IMPACT OF COMPONENT CAPACITY ON THE PERFORMANCE OF A HYBRID PHOTOVOLTAIC SYSTEM

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Abstract

This study investigates a stand-alone hybrid photovoltaic system consisting of photovoltaic (PV) panels, a small wind turbine, a lead-acid battery bank, and a hydrogen subsystem with a PEM electrolyzer, hydrogen compressor, storage tank, and PEM fuel cell. For reliable analysis of system performance under constant load profile, hourly meteorological data over several years is used. Energy management strategies using standard energy balance and double hysteresis control were compared. The temporal evolution of capacity degradation in critical components is intrinsically governed by the system's operational regime, while these degradation phenomena simultaneously exert a coupled influence on the overall system efficiency and performance stability. Emphasis was placed on modeling the dynamic capacity loss in the battery, PEM electrolyzer, and PEM fuel cell, showing how these losses affect system reliability and operational strategy. Results show that double hysteresis extends battery life, but shifts the operational load to the hydrogen subsystem, directly affecting its longevity and long-term system reliability.

Keywords: hybrid energy system, photovoltaic, hydrogen subsystem, energy management, capacity

1. Introduction

A typical standalone energy system consists of a photovoltaic (PV) array or a wind turbine, complemented by batteries for energy storage. The hybridization of these systems, i.e., the integration of both PV panels and wind turbines, enhances the overall system resilience. Performance analyzes are performed and optimization methods are proposed for sizing battery-based hybrid renewable energy system (HRES) components for different load profiles, Tito et al. 2016. Beyond configurations where the battery (BT) is the sole form of energy storage, other studies have considered hydrogen subsystems (HS) exclusively as the energy storage solution. A multi-objective techno-economic optimization of such a system configuration, revealing that component outages can notably affect system reliability. The power control strategy for hybrid renewable energy systems aimed at enhancing battery performance and lifespan was proposed in Lamzouri and Boufounas 2021. Mahesh and Sushnigdha 2022 conducted a techno-economic evaluation of a PV/wind/battery HRES incorporating electric vehicles as additional end-user loads and alternative energy storage options. Besides configurations relying solely on batteries (BT) for energy storage, several studies investigate HRES architectures employing hydrogen subsystems (HS) exclusively for energy storage. For example, Baghaee 2021 presents a multi-objective techno-economic optimization of such a system, demonstrating that component outages significantly affect system reliability.

The hydrogen subsystem, comprising an electrolyzer, hydrogen storage, and a fuel cell, serves as a long-term energy storage mechanism, thus enhancing overall system resilience. Zhang et al. analyzed three HRES configurations utilizing only hydrogen-based storage combined with artificial neural network-based weather forecasting. In configurations with multiple energy storage types, implementation of an energy management strategy is essential to fulfill system objectives efficiently Vivas, 2017. Castaneda, 2013 examined HRES performance under three distinct energy management strategies predicated on system energy balance.

Key HRES components—photovoltaic panels, batteries, electrolyzers, and fuel cells—experience performance degradation over time, which must be incorporated into system sizing and control strategy development. The capacity degradation dynamics of batteries, PEM electrolyzers, and PEM fuel cells are dependent on operational conditions and, reciprocally, influence the overall system performance.

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Garcia et al. 2013 analyzed HRES performance under two energy management strategies with economic objective functions, determining battery, fuel cell (FC), and electrolyzer (EL) lifespan based on battery charge/discharge cycles and fuel cell and electrolyzer operational hours and on-off cycles. This investigation was extended in Garcia et al. 2014 to include two additional energy management strategies characterized by technical objective functions. Behzadi and Niasati 2014 conducted simulations evaluating three energy management strategies combined with three component sizing methodologies based on system energy balance. Torreglosa et al. 2013 assessed HRES performance using a hierarchical control strategy where the master control algorithm is guided by battery and hydrogen storage state of charge, while the slave algorithm utilizes cascade control loops. Torreglosa et al. 2014 compared system performance using dual hysteresis control loops for battery and hydrogen storage against predictive control algorithms. Marrocco et al. 2021 performed techno-economic sizing and performance assessment of an off-grid hydrogen-based system over one year employing an energy balance-based management strategy; component lifespans were derived from operational dynamics. Subsequent Marrocco et al. 2022 incorporated a wind turbine (WT) and diesel generator (DG) into the system. Huangfu et al. 2022 conducted a comparative study of two energy management strategies based on subsection bi-objective optimization (SBO) and multi-objective genetic algorithm (MOGA).

