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Comparative study of hydrogen storage and battery storage in grid connected photovoltaic system: Storage sizing and rule-based operation ☆

Yang Zhang [a,b,*], Pietro Elia Campana [c], Anders Lundblad [a,c], Jinyue Yan [a,c,*]

[a] Department of Chemical Engineering and Technology, School of Chemical Science and Engineering, KTH Royal Institute of Technology, SE-10044 Stockholm, Sweden
[b] Ningbo RX New Materials Tech. Co. Ltd., 315200 Ningbo, China
[c] School of Business, Society & Engineering, Mälardalen University, SE-72123 Västerås, Sweden

HIGHLIGHTS

- A hybrid operation strategy is proposed for grid-connected PV-hydrogen system.
- Component capacities and operation parameters are optimized simultaneously.
- Three operation strategies are compared through multi-objective optimization.
- Hydrogen storage and battery storage are compared.
- High Net Present Value and Self Sufficiency Ratio are achieved at the same time.

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ABSTRACT

The paper studies grid-connected photovoltaic (PV)-hydrogen/battery systems. The storage component capacities and the rule-based operation strategy parameters are simultaneously optimized by the Genetic Algorithm. Three operation strategies for the hydrogen storage, namely conventional operation strategy, peak shaving strategy and hybrid operation strategy, are compared under two scenarios based on the pessimistic and optimistic costs. The results indicate that the hybrid operation strategy, which combines the conventional operation strategy and the peak shaving strategy, is advantageous in achieving higher Net Present Value (NPV) and Self Sufficiency Ratio (SSR). Hydrogen storage is further compared with battery storage. Under the pessimistic cost scenario, hydrogen storage results in poorer performance in both SSR and NPV. While under the optimistic cost scenario, hydrogen storage achieves higher NPV. Moreover, when taking into account the grid power fluctuation, hydrogen storage achieves better performance in all three optimization objectives, which are NPV, SSR and GI (Grid Indicator).

1. Introduction

There is a rapid increase in installed Photovoltaic (PV) capacity in recent years. 38.7 GW were installed worldwide in 2014 [1]. Supporting policies, such as feed-in-tariff and net-metering, act as important incentives for the rapid increase [2]. However, with the decreasing cost of PV modules and the PV intermittency problem, the supporting incentives are expected to be gradually phased out. The PV self-consumption becomes more attractive because the self-consumed electricity generally has more economic values than the exported electricity [3,4]. The self-consumed electricity not only generates economic benefits to the PV system owner, but also improves the power quality. Energy storage plays a vital role for increasing PV self-consumption [4]. However, increased capital investment with energy storage calls for detailed analysis and optimal solutions should be carried out to simultaneously determine the energy storage method, the storage capacity and the operation strategy.

Many studies have focused on the optimization of either storage capacity or operation strategy. Genetic Algorithm [5] and particle swarm optimization [6] were introduced to find the optimal component capacity. Dynamic programming was employed to determine the 24-h ahead power schedule [7]. A short-term

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* Corresponding authors at: Teknikringen 42, SE-11428 Stockholm, Sweden.
E-mail addresses: yaz@kth.se (Y. Zhang), pietro.campana@mdh.se (P.E. Campana), lundbla@kth.se (A. Lundblad), jinyue@kth.se (J. Yan).

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Nomenclature

$C_{O\&M,y}$ operation and maintenance cost at year y [SEK]
$C_{R,y}$ replacement cost at year y [SEK]
CAP_i capacity for component *i* [kW/kW h/kg]
$El_{r,t}$ retail electricity price at time t [SEK/kW h]
$El_{w,t}$ wholesale electricity price at time t [SEK/kW h]
Inv investment cost [SEK]
$P_{Net,t}$ net Power at time t [kW]
$P_{L,t}$ load at time t [kW]
$P_{PV,t}$ PV production at time t [kW]
$P_{HS,t}$ hydrogen storage system power at time t [kW]
$P_{Batt,t}$ battery power at time t [kW]
$P_{G,t}$ grid power at time t [kW]
$P_{Gim,t}$ imported grid power at time t [kW]
$P_{Gex,t}$ exported grid power at time t [kW]
P_E export limit [kW]
P_{PL} grid peak limit [kW]
P_{CL} charge limit [kW]
P_{PR} grid peak power reduction [kW]
R_y system revenue at year y [SEK]
$R_{ER,y}$ electricity reduction revenue at year y [SEK]
$R_{EX,y}$ export revenue at year y [SEK]
$R_{PS,y}$ peak shaving revenue at year y [SEK]
$r_{O\&M,i}$ O&M ratio for component *i* [%/Year]
$SOH2_L$ state of hydrogen level limit [%]
SOC_t state of charge at time *t* [%]
t_s conventional operation start time [h]
t_e conventional operation end time [h]
UIC_i unit investment cost for component *i* [SEK/Capacity Unit]

