen, with a relative increase of 7–8% compared to the AC configuration. The grid-connected AC configuration produced a baseline case to compare the characteristic losses, efficiency, and dynamics of the PV integrated DC case. The highly dynamic PV production during cloudy weather was handled by the system, accommodating input power ramp rates as high as 1270 W/s, and part load conditions as low as 7.6% of rated power. Transient operation exhibited small performance degradation compared to steady solar conditions. Hydrogen production was more efficient for high stack operating temperatures and high ambient temperatures.

Introduction

Background

Rising greenhouse gas emissions coinciding with increasing global energy demands have brought the need for more carbon neutral power generation sources. Renewable sources of energy such as wind and solar have the greatest potential in meeting this need. Additionally, they are attractive in that they offer a renewable solution in the face of dwindling energy resources such as fossil fuels. In 2014, solar and wind power generators were the two fastest growing sources of renewable electricity in the United States; wind energy comprised 27% of total electricity generation capacity additions, and large solar energy installations (greater than 1 MW capacity) comprised 22% [1].

Solar and wind power generators face challenges with their intermittency and uncontrollability that can lead to curtailment as market penetration rises [2]. Curtailment refers to the

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intentional reduction in output of a solar or wind generator because it is not needed at that moment due to overgeneration, effectively "wasting" the power generation [3]. Overgeneration occurs whenever the solar or wind output becomes greater than the grid demands in any specific location or moment in time. California's electrical grid is already experiencing the challenges of high market penetration of solar and wind power that is leading to renewable energy curtailment. In one particular event on March 23, 2015, renewable energy generators had 1142 Megawatts of power curtailed for over 90 min, comprising enough power for hundreds of thousands of residences during this period [4]. With California's SB350 pushing for even greater renewable power use (50% renewable energy sources are required by this new law), more than double the current amount of renewable resources will be installed there [5]. Solar and wind capacity have been identified as needing to comprise a large share of this high renewable energy portfolio [6]. As a result, overgeneration of variable renewable energy resources will be an inevitable consequence of any highly renewable electricity system [3]. This was the case discovered in a study considering a renewable portfolio standard (RPS) of 50% in California [7], a high RPS case for the United States eastern interconnection regional transmission organization PJM [8], and a study of 100% RPS cases in the Australian National Electricity Market [9]. With these policies in California and around the world, large amounts of energy storage will become an absolute necessity in the future, more renewable utility grid network.

Tarroja et al. determined that high renewable penetration levels would impose 'severe challenges' for load balancing costs and operation in lieu of any 'energy management strategies' [10]. A promising strategy to mitigate the intermittency of wind and solar is energy storage [11]. Energy storage brings to the electrical grid the capability to decouple the temporal aspects of electrical generation versus demand. Conventional energy storage technologies include battery, fly wheel, compressed air, and pumped hydro.

For the purposes of energy storage technologies in capturing renewable energy resources, there are several critical attributes desired. For instance, these storage technologies should be efficient, must be able to meet high charge/discharge rates, and must exhibit fast ramping capabilities. Especially when very high renewable power use is required, the storage solutions must also be able to store tremendous amounts of energy. Combined with the challenging power demand dynamics of any massive electrical grid, appropriate grid scale energy storage technology needs to have as high response times as possible, together with the appropriate energy and power storage capacities to handle instantaneous, hourly, diurnal, and seasonal storage requirements [12].

One archetype of energy carrier that meets some of the energy storage criteria is chemical energy storage. Fig. 1 describes the available sustainable energy storage technologies that various electric utility scale organizations are considering to support grid integration of renewables. Synthetic natural gas (SNG) and Hydrogen (H_2) are the clear frontrunners in the massive energy storage and long discharge time range of storage technologies. This is because these technologies offer independent sizing of the system energy and power capacity. The use of these technologies enables storage of large amounts of energy in existing storage, transport, and conversion resources (e.g., use existing caverns and pipelines for gas storage, the natural gas system for energy transport, and existing high-efficiency fuel cells or combined cycle gas power plants to return electricity).

Power-to-gas is a concept wherein a chemical energy carrier is produced during peak renewable power production periods. This potentially provides frequency regulation and voltage support ancillary services, in addition to reducing the

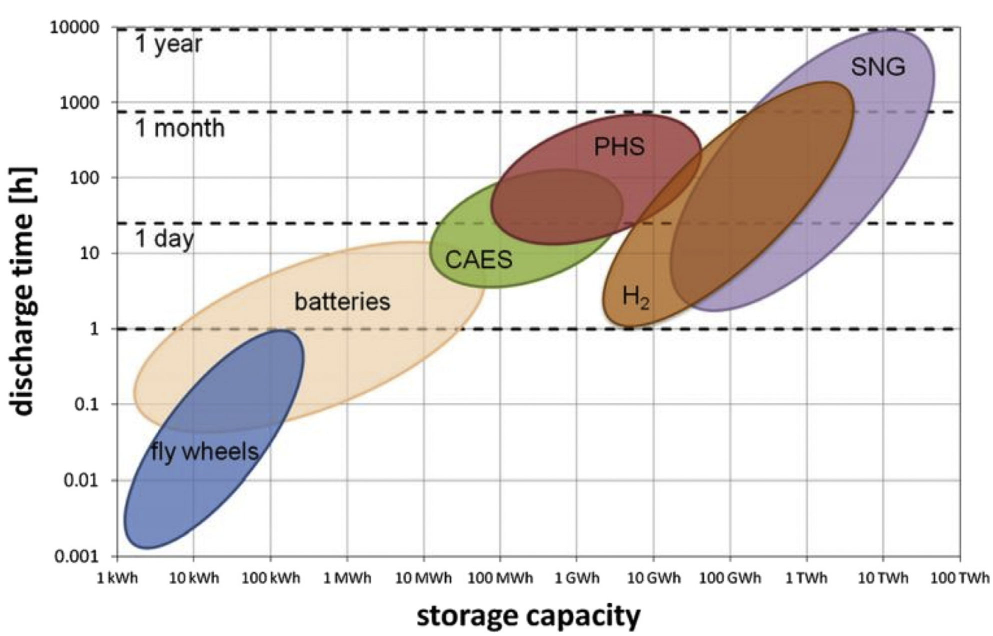

Fig. 1 – Comparison of energy storage technologies [13].