Notably, these studies typically do not incorporate progressive capacity degradation of HRES components over the simulation time frame nor assess its impact on overall system performance. Ozden et al., 2017 investigated the effect of PEM component degradation on system performance by implementing a model of degraded PEM components and conducting techno-economic analysis of a PV/hydrogen system; however, the degradation dynamics were not modeled, as the focus was centered on the effects of existing component degradation.

Most HRES simulation studies adopt a one-year simulation period with hourly timestep resolution (Erikson and Gray, 2018, Khan and Javaid, 2020, Ma and Javid, 2020, Zhang et al. 2022, though some extend simulations to 25 years. MATLAB is widely used for mathematical modeling and performance simulation of HRES components (Ceylan and Devrim, 2021, Kamel et al. 2021, Rullo et al. 2019, Sanchez et al. 2014., Zhang et al. 2020.). HOMER is another prevalent tool for HRES sizing and simulation due to its extensive component libraries and global meteorological datasets (Babaei et al. 2022, Bezmalinovic et al. 2012, Duman and Guler 2018, Mori et al., 2020, Qi et al. 2022), albeit with limited model customization capabilities. Additionally, some investigations employ TRNSYS for system performance simulation (Behzadi and Niasati 2014, Farroki et al. 2022, Ozden and Tari 2017).

This study conducts a performance analysis of a hybrid renewable energy system under constant end-user load profiles and two energy management strategies. The performance assessment incorporates dynamic capacity degradation models for the battery, proton exchange membrane (PEM) electrolyzer, and PEM fuel cell, which are functions of system operational conditions, alongside the time-dependent degradation of the photovoltaic (PV) modules. The primary objective of the HRES configuration is to ensure uninterrupted energy supply to the end user. This investigation aims to quantify the impact of component capacity degradation on overall system performance and energy reliability. Simulations were implemented in MATLAB to evaluate system behavior.

This paper applies detailed degradation models to analyze how loss of capacity in PV modules, lead-acid batteries, electrolyzers, and fuel cells impacts HRES operation over two decades. It further evaluates how two control strategies (EMS-A: energy balance, EMS-B: double hysteresis) influence component ageing and system reliability for both smooth and fluctuating load scenarios.

2. System Description and Methodology

The hybrid renewable energy system investigated in this study consists of: a photovoltaic (PV) array 1.9 kW for primary solar generation; a wind turbine 1.6 kW for supplementary energy production; a lead-acid battery 30 kWh and 45 kWh (depending on control), serving as short-term energy storage; and a hydrogen subsystem, including: 1.2 kW PEM electrolyzer, hydrogen compressor 1kW, storage vessel 0.75 m^3. A schematic diagram of the configured HRES is shown in Figure 1.

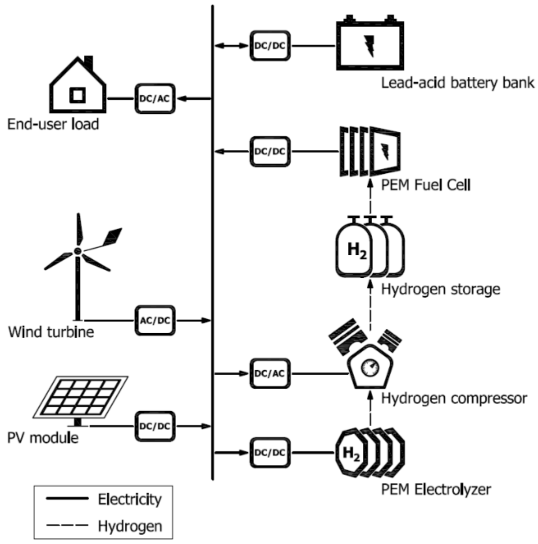

Fig. 1: Hybrid photovoltaic system

Simulations use twenty years of hourly meteorological data from Mediterranean area, to reflect realistic seasonal and intraday variations. The photovoltaic power P_{PV} is determined according to Zhang et al. (2022):

$$P_{PV} = E_\beta A_{PV}\left[\eta_{PV} + \mu_{P,st}\left(T_c - T_{c,st}\right)\right]\eta_{s1}$$

