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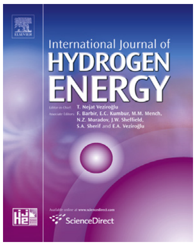

Hydrogen systems for large-scale photovoltaic plants: Simulation with forecast and real production data

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ABSTRACT

The unevenness of solar photovoltaic energy output poses a number of issues that reduce its capability to be considered a reliable substitute for fossil fuels. For instance, solar photovoltaic plants convert and inject energy in the grid during the daytime, but fail to do so during bad weather conditions or at night. Variable weather conditions also render a reliable energy injection planning impossible, causing the photovoltaic power plant output to be most often unpredictable. Furthermore, all the energy converted and immediately injected in the grid poses the risk of creating imbalances in the electric energy distribution lines. A nation-wide energy system characterized by a large penetration of photovoltaic and wind energy sources can therefore be extremely difficult to manage and cannot be considered dependable. The core issue is how to improve the reliability of electricity production from such renewable energy sources.

One way to tackle such unpredictability is to add an energy storage system. Many storage technologies are already available, although none of them has stood out to be the one and only answer to the problem. Different specific conditions require different storage technologies, and this is why that a combination of different solutions, rather than a single one, can be the right approach to storing energy.

In this paper, a hydrogen energy storage system has been designed and simulated using real-life data taken from a PV plant of 1616.8 kW_p successfully operating in central Italy. The aim is to understand the main operating conditions and the financial feasibility for infrastructure institutional investors to deploy hydrogen storage technology. The results show that such system is capable of guaranteeing a reliable energy injection in the grid, making the photovoltaic power plant as dependable as traditional fossil-fuel power plants.

The advantages of such substitution are numerous: sizable decreases in green-house or toxic gases and pollutants, healthier environment, total energy independence from foreign energy fuel imports, local job creations, just to name a few.

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1. Introduction

To be able to successfully substitute fossil-fuels in a reliable manner, renewable energy (RE) sources (RES) like photovoltaic (PV) and wind energy (WE) need to cope with their inherent unevenness. Changes in solar radiation or wind speed often cause the energy injection in the grid to be largely unpredictable in terms of timing and volume. Furthermore, all the energy converted by a PV or WE power plant is immediately injected in the grid, running the risk of causing potential imbalances in the distribution lines. To efficiently deal with these problems, the distribution networks are starting to adopt new demand-side or supply-side management methodologies and to shift towards a new *smart grid* paradigm. However, real-time management is still unlikely to be sufficient to cope with the new challenges posed by the substitution of fossil-fuels, since there must be a solution in place to postpone the use of energy when the unbalance between energy demand and supply occurs. Innovative energy management therefore must be capable of distributing energy both in space as well as in time. Energy storage systems (ESS) is then the key to enable decisions on when to use the energy converted from natural sources that cannot be otherwise time-controlled and an important development of energy networks [1–6].

Energy storage can be employed for *power-intensive* (power for relatively short periods of time) or *energy–intensive* (energy for relatively long periods of time) applications. Power applications can be intended as *power smoothing* to even out for short-term power fluctuations or *power quality* for voltage support and frequency regulation with fast response times (from less than 1 s to a few seconds). Energy applications also entail time-shifting capabilities for the energy system: energy must be available when needed. For this purpose, *load shifting* applications are envisioned to cut high regimes of energy conversion and store such energy for postponed uses, such as covering energy demand, deferring new distribution line investments, reducing power draw and leveraging the energy price spread between peak and off-peak periods.

Storage applications can benefit from accessing electricity markets like the *day-ahead*, *intra-day* or *ancillary service* markets for programming or balancing energy supply and demand on nation-wide distribution grids. Another advantage comes from *capacity payment*, namely renting out the capacity of a power plant to a grid operator to guarantee the necessary power availability for the next day. Finally, industrial uses are also made possible by employing large energy storage installations. All these applications can provide the energy storage project a sizable stream of revenues to cover capital and operating expenditures.

To name but some of the energy storage technologies available:

- electrochemical storage: batteries like lead-acid, lithium-ion, molten salts, aqueous electrolyte, flow batteries;
- electric storage: ultra-capacitors, superconducting magnetic energy storage (SMES);
- mechanical storage: flywheels, compressed air energy storage (CAES), pumped water (or pumped hydro) energy storage (PWES or PHES);
- thermal storage: pumped heat, sub or super-critical steam, hot pressurized water, cold temperature storage;
- chemical storage: methanization, hydrogen.

Many of these storage technologies are already commercialized or in an advanced stage of development [7].

Nowadays, the most exploited large-scale form of energy storage is PWES, with a worldwide capacity around 100 GW, although there is not a single solution yet to store and release energy quickly and reliably when needed [8]. Different conditions require different technologies, this is why a mix of storage technologies tend to be the answer. This has always happened in the past and there is no reason why it should not be the same in the future. The most important issue therefore is to choose the most suitable technologies and optimize them for each particular application [9].

Installed capacity of intermittent RES is increasing in many countries and this is happening alongside an increasing market liberalization trend that opens up possibilities for new developments in the energy markets. In situations with high penetration of intermittent energy injection, ESS with reasonable capital costs can prove to be economically viable even if they are not characterized by the highest overall efficiencies [10,11].

A life cycle analysis (LCA) performed on three energy storage technologies (PWES, CAES, advanced battery energy storage using vanadium and sodium polysulphide electrolytes) coupled with RES shows that green-house gas (GHG) emissions are lower than GHG emitted from electricity obtained from fossil-fuels [12]. The storage technology with the lowest impact is considered to be the PWES, since this technology need the construction of dams and reservoirs that show a higher-than-one energy ratio when compared to the quantity of energy stored. Superiority of PWES, as well as of CAES, is also suggested in Ref. [7].

Cost effectiveness of ESS is evaluated in Ref. [13] for Greek islands autonomous electricity networks. PV and wind energy systems are considered a promising solution to cope with the mismatch between electricity production and local demand, together with hydrogen storage when a long autonomy is needed. Ntziachristos et al. [14] maintain the feasibility of replacing traditional power stations with hydrogen ESS when fuel cell sizing is at least one-third of the nominal RES power (in the study: wind energy) with overall efficiencies that exceed 60%. Converse [15] states that large-scale energy storage for intermittent renewable energy sources like solar PV or wind could justify the choice of hydrogen rather than electricity as the preferable storage medium. A comparison between several storage technologies like PWES, electrochemical batteries, flow batteries, flywheels, CAES, brings about a preference for underground storage of compressed hydrogen due to much lower capital costs than the other technologies. For Hedegaard and Meibom [16], there exists the need for flexible electric storage technologies characterized by charging/discharging capabilities to perform the tasks from within an hour up to a period of months (for seasonal storage). The feasible technologies for this purpose can be PWS, CAES and underground compressed hydrogen, which are all well-suited for both short-term as well as seasonal storage.