Abbreviations
DOD Depth of Discharge
Elspot Electricity Spot
Fit Feed-in-tariff
GA Genetic Algorithm
GI Grid Indicator
NPV Net Present Value
PV Photovoltaic
SSR Self Sufficiency Ratio
TOU Time-of-Use

scheduling method using a Lagrangian relaxation-based optimization algorithm was suggested in Lu et al. [8]. There are also approaches aiming at achieving the optimal storage capacity and operation strategy simultaneously. Ru et al. [9] and Khalilpour et al. [10] addressed the sizing problem with consideration of the operation strategies. Zhang et al. summarized the existing methods and proposed an approach, which simultaneously obtained the storage capacity and rule-based operation strategies [11].

Battery is usually chosen as the energy storage method, because it is considered as a mature technology [12]. However, it is not suitable for long-term storage because of the low energy density and high self-discharge rate. Thus battery storage cannot address the seasonal mismatch between the PV production and load, which is quite common in residential buildings of Nordic countries. On the other hand, hydrogen storage converts electricity into the form of hydrogen. It has higher energy density and insignificant leakage (discharge) rate [13]. It is an appropriate long-term storage method to solve the seasonal mismatch problem [14], and its potential application in residential building are closely followed by research institutions and industry stakeholders [15]. Another advantage of hydrogen storage is the flexible combination of charge power, discharge power and storage capacity, because each of them is determined by separate component. The major drawbacks of hydrogen storage are the high investment cost and low round trip efficiency (around 35%) [14]. Literature survey is conducted below to explain the current research gap in the comparison between hydrogen storage and battery storage.

Some studies on the off-grid system employed both battery storage and hydrogen storage. Bigdeli suggested that fuzzy logic control and quantum behaved particle swarm optimization have better performance than other control algorithms [16]. Carapellucci et al. presented an optimization tool by using a hybrid genetic-simulated annealing algorithm. However, the optimization of operation strategies is not included [17]. Castañeda et al. compared three control strategies for the combined battery and hydrogen storage system [18]. However, the operation strategies are all predefined and fixed.

Hydrogen storage and battery storage are also employed in grid-connected systems. Parra et al. studied the benefits of battery storage and hydrogen storage for a grid-connected single house [19]. Marino et al. carried out techno-economic analysis of a grid-connected hydrogen storage system and concluded that the system can only be realized with subsidies [20]. Avril et al. studied a grid-connected PV system with both battery storage and hydrogen storage, and carried out optimization. However, one optimization objective was to minimize the system dependency on the grid, and the operation strategy was not optimized [21]. Pellow et al. compared grid-scale hydrogen storage and battery storage. The comparison results indicated that hydrogen storage stored more electricity than battery storage through the lifetime [22]. García-Triviño et al. carried out long-term optimization for different Energy Management Systems (EMS) and concluded that EMS can be tailored for different purposes [23].

The literature review indicates that there are few studies that simultaneously optimize the hydrogen storage capacity and the operation strategy. The comparison between hydrogen storage and battery storage, especially under the seasonal mismatch case, is also lacking. This study aims to fill the above-mentioned research gap. However, it restricts the scope to employ either hydrogen storage or battery storage within the system. The combined battery and hydrogen storage system is not considered in this study.

Based on our previous study [11], we extend the methodology through developing hydrogen storage model and introducing new operation strategies for the grid-connected PV-hydrogen storage system, building a ready-to-use tool for the system. The battery storage and hydrogen storage are further compared with the extended methodology.

The paper is organized as follows: Section 1 is the introduction; Section 2 gives the system layout and component models; Section 3 discusses about the objectives of the optimization; Section 4 describes the different operation strategies in detail; Section 5 has a brief introduction about Genetic Algorithm; Section 6 presents results and carries out discussion; Section 7 draws the conclusions.

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