where E_β is the insolation on a tilted plane, A_{PV} is the PV effective surface area, η_{PV} is the PV module efficiency, $\mu_{P,st}$ is the temperature coefficient of power ($-0.35\%\ °C^{-1}$), T_c is the PV cell temperature, $T_{c,st}$ is the PV cell temperature at standard operating conditions (25 °C), and η_{s1} is the DC/DC converter efficiency (95%). Hourly solar irradiation on an inclined plane was determined from hourly global irradiation, obtained from the national meteorological service for a typical Mediterranean location. Other important parameters to fulfill energy demand such as: wind turbine power, battery state of charge, PEM fuel cell efficiency, PEM electrolyser efficiency, hydrogen storage volume, hydrogen compressor power demand, are determined according to methodology explained in Simunovic et al. (2023).

The energy management strategy (EMS) is crucial for ensuring uninterrupted operation and high reliability in hybrid renewable energy systems (HRES) with multiple energy storage types, while also significantly influencing the lifetime of system components. Two energy management strategies are investigated. The first EMS-A strategy is based on energy balancing within the HRES. The end-user load is first attempted to be met directly from RES, as it is the most efficient energy path and therefore has the highest priority level. If RES exceeds the end-user load demand, the excess energy will be used to charge the BT batteries, and if and when the BT is fully charged, the excess energy will be used to produce hydrogen via the PEM electrolyzer. Once operational, the electrolyzer will operate in a variable mode, depending on the RES production profile. If the produced RES is not sufficient to meet the end-user load, BT is used to compensate for the energy differences, if RES is insufficient and SoC_{BT} is low, the FC will use the stored hydrogen to produce electricity to meet the end-user load needs. In the second EMS-B strategy, the end-user load is first tried to be directly satisfied from the RES, and then based on the FC and electrolyzer on/off control using a double hysteresis control loop scheme, where SoC_{BT} is used as the main control parameter. EL_{up} is the on-off parameter and EL_{low} is the electrolyzer off-control parameter, while FC_{low} is the on-off control parameter and FC_{up} is the FC off-control control parameter. The double hysteresis loop diagram indicates that the active capacity of the EMS-B system is directly influenced by the operational and control parameters, despite the allowance for the battery (BT) to utilize up to 20% of the available capacity. In this investigation, the state of charge (SoC) thresholds are defined as follows: 100% for the upper limit, 80% for the charging cutoff, 50% for the mid-level threshold, and 40% for the lower limit. Establishing the lower threshold at 40% effectively mitigates the risk of deep discharge cycles, thereby enhancing battery longevity. Conversely, maintaining the upper threshold at 100% prevents the accumulation of detrimental charging cycles in the battery. Figure 2 shows the possible energy flow routs for each EMS considered.

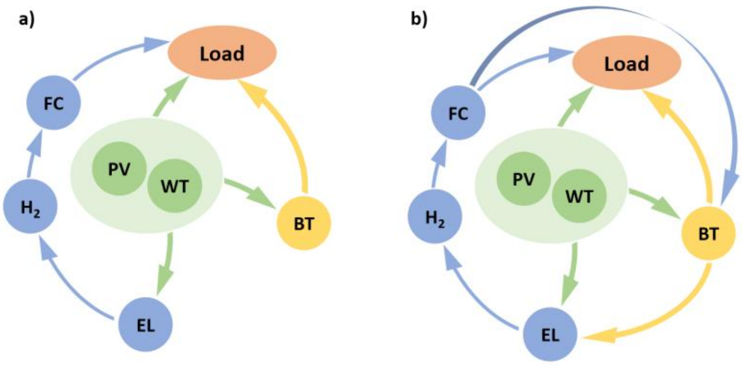

Fig. 2: Possible energy flow routes: a) EMS-A; b) EMS-B

The electrolyzer (EL) in EMS-B operates in two modes: variable and fixed. Mode selection depends on the state of charge (SoC) and the energy surplus from renewable sources (RES) relative to load demand. When SoC lies between defined limits, the EL runs primarily in fixed mode at optimal efficiency (~40% power). If RES surplus is insufficient for 40% operation, the battery (BT) compensates the deficit; if surplus exceeds this, excess energy charges the BT. Once the BT is fully charged, the EL shifts to variable mode. For negative energy difference with SoC in range and EL active, the BT supplies power to maintain EL operation at maximum efficiency, reducing on/off cycles. The fuel cell (FC) operates only in fixed mode at maximum power. When SoC is within limits and FC is active, the BT can only charge, not discharge. Independent of energy difference polarity, the FC charges the BT until SoC reaches the upper limit, ensuring full load satisfaction.

3. Results and discussion

The performance of the hybrid photovoltaic system was simulated for a period of 20 years, with a time step of one hour. Each simulation was started with a battery state of charge of 100% and hydrogen storage at a pressure of 46 bar (25% of the water storage capacity). The end-user directly used about 43% of the produced energy for both considered cases, while there was about 20% of the unused energy for EMS-A case, and 16.5% of unused energy for EMS-B case.

The EMS-A scenario failed to fully satisfied the end-user load throughout the evaluation period, failing to meet load demand for 226 hours (0.008% of total unmet energy).These shortages arose from preset FC operational constraints rather than system-wide energy scarcity, as hydrogen storage pressure remained above 60 bar throughout, Figure 3.

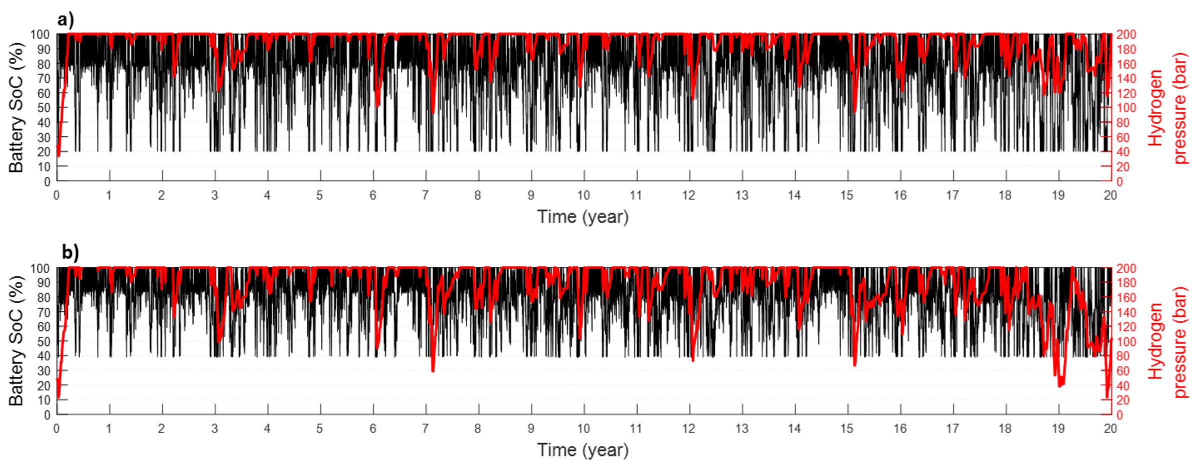

Fig. 4: The battery charge/discharge cycles and hydrogen production/consumption dynamics: a) EMS-A; b) EMS-B

About 30% of produced energy was used for battery charging for both considered cases, while all remaining energy was used for hydrogen production and compression. A noticeable increasing trend of the FC annual operating hours and the electrolyzer annual operating hours throughout the considered time period, Figure 4. The FC annual operating time increasing trend was caused by the PV capacity degradation and the battery loss of capacity. With the PV capacity degradation, the system energy production capacity was reduced, and with the battery loss of capacity, the system's short-term energy storage was reduced, which caused the system to require more frequent hydrogen utilization via FC. The EMS-A scenario exhibited 5856 hours of fuel cell (FC) operation, whereas the EMS-B scenario recorded 5437 hours. However, EMS-B demonstrated a superior FC relative average operating power of 96 %, compared to 65.5 % for EMS-A. Furthermore, EMS-B resulted in a higher FC operating hours per start ratio. Even though EMS-A resulted in a slightly higher overall operating hours, EMS-B achieved a higher operating hours per start ratio, which was made possible by FC SoC on-off control parameters. With more frequent use of FC, the average value of the hydrogen storage pressure level was lower, making it possible for the more frequent electrolyzer operation.

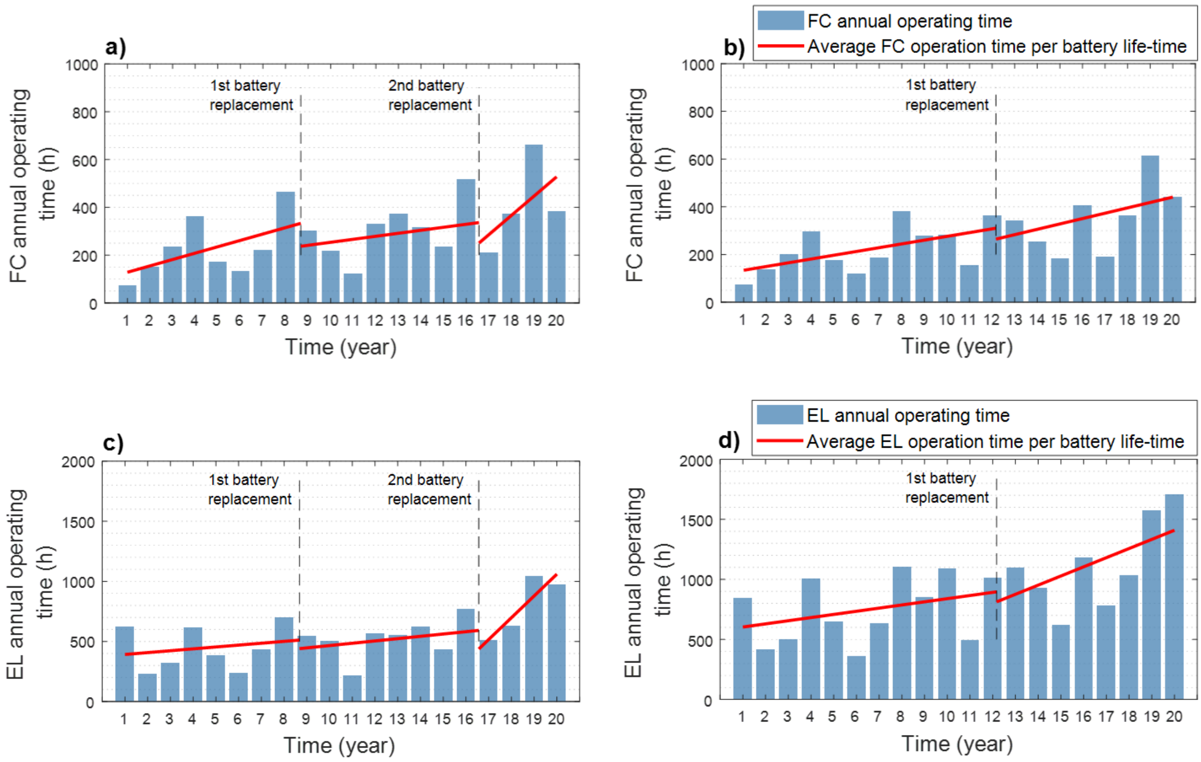

Fig. 4: Annual operation time distribution: a) FC EMS-A; b) FC EMS-B; c) EL EMS-A; d) EL EMS-B

The EMS-B resulted in a relatively higher system reliability towards the end-user load. The electrolyzer performance was highly influenced by the EMS, where the EMS-B achieved two to three times higher average operating hours per start value, compared to the EMS-A. However, both considered cases resulted in the overall increase of electrolyzer and FC operation time towards the end of the considered time period due to the PV and battery capacity loss. In order to achieve the best possible performance of hybrid photovoltaic systems, all technical, economic and environmental aspects need to be taken into account during sizing. All these aspects will be equally taken into account when developing a multi-objective optimization.

4. Conclusions

The study presented a comprehensive analysis of a stand-alone hybrid photovoltaic system integrating photovoltaic panels, a small wind turbine, a lead-acid battery bank, and a hydrogen subsystem comprising a PEM electrolyzer, hydrogen compressor, storage tank, and PEM fuel cell. Mathematical models were developed for each component to accurately represent their operational behaviors, including capacity loss dynamics of the PV module, battery, electrolyzer, and fuel cell. Two energy management strategies were evaluated: a basic energy balance-based strategy (EMS-A) and a more advanced double hysteresis control loop scheme (EMS-B). Simulation results demonstrated that EMS-B significantly enhanced battery lifespan compared to EMS-A while also improving system reliability under end-user load conditions. Both strategies showed increased operation times for the electrolyzer and fuel cell towards the end of the simulation period, attributed to degradation in PV and battery capacity. These findings emphasize the importance of implementing advanced energy management approaches to optimize hybrid renewable energy system performance. Furthermore, achieving optimal hybrid photovoltaic system operation requires a holistic approach that incorporates technical, economic, and environmental factors to ensure sustainability and efficiency over the system lifecycle.

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